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Development of the *Jatropha* cultivation and biodiesel production: case study of Karnataka State, India

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy and the Diploma of Imperial College

by

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I declare that, except where stated, the work presented in this thesis is my own

Signed

Date

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Ph.D Thesis by Alexander N. Estrin, P.Eng.

Abstract

In 2003 India launched a National Mission on Biofuels. Its main strategy has been to promote *Jatropha curcas*; a perennial shrub that bears non-edible oil seeds that can be used to produce biodiesel with the aim of achieving a target of 20% blending of biodiesel by 2012.

This thesis recommends a framework that will enable people to implement Biodiesel Production System in Karnataka State, India, and possibility replicate it in other developing countries. Detailed combinations of Life Cycle Assessment with Technical and Cost-benefit Analysis have been developed to assess the suitability of individual oilseed crops for large scale cultivation from energy, environmental and socio-economic perspectives. The ways in which biodiesel are produced with the impacts on energy balance, GHG emissions and costs have been evaluated.

All large scale agricultural and small-scale agricultural scenarios produced negative NPV per life cycle. A key common feature from all the results is that in conditions of an established market, the price of Jatropha oilseeds, as a final product of agricultural enterprise, has a strong influence on price of Jatropha SVO, the main raw material for biodiesel production. As such, it will require strong and direct government's intervention to both agricultural and industrial phases of this chain, to keep them in business. For large scale agricultural scenarios demonstrate the following options to make NPV of the feedstock production positive: a) raise Jatropha oilseed price in 1.91-2.08 times, b) impose government's subsidies on working capital at least 41.55-69.85% large, or c) impose government's subsidies on CAPEX at least 27.25-28.81% large. For small-scale agricultural scenarios sensitivity analysis produces the following options: a) to raise Jatropha oilseed price in 1.92-2.38 times, or b) to impose government's subsidies on working capital at least 41.5-51.0% large.

The results of this work do not show a way in which subsidies could be removed. In deciding whether to support this technology, the public support for early stage commercialization investment might be considered as illustrated in the "Stern Review: The Economics of Climate Change" (2006) by experience curves.

For all large scale and small-scale agricultural scenarios, the correlation results demonstrate that price of oilseeds, the *Jatropha* oilseed yields, the labour cost coefficient, and subsidies on working capital (Private Capital) are all significantly correlated with NPV and NPV/GHG avoided ratio. For both large scale and small-scale production scenarios, only the price of *Jatropha* oil significantly correlated with NPV and NPV/GHG avoided ratio.

Cost-effectiveness analysis demonstrates a very high GHG avoided (GBP/tCO_2eq) costs for all scenarios compared to the current market price of Certified Emissions Reduction (CER). To make average costs of GHG avoided comparable with current CER price, the price of Jatropha oilseeds should be reduced by 0.91-1.99 times in Irrigated and by 1.22-1.91 times for Rainfed scenarios. However, in this case, the effect on economics of Jatropha oilseeds cultivation (agricultural scenarios) will be disastrous.

To show the potential savings, the energy use and GHG emissions for each Model have been compared with the Well-to-Tank (WTT) energy and GHG emissions for diesel (basic scenario). Some Models actually save more fossil energy than is contained in the produced biodiesel as a result of the large energy savings attached to electricity production and other by-products utilization. The GHG savings has a pattern which is clearly corresponding with the energy one. The emissions from farming, especially excessive N_2O emissions, are responsible for significant fraction of total GHG emissions. All Rainfed scenarios demonstrate much better energy and GHG emissions performance than Irrigated scenarios. Unfortunately, considerable benefits of energy and GHG savings produced by small-scale in comparison to large-scale Jatropha cultivation have been challenged by the negative results of the Cost-benefit analysis for the same Models.

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"Nothing is impossible for a man who doesn't have to do it himself."

Abe H Weiler

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To all these people, my sincere thanks. I will remain indebted to them all.

Table of contents

List of tables, charts, graphs, figures and pictures

Abbreviations and acronyms

a	Annum
A/F	Afforestation/ Reforestation
AICRPDA	All India Coordinated Research Project for Dryland Agriculture
AISLUS	All India Soil and Land Use Survey Organization
ALCA	Attributional LCA
APR	Aqueous Phase Reforming Process
ARTI	Appropriate Rural Technology Institute. Pune. Maharashtra
ASTM	American Society for Testing and Materials
BAI or BDAI	Biodiesel Association of India
BIG	Biomass Integrated Gasifier
BIG/GTCC	Biomass Integrated Gasifier/Gas Turbine Combine Cycle
BIS	Bureau of Indian Standards
BPSTG	Backpressure Steam Turbo-Generator
C	Carbon
CAD	Canadian Dollar
CAPART	Council for Advancement of People’s Action and Rural Technology
CAZRI	Central Arid Zone Research Institute
CBA	Cost-Benefit Analysis
CBD	Convention on Biological Diversity
CBDA	Chhattisgharh Bio-fuel Development Authority
CBM	Coal bed methane
CBO	Community Based Organisation
CBP	Capacity Building Phase
CDCF	World’s Bank’s Community Development Carbon Fund
CEA	Central Electricity Authority
CEO	Chief Executive Officer
CER	Certified Emissions Reductions
CEST	Condensed Extraction Steam Turbine
CFO	Chief Financial Officer
CDCF	World’s Bank’s Community Development Carbon Fund
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CFM	Community Forest Management
CGES	Centre for Global Energy Studies. London: United Kingdom
CHP	Combined Heat and Power
CLCA	Consequental LCA
CNG	Compressed Natural Gas
CONCAWE	European Oil Company Organisation for Environment, Health and Safety. Brussels. Belgium
COP	Conference of Parties
CPR	Common Property Rights/ Common Property Resources

CPRI	Central Power Research Institute
CREDA	Chhattisgharh State Renewable Energy Development Agency
CRIDA	Central Research Institute for Dryland Agriculture
CRISIL	Credit Rating Information Services of India Limited
CPLR	Common Property Land Resources
CS	Carbon sequestration
CST	Central Sales Tax
CSWRTI	Centre for Soil and Water Conservation, Research and Training Institute
DAC	Department of Agriculture and Cooperation
DAS or d	Days After Seeding/Sowing
DDGS	Dried Distillers Grains & Solubles
DDP	Desert Development Programme
DFID	Department for International Development. United Kingdom
DGH	Directorate General of Hydrocarbones
DHC	District Heating/Cooling
DoLR	Department of Land Resources
DoRD	Department of Rural Development
€ or EUR	Euro
EAP	Externally Aided Programme
EFmGT	Externally Fired Micro Gas Turbine (the same as IFGT)
EfW	Energy-from-Waste
EMPRI	Environmental Management and Policy Research Institute. Bangalore
EPA	Environemtnal Protection Agency. USA
ERR	Economic Rate of Return
ERU	Emission Reduction Units
ESCO	Energy Service Companies
ESMAP	Energy Sector Management Assistance Program of The World Bank
EUCAR	European Council for Automotive R&D. Brussels. Belgium
EU ETS	European Union Greenhouse Gas Emission Trading Scheme
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Database
FCI	Food Corporation of India
FD	Forest Department
FDA	Forest Development Agency
FDC	Forest Development Committee/ Corporation
FFA	Free Fatty Acid
FICCI	Federation of Indian Chamber of Commerce & Industries
FIP	Full Implementation Phase
FPC	Forest Protection Committee
FRI	Forest Research Institute
FY	Financial Year
FYM	Farm Yard Manure

GAIL	Gas Authority of India
£ or GBP	Great Britain Pound. Pound Sterling
GDP	Gross Domestic Product
GEECL	Great Eastern Energy Corporation Ltd.
GEF	Global Environment Facility
GEMIS	Global Emission Model for Integrated Systems
GGCL	Gujarat Gas Company Ltd.
GIS	Geographic Information Systems
GHG	Green House Gases
GOI	Government of India
G.P.	General Practicioner (Physician), United Kingdom
GP	Gram Panchayat (local government body at the village level)
GS	Gram Sabha (a village level community body)
GSPL	Gujarat State Petroleum Ltd.
GTZ	Die Deutsche Gesellschaft für Technische Zusammenarbeit
GWP	Global Warming Potential
HGCA	Home Grown Cereals Authority. London. United Kingdom
HHV	Higher Heating Value
HTS	Heat Trasfer System
HRSG	Heat Recovery Steam Generator
HSD	High Speed Diesel
HUB	Heat Utilization Block
HYV	High Yielding Variety
IARI	Indian Agricultural Research Institute
ICAR	Indian Council of Agricultural Research
ICAR	Central Soil Salinity Research Institute
ICFRE	Indian Council of Forestry Research & Education
ICON	Imperial Consultants
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
ICSSR	Indian Council of Social Science Research
IEA	International Energy Agency
IFC	International Finance Corporation
IFDC	International Center for Soil Fertility and Agricultural Development. Muscle Shoals. Alabama. USA
IFGT	Indirectly Fired Gas Turbine (the same as EFmGT)
IGCC	Intergrated Gasifier Combined Cycle
IIFM	Indian Institute of Forest Management
IIP	Indian Institute of Petroleum
IISc	Indian Institute of Science. Bangalore
IIT. New Delhi	Indian Institute of Technology. New Delhi
INR or Rs.	Indian Rupee
INSAF	Indian Social Action Forum
IOC	International Oil Company

IPCC	Intergovernmental Panel on Climate Change
IPIECA	International Petroleum Industry Environmental Conservation Association. London. United Kingdom
IPO	Initial Public Offering
IRDA	The Insurance Regulatory and Development Authority
IRR	Internal Rate of Return
IRMA	Institute of Rural Management on Agriculture
ISO	International Organization for Standardization
JFM	Joint Forest Management
JI	Joint Implementation
JRC	Joint Research Centre. European Commission. Brussels. Belgium
KVIC	Khadi and Village Industries Commission. Ministry of Micro, Small And Medium Enterprises
KWDP	Karnataka Watershed Development Project
LCA	Life Cycle Analysis/ Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LNG-FPCO	LNG floating production, storage and offloading vessel
LowCVP	Low Carbon Vehicle Partnership. London. United Kingdom
LPG	Liquefied Petroleum Gas
LSHD	Low Sulphur Highway Diesel Fuel
LUC	Land Use Change
LULUCF	Land Use, Land Use Change and Forestry
MANAGE	National Institute of Agriculture Extension and Management. Hyderabad. Andhra Pradesh
MDGs	Millenium Development Goals
M&E	Monitoring and Evaluation
MoA	Ministry of Agriculture
MoEF	Ministry of Environment and Forests
MoP	Ministry of Power
MoRD	Ministry of Rural Development
MoU	Memorandum of Understanding
MoWR	Ministry of Water Resources.
MNRE	Ministry of New and Renewable Energy
MSEs	Micro and Small Enterprises
MSFCL	Maharashtra State Farming Corporation Ltd.
MSP	Minimum Support Price
NABARD	National Bank for Agriculture and Rural Development
NAP	National Afforestation Programme
NAEP	National Afforestation and Eco-Development Project
NASDORA	National Authority for Sustainable Development of Rainfed Areas
NBDB	National Bio-fuel Development Board
NBSS&LUP	National Bureau of Soil Survey and Land Use Planning

NCA	National Commission on Agriculture
NCF	National Commission on Farmers
NDC	National Development Council
NDV	Normalized Difference Vegetation Index
NELP	New Exploration and Licensing Policy
NG	Natural Gas
NG GT	Natural Gas Fired Gas Turbine
NGO	Non-Governmental Organization
NIC	National Informatics Centre
NLCB	National Land Use and Conservation Board
NOC	National Oil Company
NOVOD	National Oilseeds and Vegetable Oil Development Board
NRAA	National Rainfed Area Authority
NRCAF	National Research Centre for Agro-Forestry, Uttar Pradesh
NRCan	Natural Resources Canada. Ottawa
NREGA/P/S	National Rural Employment Guarantee Act/ Programme/ Scheme
NREGS	National Rural Employment Guarantee Scheme
NRM	Natural Resource Management
NTPS	National Thermal Power Corporation
NWDPRA	National Watershed Development Programme for Rainfed Areas
OCFSS	Orissa Coalition for Food Safety and Sovereignty
O+OEG	Oil and Oil Equivalent of Gas
OECD	Organization for Economic Co-operatin and Development
OIL	Oil India Ltd.
ONGC	Oil & Natural Gas Corporation
OREDA	Orissa Renewable Energy Development Agency
OVL	ONGC Videsh Ltd. - overseas arm of ONGC
PAH	Polycyclic Aromatic Hydrocarbons
PCRA	Petroleum Conservation and Research Association
PDS	Public Distribution System
PFA	Project Facilitating Agency
PIA	Project Implementation Agency
PM	Particulate Matter
PMU	Project Management Unit
PPO	Pure Plant Oil, the same as SVO
PPP	Public Private Partnership
PRI	Panchayati Raj Institution
R&D	Research and Development
RETs	Renewable Energy Technologies
RFS	Renewable Fuel Standard
RGPPL	Ratnagiri Gas and Power Private Ltd.
RGTIL	Reliance Industries Transportation Infrustructure Ltd.

RIDF	Rural Infrastructure Development Fund
RIL	Reliance Industries Ltd.
RNRL	Reliance Natural Resources Ltd.
RPS	Renewable Portfolio Standards
RSB	Roundtable on Sustainable Biofuels
SE	Social Enterprise
SEI	Stockholm Environment Institute. Sweden
SEZ	Special Economic Zone
SHG	Self-Help Group
SLUB	State Land Use Board
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SVO	Straight Vegetable Oil, the same as PPO
TBOs or TBOS	Tree Borne Oilseeds
TEDDY	TERI Energy Data Directory & Yearbook
TEM	Techno Economic Model
TERI	The Energy Research Institute
TFP	Total Factor Productivity
TNAU	Tamil Nadu Agricultural University. Coimbatore
ToR	Terms of Reference
TPES	Total Primary Energy Supply
TTW	Tank-to-Wheel
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific. Bangkok
UNFCCC	United Nations Framework Convention on Climate Change
USD or US$	United States Dollar
UBB	Uttaranchal Biofuels Board
VAT	Value Added Tax
VDC	Village Development Committee
VER	Voluntary Emissions Reductions
VRC	Village Resource Centre
WB	World Bank
WG	Working Group
WGDP	Western Ghats Development Programme
WFPS or WPS	Water Filled Porosity or Water Filled Pore Space
WSD	Watershed Development
WTT	Well-to-Tank
WTO	World Trade Organization
WTW	Well-to-Wheel

Measures

atm	Standard Atmosphere - unit of pressure equal to101,325 Pa
bar	bar - unit of pressure equal to100,000 Pa
bbl	Barrel - unit of volume for crude oil and petroleum products
BBLS	Billion barrels
bcfd	Billion cubic feet per day
bcm	Billion cubic meters
b/d or bpd	Barrel a day
Btu or BTU	British Thermal Unit
°C	Degree Celsius
Cr	Crore (100 lakh or 10 million)
dS/m	Salinity level. Decisiemens per metre at 25°C
F or °F	Fahrenheit
g	Gram
GJ	Gigajoule
Ha or ha	Hectare
hr	Hour
kcal	Kilocalorie
kg	Kilogramm
kWh	Kilowatt-hour
L or l	Litre
lakh or lac	One hundred thousand (100,000; 10^5).
mbpd	Million barrel per day
mmbo	Million barrels of oil
mmboe	Million barrels of oil equivalent
MMBOPD	Million barrels of oil per day
mmcf/d	Million cubic feet per day
MMCMD	Million cubic meters of gas per day
MMt	Million metric tonnes
MMtC	Million metric tonnes of carbon
MMSCMD	Million standard cubic meters per day
MMtpa	Million tonnes per annum
MPa	Megapaskal
mtoe	Million tonnes of oil equivalent
mtpa	Million tonnes per annum
MW	Megawatt
MWe	Megawatt electrical
MWth	Megawatt thermal
s	Second
t or MT	Metric Tonne (1,000 kg)
TBLS	Trillion barrels
Tcm (Tcf)	Trillion cubic metres (Trillion cubic feet)

Preface

> "Khrushchev wanted to push maize further to the North by the [Communist] Party boot, but we will extend the planting zone region for maize by 200-300 kilometers by means of scientific approach."
>
> Yury Luzhkov, Mayor of Moscow. 17 July, 2008.

"The queen of the fields" - the official bombastic periphrasis current during Khrushchev's obsessive campaign for planting corn in Russia. Soviet leader Nikita Khrushchev started his campaign for planting corn in Russia after visiting a family farm of American agricultural innovator Roswell "Bob" Garst near Coon Rapids, Iowa on 23rd September 1959 (Frese: 2004). He was impressed by Iowa prairies full of maize, and became convinced that the Soviet Union's agricultural crises could be solved through the planting of maize on the same scale as the United States, failing to realize that the US is far south of most of the Soviet Union and the differences in soil made this inadvisable. Corn requires a relatively long and warm growing season and much more moisture than wheat or most other grains. Most of the farm areas of the USSR were short on all three of these. Nevertheless, a Corn Research Institute was established. The scholarly journal Corn appeared (Prokhorov: 2002). In the end, Garst sold about USD 1.0 million worth of hybrid seed corn to the Soviets (Rubiner: 2000). Nobody was allowed to challenge the authority of the "queen of the fields".

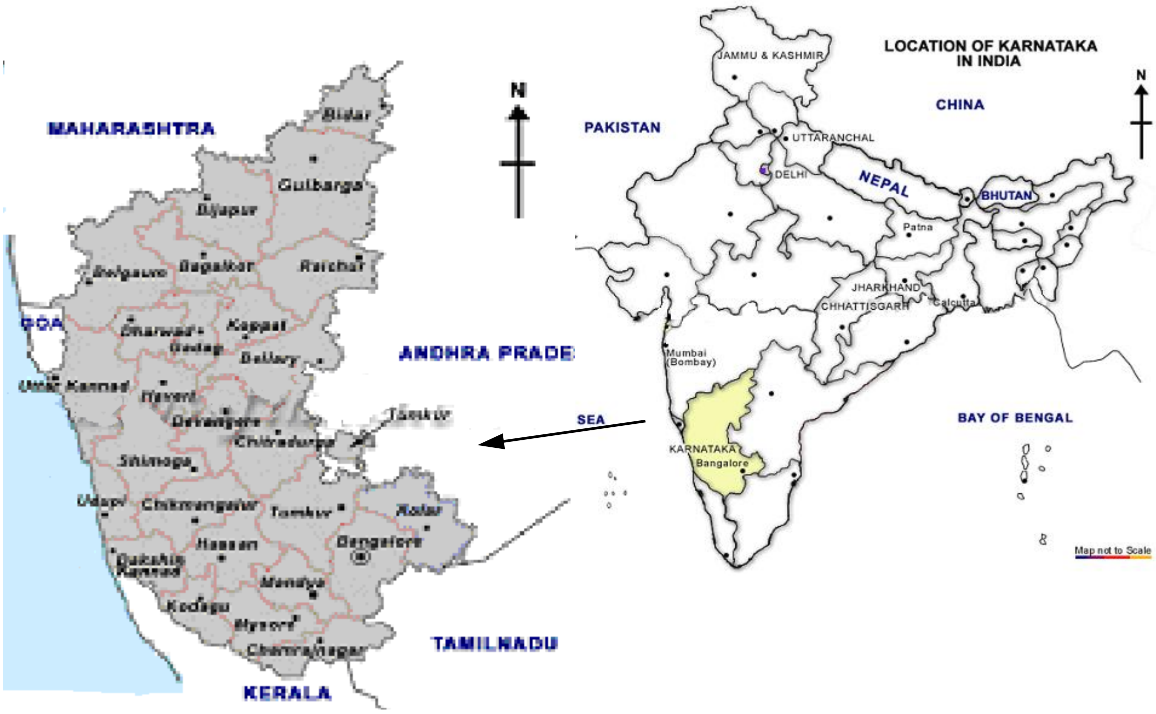
Khrushchev had put too much strain on the countryside and demanded too much. The people had to conform, they had to hit targets, and so farm managers were forced to plant corn, and not grasses and oats, regardless of whether the crops suited the conditions or not. Again there was poor planning and of the 85 million acres of maize planted at Khrushchev's demand only 60 million acres could be harvested. The early sowing of crops and the lack of fallow land brought massive weed infestation that choked off the grain, as there were no herbicides to deal with it. A report from Kazakhstan reported that because of this problem a good yield of grain was cut in half after it was cleaned (Prokhorov: 2002).

I. Introduction

> "Biofuels are not the silver bullet for meeting the rising demand for transport fuels while tackling emissions."
>
> The Royal Society (UK) cited by The Petroleum Economist. February 2008

India, with a land area of 3.29 million km^2, is diverse in geography, ecology and culture. Variety is seen in climatic conditions, habitats, and the flora and fauna. The socio-economic progress achieved by the country is commendable, keeping in mind the population, that has risen to an estimated 1,027,015,247 (2001) at a rate of 1.59% every year. Although India occupies only 2.4% of the world's land area, it supports over 15% of the world's population.

Figure 1.1: Location map of Karnataka State, India



Source: CST, IISc: 2006

India's total economy, and in particular the service sector, is booming. Country's GDP growth, which averaged 9.5% in 2006 and 2007, is showing 6.6% of growth during 2008-2009, a year when most economies have experienced negative or no growth (CGES: December 2008, Eastern Eye: 5 June, 2009). India logged an unexpectedly robust 5.8% growth in the final quarter of 2008 to March 2009, fuelled by aggressive interest rate cuts and fiscal stimulus measures. According to HSBC's relatively conservative analysts, Indian GDP is expected to grow by 8% next year, Naina Lai Kidwai, the bank's group general Manager and country head, had stated (Ibid.).

The agricultural sector, however, has close to stagnated. While the service sector grew by 9.9%, the agricultural sector grew at a rate of only 0.7%. This adversely affects the rural poor who depend on agriculture for their livelihoods (World Bank: 2006b cited by Altenburg, *et. al.*: 2009). The sector contributes only 18% to GDP (World Bank: 2007 cited by Altenburg, *et. al.*: 2009), although it employs almost 60% of the Indian workforce (World Bank: 2006a cited by Altenburg, *et. al.*: 2009). 72% of the Indian population (770 million) lives in rural areas. Almost 1/3 of the rural population lives below the poverty line (260 million people, which is equal to 20% of the world's poor (Friends of Earth: 2008) in contrast to 1/4 of the urban population (World Bank: 2007 cited by Altenburg, *et. al.*: 2009). 77% household in rural areas and 23% in urban areas still depend on firewood and dung for fuel (Shrivastava & Mathur: 2007 cited by Nagar: no date).

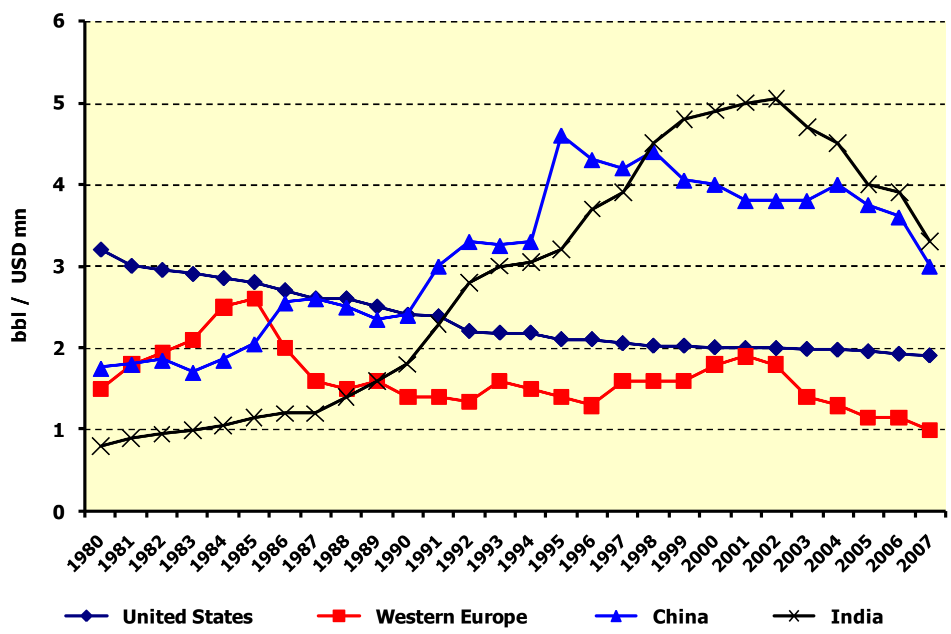
Since power sector liberalization started in India in 1991, energy demand has doubled to over 400 million tonnes of oil equivalent (mtoe) with a growth rate over 5% (Mukundan: 2009). At present, India is sixth in the world in energy need (ICRISAT: 2008). The Indian government says that overall fuel demand in 2009 is projected to increase by 6% from last year (Upstream: 27 February, 2009). Increasing urbanization, industrialization, deforestation, transportation, high-intensity agriculture, population migration and soil erosion are some of the major environmental problems being faced by the country (Bhardwaj, *et. al.*: 2003).

1.1 Review of the energy development in India

Energy is a one of the most important prime movers of India's import-dependent economy, and is the prerequisite for all commodities, but it also the prominent sector for GHG emissions and contributes over 60% of total Indian GHG emissions (Garg & Halsnæs: no date, Halsnæs & Garg: 2006). The consumption of commercial energy and emissions of greenhouse gases in India during the past three decades have grown at rates that are higher than the growth rate of gross domestic product (GDP) due to the following structural transformations.

First, decline in the share of agriculture in total GDP and the enhanced share of industry and services sectors. Second, shift in transport sector from rail to road as well as from mass transport to personal transport vehicles. Third is an enhanced share of commercial fuels in the households sector at the expense of traditional biomass fuels. Energy intensity within the industrial sector is showing a downward trend with an average annual decline over the 1990s of just over 2%. On the other hand, the agricultural sector has recorded an increase in the energy intensity of 6.5% over the same period (Chart 1.1) (Bhardwaj, *et. al.*: 2003).

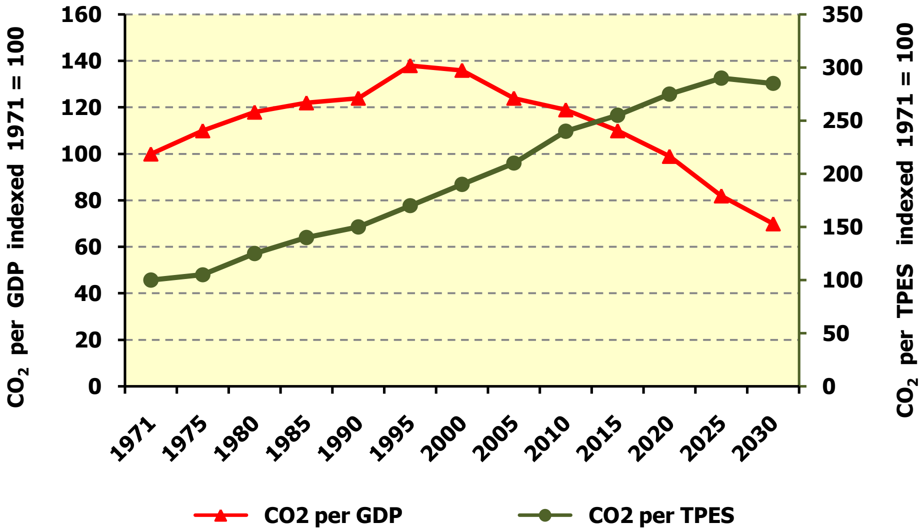
Chart 1.1: Oil intensity in the U.S., W. Europe, China, India (bbl per USD million real GDP)



Sources:
1) Zainu: 2009;
2) CGES: 2009

India is the focus of attention of the world community for two reasons. Firstly, it may be the world's most populated country by 2025 and its green house gas (GHG) emissions will rise subsequently. Despite the fact that India emits only 0.2 tonnes per capita of carbon dioxide from fossil fuels (compared to 5.2 tonnes for the US and a world average of 1.2 tonnes), with 243.0 $MtCO_2eq$ released from the consumption of fossil fuels in 1999 (Bhardwaj, *et. al.*: 2003), and 1,443.0 $MtCO_2eq$ released in 2000 (Table 1.1, Table 1.2, Chart 1.3), India is ranked fifth in the world in terms of the volume of emissions behind the United States, China, Russia and Japan (Bhardwaj, *et. al.*: 2003).

Chart 1.2: CO_2 intensity of Gross Domestic Product (GDP) and CO_2 intensity of Total Primary Energy Supply (TPES)



Sources:
1) Halsnæs and Garg: 2006;
2) Garg and Halsnæs: no date

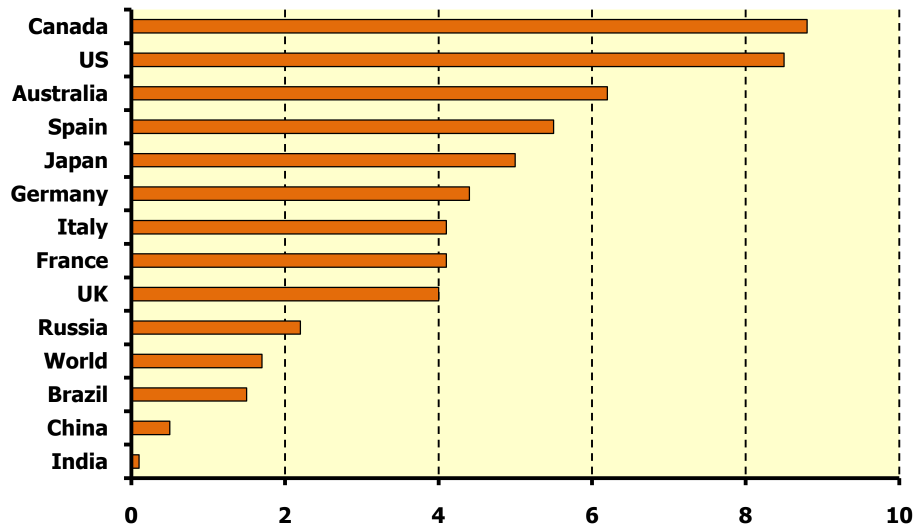
Economic growth is directly linked to rising GHG emissions, which increased annually by ~7% from 682 million tonnes in 1990 to 1,342 million tonnes in 2004 (UNDP: 2007 cited by Altenburg, *et. al.*: 2009). While per capita emissions is very low, estimates suggest that by 2020 they will increase by 400% over 1990 level and reach 3,000 million tonnes by 2020, making India the third largest emitter worldwide, after the United States and China (Sharma, *et. al.*: 2006 cited by Altenburg, *et. al.*: 2009).

Table 1.1: Main contributors to CO_2 equivalent emission in India in 2000

Source categories	Main emissions	Share (%)	Emission ($MtCO_2eq.$)
Coal based electricity	CO_2	29.9	431.6
Steel industry	CO_2	8.8	127.0
Cement industry	CO_2	5.1	73.6
Livestock related	CH_4, N_2O	12.6	181.8
Paddy (rice) cultivation	CH_4	6.6	96.1
Biomass consumption	CH_4, N_2O	5.2	75.0
Synthetic fertilizer use	N_2O	4.1	59.2
Transport sector	CO_2	9.5	137.1
Waste disposal	CH_4	3.8	54.8
Other sources	CO_2	14.4	207.8
All India ($MtCO_2eq.$)			**1,443.0**

Sources:
1) Shukla, *et. al.*: 2003;
2) Palm: 2004

Chart 1.3: CO_2 emissions from petroleum use 2006. Tonnes of CO_2 per capita



Notes: At a crude oil price of 48.0 USD/bbl

Sources:
1) EIA: no date;
2) GTZ International Fuel Price Survey: no date;
3) Financial Times. 20 May, 2009

Secondly, the major share of India's energy comes from coal (Chart 1.5). After India's electricity sector reforms in early 1990's the sector became more dependent on domestic coal, as hydropower confronted anti-large dam movements and inter-state water disputes (Halsnæs & Garg: 2006, Mukundan: 2009, Scaife, *et. al.*: 2006).

As a result, electric power generation contributes almost half of India's CO_2 emissions and the majority of it comes from coal and lignite consumption (Table 1.2) (Garg, *et. al.*: 2001). Thus, the average carbon content of electricity produced in Andhra Pradesh raised from 0.55 $kgCO_2/kWh$ in 1980 to over 0.65 $kgCO_2/kWh$ in 2001 (Halsnæs & Garg: 2006).

Table 1.2: Carbone dioxide generation from unit heat energy in fuels

	Carbon	**Hydrogen**	**Carbon to hydrogen ratio**	**Higher caloric value**	**CO_2 per unit heat energy in fuel**
Particular	%	%		GJ/t	t/GJ
Hydrocarbon fuel gases	30-40	20-40	1-2	45-47	16.5-35.4
Fuel oils	82-85	11-15	5-8	45-47	61.8-71.1
Wood and biomass	40-60	6-7	7-9	17-19	86.6-94.6
General coals	30-94	2-4	10-47	14-34	72.1-103.2
Indian power station coals	30-40	2-4	10-22	14-19	79.1-88.7

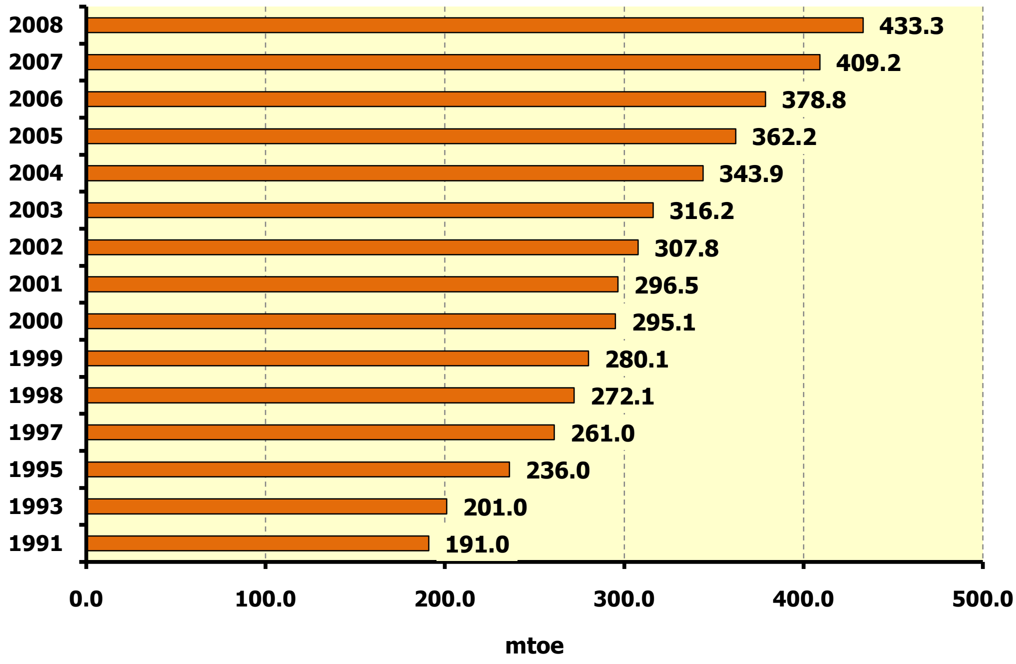
Source: Bhatt: 2000

1.2 India's energy scenario

From the beginning, India's energy scenario has been characterized by a mix of commercial and non-commercial sources of energy, namely cow dung, agricultural waste, coal, hydro, oil, gas and now nuclear. The steady rise in energy consumption over the past decade has been accompanied with changes in the relative share of different fuels. About 31% of India's primary energy needs are met from bio-energy produced on a non-commercial basis from agricultural and forest waste, wood chips, animal waste and bio-fuels (Friends of Earth: 2008, Gokhale: 2006 cited by Nagar: no date).

The country currently ranks as the world's seventh largest energy producer, accounting for ~2.49% of the world's total annual energy production. It also the world's fifth largest energy consumer, accounting for ~3.45% of the world's total annual energy consumption in 2004 (Planning Commission of India website. Visited 25 May, 2009). Planning Comission (no date) also informes that India imported 13.4% of its coal requirement, 73.4% of oil and products needs, and 1.6% of gas requirement. Net imports of 131.97 mtoe in 2006-2007 includes the import of 95.43 million tonnes of crude oil and petroleum products, 44.29 million tonnes of coal and 5.0 million tonnes of LNG.

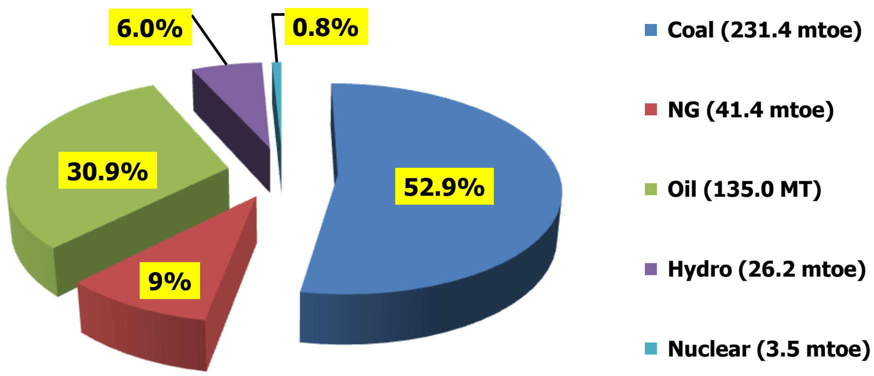
Chart 1.4: Indian primary energy consumption (mtoe)



Note: Estimated energy requirement is 1,651 mtoe by 2032. This assumes 8% GDP growth rate through 2032 (Planning Comission of India: 2006, IBEF: 2008)

Sources:
1) Mukundan: 2009;
2) BP Statistical Review of World Energy: 2009

Chart 1.5: Distribution of primary energy consumption in India at the end of 2008



Sources:
1) BP Statistical Review of World Energy: 2009;
2) Joshi & Jung: 2008

At present, coal remains the dominant fuel at 55% (Bhardwaj, *et. al.*: 2003) (51% - Mukundan: 2009, 56.2% - BP: 2007, 65% - TERI/TEDDY: 1999 cited by Bhatt: 2000, ~70% - TERI/TEDDY: 2003) of primary energy consumption and it will continue to provide over 60% of the total energy in the future (Bhardwaj, *et. al.*: 2003). 96% of all coal consumed by Indian power sector is indigenous (Bhatt: 2000). The indigenous coal supply projection in the terminal year of XI Five-years Plan, i.e. 2011-2012, is projected to be 680 MT (Ministry of Coal: no date).

Table 1.3: Lignite production and power generation in Neyveli Lignite Corporation, India

Product	**Actual production 2006-2007**	**Achievement April to December 2007**	**Tatget for 2007-2008**
Lignite (MT)	21.01	15.28	20.05
Power Generation (MU)	15,786.00	12,710.82	15,705.00

Source: Ministry of Coal (no date). Visited 25 April, 2009

According to the BP Statistical Review of World Energy (2008) Indian coal consumption grew by 6.6% during previous year. Further increase in coal-based generation capacity will require large quantities of coal that will have to be imported as demand would outstrip domestic production. By the year 2031-2032 country's coal imports dependence could be in the range of 72-462 MMt or 11-45% (Joshi & Jung: 2008).

Indian oil consumption has grown from 60 mtpa in 1991 to over 125 mtpa in 2007. Only in the last few years oil share has grown to 36% of total energy consumption (Mukundan: 2009). Total crude demand has been growing by more than 6% annually (Winrock International India: 2008) and petroleum products consumption has been grown by 8-9% per annum (Rajvanshi: 2007). Overall demand of crude oil is expected to rise by 5.6% until 2011 (ICRISAT: 2008). Diesel accounted for 60% rise, due to its use in the commercial transport sector and as a fuel for small-scale electricity generation (CGES: December 2008). At the same time, the country's annual per capita energy consumption with 480 kg oil equivalent is quite low (Bhattacharya & Joshi: 2006, Swamy & Singh at Singh, *et. al.*: 2006, Kumar, *et. al.*: 2008, Earth Trends: 2008, Friends of Earth: 2008).

Even though indigenous oil production has increased from 0.45 million tonnes in 1960-1961 to 34.12 million tonnes in 2007-2008, India's crude oil and natural gas production has stagnated in recent years (Chart 1.7, Tables 1.4 & 1.7) (Riemer & Von Lonski: 2008, IBEF: 2008). Moreover, India upstream players missed the country's crude production target by almost 7% for the financial year ended 31 March, 2009, the Ministry of Petroleum & Natural Gas said (www.upstreamonline.com, 30 April, 2009).

Domestic supply can presently satisfy only 22% of annual crude oil requirement of 111 million tonnes and, therefore, dependence on crude oil imports to the tune of 18 billion USD/yr (71,784 crores Rs./yr, ~9.1 billion GBP/yr, using exchange rate USD/GBP = 0.503, GBP/INR = 79.23 - April 2008. www.xe.com/ucc/convert.cgi) is increasing. As such, there is a growing demand gap between production and consumption (Table 1.4, Mukundan: pers. comm.).

Table 1.4: Increasing crude oil demand and supply gap in India (million tonnes)

	Demand	Supply	Gap
2001-2002	99.70	32.03	67.67
2002-2003	114.30	33.05	81.25
2005-2006	140.00	33.98	106.02
2011-2012	199.60	33.47	166.13
2024-2025	376.50	61.40	315.10

Sources:
1) IBEF: 2008;
2) Popli: no date

The result has been a rapid rise in oil imports (Tables 1.5 & 1.6), which was expected to go up from 21 million tonnes in 1990-1991 to 111 million tonnes in 2006-2007 (Winrock International India: 2008). This account for ~30% of India's total import bill (Mukundan: 2009).

Table 1.5: India's import burden of crude (1)

Demand of petroleum products	146 million tonnes
Production of crude	35 million tonnes
Import of crude	111 million tonnes

Source: Winrock International India: 2008

India's foreign exchange for oil imports skyrocketed from 61 billion Rs. (1.29-2.23 billion GBP, GBP/INR = 27.36 - March 1990. GBP/INR = 47.11 - December 1991. www.x-rates.com) on 1990-1991 to 2,200 billion Rs. (25.13-28.24 billion GBP, using GBP/INR = 77.91 - December 2007. GBP/INR = 87.55 - December 2006. www.xe.com/ucc/convert.cgi) in 2006-2007 (MoP: no date cited by Altenburg: 2009), which in 2003 amounted to ~3% of India's GDP (GTZ/TERI: 2005 cited by Altenburg: 2009). India's oil import dependency is projected to rise to 91.6% by 2020 (The World Energy Outlook, IEA: 2003 cited by Scaife, *et. al.*: 2006); 93% by 2030 (Kumar & Dhavala: 2006 cited by Altenburg: 2009).

Table 1.6: India's import burden of crude (2)

Year	Rs. (in crores)	Billion £
2004-2005	1,01,963	11.37
2005-2006	1,50,557	17.16
2006-2007	2,19,029	27.56

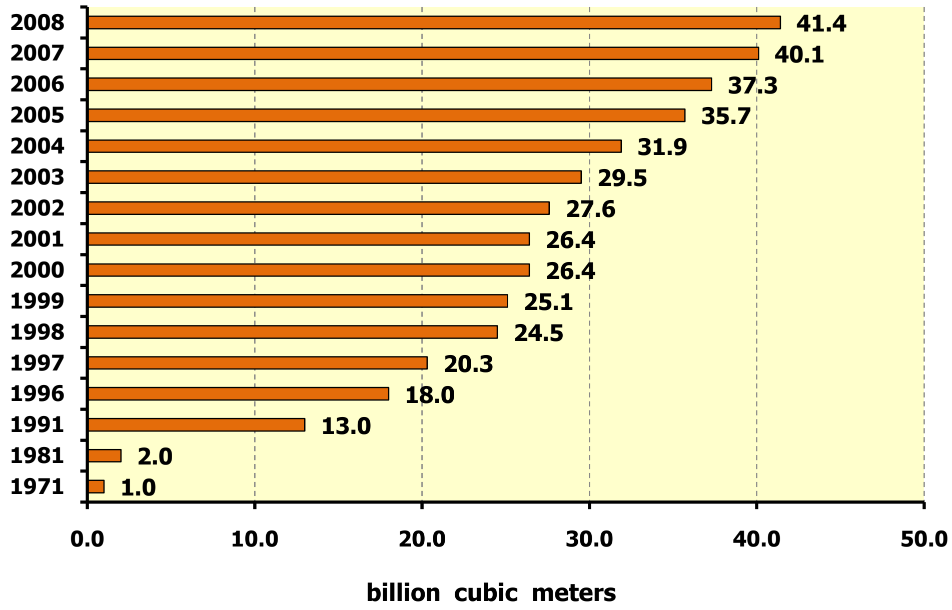
Note: INR/GBP = 79.23 - April 02, 2008. www.xe.com/ucc/convert.cgi.

Source: Winrock International India: 2008

The situation is further aggravated by price fluctuations and uncertainty of crude oil and its products, as well as global instability in the world petroleum market. Thus, during the 2007-2008 financial year, to March 2008, India imported 2.93 million tonnes of diesel (The Petroleum Economist: September 2008). CGES oil demand trends analysis reports that Indian oil demand in the ten months to October 2008 was almost 200,000 bpd higher than in the same period of 2007. According to an estimate, even 5% replacement of fossil fuel by biodiesel will help save foreign exchange of over Rs. 4,000 crores (~505 million GBP, GBP/INR = 79.23 - April 2008. www.xe.com/ucc/convert.cgi) annually (Bhattacharya & Joshi: 2006, Swamy & Singh at Singh, *et. al.*: 2006, Kumar, *et. al.*: 2008).

Barriers to hydro power plants development caused by opposition movements against large dam movements and inter-state water disputes, as well as bottlenecks in coal supplies caused the electricity supply to shift to gas market where the combined cycle gas technology offered advantages of low investment, short gestation and low local emissions. Consequently, the average carbon content of fossil power has declined since more gas-based power was added since 1990's (Chart 1.6; Halsnæs & Garg: 2006).

Chart 1.6: Increasing gas consumption in India



Sources:
1) Mukundan: 2009;
2) The Petroleum Economist: November 2008;
3) BP Statistical Review of World Energy: 2009

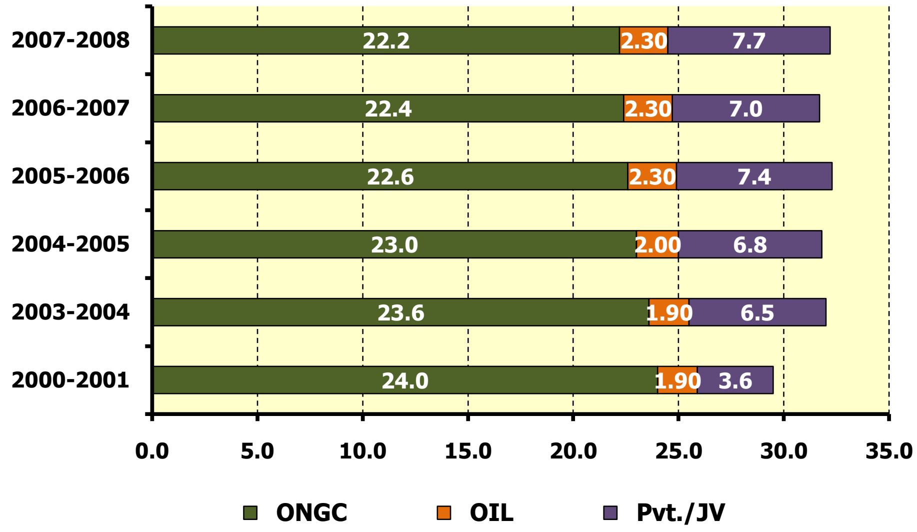
The major consumers of gas are the power (40%) and fertilizer industries (29%), while petrochemicals accounts for 9%, sponge iron for 3% and city gas just 4% (Joshi & Jung: 2008).

Table 1.7: Increasing natural gas demand and supply gap in India (MMSCMD)

	Demand	Supply		Gap	
2001-2002	151.00	81.40[1)2)]	70.0[3)]	69.60[1)2)]	81.0[3)]
2006-2007	231.00	94.84[1)2)]	64.0[3)]	136.16[1)2)]	167.0[3)]
2011-2012	313.00	158.05[1)2)]	78.0[3)]	154.95[1)2)]	235.0[3)]
2024-2025	391.00	170.00[1)2)]	84.0[3)]	221.00[1)2)]	307.0[3)]

Sources:
1) IBEF: 2008;
2) Popli: no date;
3) Scaife, *et. al.*: 2006

Chart 1.7: Annual Natural Gas production, bcm



Notes:
a) Total production of Natural Gas in 2007-2008 is 32.3 bcm;
b) LNG production and imports in 2006-2007 is 8.31 bcm;
c) Contribution from Pvt./JV small, medium and discovered fields during 2007-2008 is 7.727 bcm of gas, which accounts for about 24% of the national gas production

Sources:
1) IBEF: 2008;
2) GOI, Ministry of Petroleun and Natural Gas;
3) Joshi & Jung: 2008

In 2005-2006, with the commencement of LNG imports, the actual gas supply was 10.4 bcm against demand of 12.0 bcm from existing fertiliser units. Presently (2003), there are 65 large-sized fertilizer plants in India. Of these, 32 units produce urea, 20 produce di-ammonium phosphate (DAP) and complex fertilizers, and 13 manufacture ammonium sulfate (AS), calcium ammonium nitrate (CAN) and other types of fertilizers. Indian nitrogenous fertilizers are mostly composed of urea (88%); the remaining share consists of the complex fertilizer di-ammonium phosphate (10%) and different types of ammonium fertilizers (2%). According to the Report of the Working Group on Fertilizers set up by the Planning Commission in 2006, the total gas requirement at the end of the XI Five-years Plan in March 2012 would be around 28 bcm (Planning Commission of India: 2006 cited by Joshi & Jung: 2008). For the fertiliser sector all non-gas based urea plants should be converted to gas over a three-year period (Joshi & Jung: 2008).

The all-India installed generating capacity of utilities at the beginning of X Five-years Plan (2002) was 104,917.50 MW. This included 26,261.22 MW of hydro, 74,428.82 MW of thermal, 2,720.00 MW of nuclear power, and 1,507.50 MW of wind energy. A capacity addition of 21,080.24 MW was actually achieved during the X Five-years Plan period (2002-2007) (Planning Commission of India website. Visited 25 May, 2009).

Table 1.8: Power sector-wide installed capacity (MW) as on 31.03.2008

Sector	Hydro	Thermal				Nuclear	Renew.	Total
		Coal	Gas	Diesel	Total			
State	26086.76	42047.50	3834.22	604.61	46486.44	0.0	2200.04	74773.13
Central	8592.00	29010.0	6638.99	0.0	35648.99	4120.00	0.0	48360.99
Private	1230.00	4991.38	4183.00	597.14	9771.52	0.0	9994.53	20996.05
All India	35908.76	76048.88	14656.21	1201.75	91906.84	4120.00	12194.57	144130.17

Source: Bhawan & Puram: 2008

Table 1.9: Breakdown of generation capacity in India as on 31.03. 2008

Coal	Hydro	Nuclear	Oil
54.2%	27.5%	3.1%	1.2%
Naphta	**Lignite**	**Gas**	**Diesel**
0.4%	2.9%	8.8%	0.9%

Notes:
a) The total corresponds to 144,130.17 MW as on 31.03.2008;
b) Non-conventional renewable energy stations, including power generation from wind, biomass, solar photovoltaic, and hydro below 3 MW capacity are not included to this table

Source: Bhawan & Puram: 2008

Even though the power sector is the biggest consumer of gas, only 16% of thermal power generation capacity and just 10% of the total installed capacity is gas based. Coal accounts for over 50% of the country's primary energy supply and still dominates thermal power with a capacity share of 83% (Joshi & Jung: 2008).

The renewable energy potential in India is substantial, particularly for biomass. "Bio-fuels have been used for centuries by the tribals. Non-commercial energy will constitute at least 10-12% of India's primary energy mix even in 2031-2032 and remain as the third important energy source for next 25 years after coal and fossil oil", acknowledged Surya P. Sethi, Government of India's energy adviser (Ibid.).

Table 1.10: Renewable energy potential

	Annual Thermal Energy (EJ)	Electricity Potential (GWe)
Hydro	2.1	68
Biomass	30.7	139
Wind	0.4	14
Solar	44.9	139
Total renewables	**78**	**360**

Source: Scaife, *et. al.*: 2006

The 30.7 EJ ($30.7*10^{18}$ J) of biomass reserve (Table 1.10) is equivalent to utilisation of ~3 billion tonnes of biomass annually (MNES: 2005, Scaife, *et. al.*: 2006). As on 31 March 2007, the contribution of power generation from renewable had reached 10,406.69 MW representing ~8.1% of total installed generation capacity. Of this, wind power accounted for 7,092 MW followed by small hydro at 1,975.60 MW and biomass (including co-generation) at 1,158.63 MW (Planning Commission of India website. Visited 25 May, 2009).

However, there are situations whereby people are not so much facing a high bill but are actually lacking access to energy services that are taken for granted in other parts of the World (and India in particular (AE)). The absence of electricity grid or gas grid in many areas is a prime example of this problem.

Where renewable energy alternatives are found to be relatively expensive, it could be argued that the term "energy poverty" would be more appropriate than "fuel poverty", since biomass (and biofuels) are the only renewable energy source that tends to be seen as a fuel (Van der Horst: 2008).

1.3 Biodiesel encroachment into Indian automotive industry and small-scale generation

For much of the world, interest in biofuels expansion (Table 1.11) is driven by a more general interest in the potential for biofuels to substitute for petroleum products in transportation applications. This more general interest targets three primary objectives:

- Concerns about energy security arising from increasing world petroleum prices and the prospect of eventual depletion of petroleum;

- Environmental considerations that motivate governments to seek ways of curbing rising GHG emissions overall and especially from the transport sector, and, to a lesser extent, reducing tailpipe emissions of harmful pollutants;
- A desire to support domestic agriculture in the face of international negotiations to liberalize agricultural trade (ESMAP: 2007).

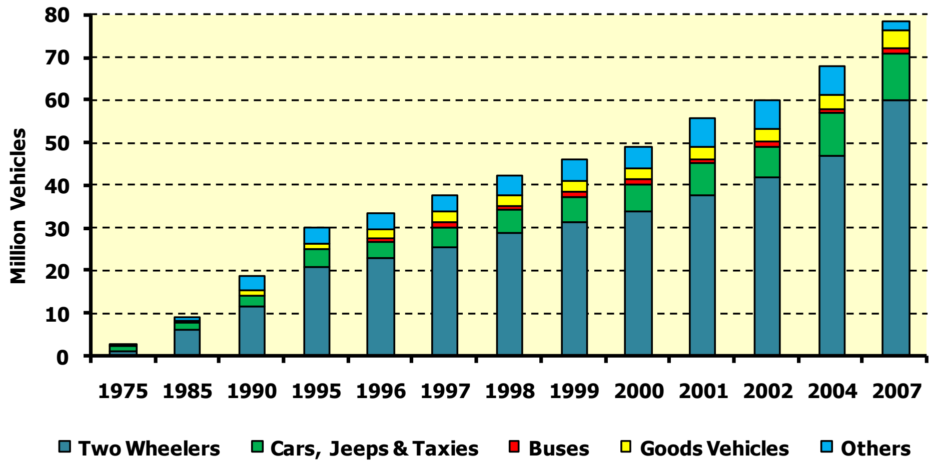
Table 1.11: Top producing countries by total biofuel production in 2007

Country	Ethanol (million litres)	Biodiesel (million litres)	Total (million litres)
USA	26,500	1,688	28,188
Brazil	19,000	227	19,227
EU	2,253	6,109	8,361
China	1,840	114	1,954
Canada	1,000	97	1,097
India	400	45	445
World	52,009	10,204	62,213

Source: OECD: 2008

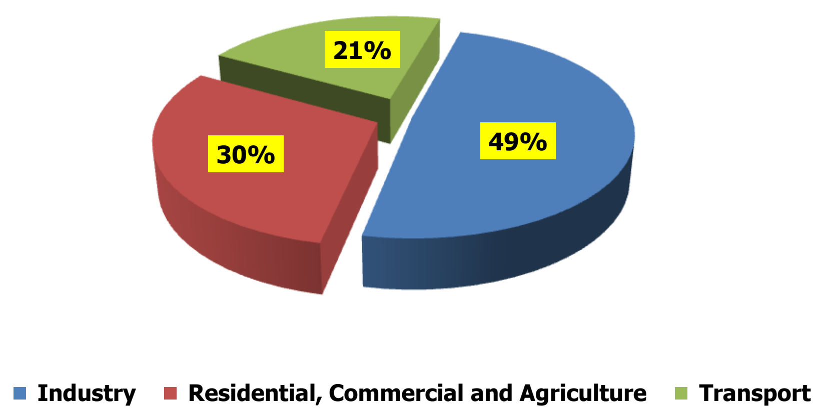
Transport currently represents 14% of global emissions and has been the fastest growing source of emissions because of continued growth of car transport (Stern: 2006). In just six years, from 2001 the number of vehicles in India has increased by almost 100%. Commercial vehicles see an increase over 200% during this period. Increased individual economic purchasing power is also pushing up sales of vehicles in the personal use sector.

Chart 1.8: Vehicular growth in India



Source: Winrock International India: 2008

Chart 1.9: Indian energy demand by sector (2005)

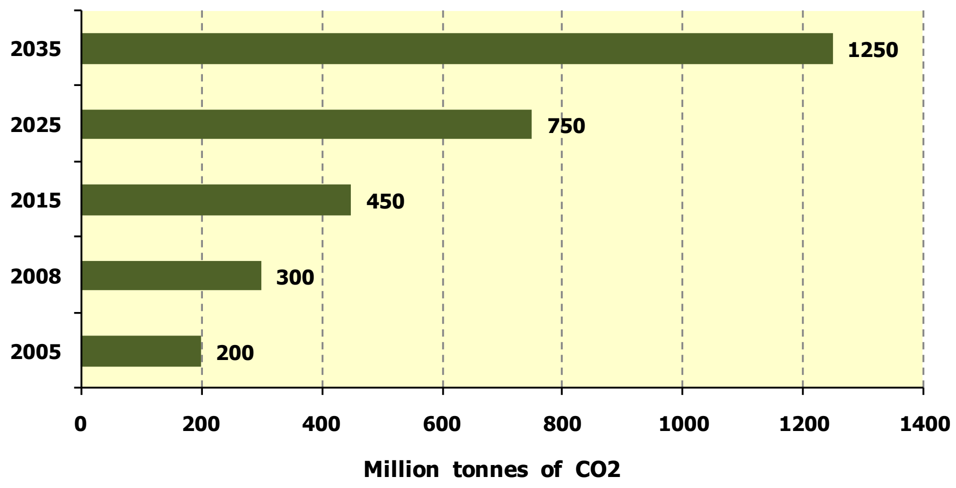


Source: Earth Trends: 2008

With car ownership (currently 8 per 1,000) forecast to increase considerably over the next two decades, diesel demand will rise from 52 million tonnes in 2006-2007 to ~67 million tonnes by 2011-2012 (Business Standard: 25 September, 2008).

Overall, transport crude oil consumption was expected to rise at an annual 5.6% rate until 2011 (Friends of Earth: 2008). However, a sharp fall in sales of new vehicles in 2008 - beginning 2009 (for example, sales of buses and trucks, the largest consumers of diesel on the roads, are dropped by 50% year-on-year in November 2008) signals an imminent slowdown in the use of diesel as a transport fuel in following year (CGES: December 2008).

Chart 1.10: Indian total CO_2 emissions (well to exhaust) from on-road vehicles



Source: Woodcock, *et. al.*: 2007

Petrodiesel fuel is currently used in both road and non-road vehicles. First, biodiesel cannot possibly replace a significant portion of petrodiesel used in on-road engines; it can supplant a far larger share of non-road petrodiesel demand. Second, the benefits of using biodiesel in non-road engines probably exceed those from on-road use. To the extent that non-road diesel equipment emits more pollutants than onroad trucks, this estimate will understate the cost per gallon of air pollution from non-road diesel users. However, biodiesel does not eliminate emissions; it simply reduces them (Reaney, *et. al.*: 2006).

Furthermore, due to thermodynamics, internal combustion engines are no more than 45% efficient. For a diesel engine running on fossil diesel, the well-to-wheel (WTW) energy efficiency is about 35%. WTW efficiencies for biodiesel and bioethanol are limited to 18% and 13% respectively (Klintborn: 2008 cited by Porder, *et. al.*: 2009). When idling and driving patterns in cities are considered, WTW efficiencies can be less than 20% for fossil transport fuels and less than 10% for liquid biofuels, or comparable to cooking over an open fire. On the other hand, electric cars have grid-to-wheel efficiencies of 60-70%. This suggests that liquid biofuels may not be the wisest use for transportation (Bossel: 2006 cited by Porder, *et. al.*: 2009).

The exponential growth in the automotive sector as well as energy production for rapidly growing industry and housing sectors has also overwrought India's resources. As India is already importing a large percentage of its oil yearly, to maintain growth patterns, it will be critical to find and utilize alternative fuel sources.

Given the periodic scarcity, violent fluctuations in oil prices combined with the logistic difficulties of transportation to remote areas, attempts have to be made to find alternative fuels all over the world. In this scenario, biofuel derived from renewable resources hold an immense potential for meeting India's future energy needs. Nevertheless, the credit crisis and falling product prices after mid-year 2008 slowed things down and left, for example, the US ethanol industry with overbuild capacity - by year-end 2008 about 15% of U.S. ethanol production capacity lay idle (Rühl: 2009).

Another factor for use of clean burning biodiesel for distributed power as well as backup generators is the availability and reliability of grid electricity supply.

As on May 2006, 439,502 villages are electrified representing 74% of the total 593,732 villages in India; however, only 43.5% of households in and around these villages have access to electricity in their homes. Winrock International India (2008) and the Central Electricity Authority (2006) reported country's per capita annual electricity consumption of 615 kWh *-ef* to 31,147.3 kWh in Iceland (2006), 12,924.2 in the United States (2007), 5,773.6 kWh in the UK (2006), and 2,179.5 kWh in China (2006) (CIA World Factbooks: 2008) is among the lowest in the world. The cited annual electricity consumption per capita in rural households can be as low as 57 kWt (Rajvanshi: 2007). Currently, there are small number of NGOs that are involved in using biofuels as means for rural electrification in remote villages. NGOs like Winrock in Jharkhand, IRADE in Haryana and Gram Vikas in Orissa are involved in remote villages electrification through biofuel run generators (Nagar: no date). Thus, in Karnataka, reciprocating engines (both large and small), and farming equipment have a wide variety of market applications, ranging from continuous power generation as a distributed asset to mechanical drive for irrigation pumps or gas compressors. Bekunda, *et. al.* (2009) also reported that three villages in the State of Chhattisgharh has been electrified using diesel generators operating on SVO derived from *Jatropha*. This project was initiated by Winrock International India as a technical and financial viability demonstation project. Peak shaving and grid price of electricity can also play a major role for green power use of biodiesel.

Table 1.12: Electrification of rural houses by using straight Jatropha oil

Number of households	100
Demand per household (watts)	70
Hours of supplies per day	4
Total energy supplied per annum (kWh)	10,220
SEGR of DG sets (kWh/l)	3
Oil required (l/a)	3,400
Seeds required (t/a)	~15
Number of saplings	4,285[a)] 30,000[b)]

Notes:
a) yield of 3.5 kg/tree/yr;
b) yield of 0.5 kg/tree/yr;
c) The specific energy generation ratio (SEGR) of a DG set is defined as units of electricity generated per liter of fuel (kWh/l)

Source: Winrock International India: 2008

Co-generation for small systems is another benefit for the local Karnataka economy. In this case, environmental gains might be even more significant compared to on and non-road engines. Up to date, studies on the emissions impact of biodiesel use in heating units and commercial boilers (e.g. CCHP (Combined Cooling Heating and Power) also known by a variety of acronyms as Trigeneration, CHPB (Cooling, Heating and Power for Buildings), BCHP (Buildings Cooling, Heating and Power) and IES (Integrated Energy Systems (AE)) are not as extensive as those done for on and non-road diesel vehicles.

Table 1.13: Back of envelope calculation of land needed to produce electricity for a village

Number of households in a village	100		
Energy supplied per household per day (Watt hours) (@ 100 watts per household for 6 hours a day)	600		
Total Energy for village per year (kWh)	21,900		
Specific fuel consumption of diesel generator, i.e. straight vegetable oil consumed to produce one unit of electricity (g/kWh)	250		
Oil needed per year (tones per year)	5.5		
Three scenarios for oil yield [1)]	Low	Medium	High
Yield of oil per hectare (t/ha)	0.5	1	2
Land needed to produce oil (ha)	11	5.5	2.7

Note:
Reported extractable *Jatropha* oil yields:
a) 540 to 2,700 kg/ha/yr (2);
b) 1.8 to 3.5 t/ha/yr (3)

Sources:
1) Rajagopal: 2007;
2) Jongschaap, *et. al.*: 2007;
3) Connor & Hernandez: 2009

However, a study conducted by Brookhaven National Laboratory (Upton, New York) and the New York State Energy Research Development Authority found the emission benefits of biodiesel/heating oil blends to be even greater than for use in motor vehicles and diesel engines (Krishna: 2004). A second study, also by Brookhaven National Laboratory provided similar results, showing the use of biodiesel blends in both home heating and commercial boilers reduce emissions of particulate matter, carbon monoxide, and nitrogen oxides (Krishna & Albrecht: 2006).

1.4 Business challenges in growing economy

Sashi Mukundan, Country Manager of BP India Services Pvt. Ltd. believes that the business challenges in India are no different from the challenges faced by any other growing economy. He grouped all key challenges into four categories: a) Political, b) Economic, c) Infrastructure, and d) Resources.

a) Political:

India has a multi-party coalition democracy with each stakeholder having a different agenda that they want to fulfill. As such, any decision by the government needs to find a mid-path. As India is opening up and rapid growth is happening, policy and regulatory framework is either lagging or in many cases remain flexible and evolving. This flexibility creates uncertainty for most traditional investors (Mukundan: pers. comm.).

Procedures for doing business at times can be complex. Most approvals still require working with multiple government agencies and layers of coordination. Thus, delivering a sustainable transport system will require "combining biofuels with other developments, including the improved design of vehicles and engines, increasing use of public transport and better urban and rural planning" (The Petroleum Economist: February 2008 (Ed.)).

It is not only conventional, energies that are used inefficiently. Renewables, particularly the use of biomass as an energy source, seems to be developing in inefficient ways. Many policies are geared towards using biomass for electricity production or for conversion to biofuel - both of which lead to losses of the potential energy of the biomass of up to 80% (Rakos: 2008).

There is a lack of knowledge on the environmental impacts of TBOS and other oleaginous plants cultivation. According to the Forestry Research Institute in Uttarakhand, the environmental impacts of *Jatropha* cannot yet be foreseen (Negi: no date cited by Altenburg, *et. al.*: 2009).

b) Economic:

India is still a nascent market with few advantaged players across the chain - the goal of the government is to rapidly move towards a free market. However, affordability and access to energy is a key factor driving the pace of regulation and pricing, which results in demand distortions.

The German Development Institute studies (2009) find that TBO-based biodiesel production is a risky business: a) because markets are not yet established neither for tree born oilseeds, nor for straight vegetable oil; b) because of the long-term nature of investments as most TBOS have very long gestation periods; and c) because some of them can only be used for the production of non-edible oil and are thus worthless if the biodiesel market does not take off.

Jatropha curcas is a perennial crop with a commitment period of 20 to 30 years. Therefore, there is no flexibility in crops diversification and, hence, income sources, as in case of annual crops.

The numerous semi-structured interviews and informal conversations with farmers in India make the author to understand that *Jatropha* as a feedstock crop for the local biodiesel production in India will not sustain unless it will be not less profitable then any other cash crop to the rural dwellers in reasonably short period of time. Otherwise the farmers' threat to remove recently planted *Jatropha* shrubs (even before they reach maturity enough to produce significant oilseeds yield) and replace them with another agricultural crop will come true.

Most importantly, the oils from which biodiesel are made have become expensive, and are likely to remain so. That is because plant oils are a long-established agricultural product and account for most (80%) of the total cost of the fuel. Large-scale production will not substantially reduce unit costs. Worse, the high cost of making biodiesel from dedicated crops - whether soy, palms, or other plants - is unlikely to diminish. At current prices (over 900.0 USD (453.0 GBP, USD/GBP = 0.503 - 02 April, 2008. www.xe.com/ucc/convert.cgi) per tonne) the plant oils by themselves cost well over 0.75 USD (0.38 GBP) per litre in most cases. Add in processing, distribution, and retailing costs, and it easily exceeds 1.0 USD (~0.5 GBP) per litre. It can only compete with diesel fuel when crude petroleum is selling at about 150.0 USD or more per barrel. In contrast with other alternative fuels; these costs are unlikely to recede much in the future (Sperling: 2008).

It is important to choose the right policy framework which protects and balances the needs of the investors as well as the consumers. For example, it will be necessary to provide incentive to early entrants who are willing to bet and take large market risks. To avoid perverse incentives and negative impacts, which cannot easily be reversed, all large-scale plantation and agricultural schemes should be subject to detailed environmental and socioeconomic audits before they become part of any climate-change mitigation strategy (Danielsen, *et. al.*: 2008).

Small and marginal farmers should not be encouraged to cultivate fuel crops on their farms until certified high-yielding seeds are available and investment are calculable. Especially, monoculture cultivation should not be fostered (Altenburg, *et. al.*: 2009).

"Land is being acquired in many parts of India to fuel the cars of the rich… land grab for biofuels has emerged as a threat for the agrarian and livestock economy in many states of India. It also threatening the decentralize democracy of the country, which has made local communities, the competent bodies to make decision on natural resources… this kind of land grab will totally pauperize our peasantry and destroys their livelihood" (Shiva & Sankar: 2008 cited by Nagar: no date).

c) Infrastructure:

Inadequate infrastructure is to some extent holding back India's development. It is critical to bring resources to market to meet the economic growth engines (Mukundan: pers. comm.).

Procedures for availing credits/loans should be simplified (FICCI Core Group: no date). Clear rules need to be set - and transparently implemented - for purchasing agricultural land. Land lease charges should start from fourth year, when the income generation starts. Land lease charges should not be more than 5% of the income or maximum of 1,500 Rs./ha (~19.0 GBP/ha), which should be uniform for all the states (FICCI Core Group: no date). The wasteland can be allotted by Letter of Intent to plant the trees along with Lease Agreement. It should be leased for a crop period of 35-40 years (Ibid.).

In India is still little use of biomass waste in co-firing and biomass gasification as yet. This is largely because the horizontal integration between farmers and power station managers is not yet in place, and the transport infrastructure necessary to get biomass from many small farms to large central power plants is not yet fully developed (PEI: May 2009).

d) Resources:

Manpower, technology and capital needs have to be well planned to ensure such large investments get developed and executed in a timely and efficient manner (Mukundan: pers. comm.). Farmers going ahead with *Jatropha* plantations experience lack (or even complete nonexistence) of extension services from local agriculture and agroforestry research and development institutions or Biofuel Development Authorities.

Model plantations and nurseries are still being developed. Pilot projects of TERI and ICRISAT are still operational. They are all grappling with the issues of germplasm, better plant variety, yield, costs of plantation and esterification (Govda: pers. comm.).

Picture 1.1: Six months old drip-irrigated *Jatropha* plantation. Tamil Nadu. December 2005

Source: author's picture

"Technologies that clearly do build capacity in the community are not "fit and forget" but rather "fit, fumble, fidget and finally fine-tune". Biomass (and biofuels (AE)) would be the most obvious example for that. Getting it to work is not simply a triumph of hands-on technical" skills, but requires active management, sourcing of fuel, supporting (or even creating) a fuel (feedstock (AE)) supply chain that is local and provides further jobs and economic opportunities" (Van der Horst: 2008).

A recent commentary noted that "The competitiveness of a biofuels industry is highly dependent on gaining economies of scale. Costly, sophisticated processing plants require massive, steady inflows of feedstock in order to produce sufficient volumes of fuel at competitive prices. Small-scale operations will not be economically competitive except perhaps for running village pumps and engines in remote, impoverished areas that are largely disconnected from the cash economy" (ICRISAT: 2007).

The expectation that oil-bearing trees, especially *Jatropha*, would give good yields even on marginal and dry lands without inputs such as irrigation, fertilisers and pesticides has not materialized. In order to achieve economically viable yields, farmers would have to bear high input and opportunity costs. Therefore, without government subsidies, at this moment only niche markets such as the reproduction of seedlings, oil extraction for the chemical industry and CDM funded projects are economically viable (Altenburg, *et. al.*: 2009). Organisations like ICAR and CRIDA will need at least 10 years of research on *Jatropha* before coming out with a set of data and relevant information (Friends of Earth: 2008; Govda: pers. comm.).

Chapter 2: Background to the research

Subject: Shocking - it will be flop.
I am just returning from Andhra Pradesh, had gone with Alex;
it is going to be difficult, unless done completely differently;
the growth rate and performance of Jatropha is very poor.

Professor Ravindranath N. H. 02 March, 2006.

In this chapter an extensive literature review will cover all botanical and agroforestry aspects of the *Jatropha curcas* (Linnaeus) taxa. Then the chapter outlines the general theory of Life-Cycle Assessment (LCA), followed by the latest Searchinger-Wang debate (2008) over validity of including "indirect" costs of biodiesel production, especially indirect land conversion to biocrops production to the LCA, as well as scale of such impact. Finally, biodiesel production process will be examined covering state of the art biodiesel production technologies and various costs of biodiesel production.

2.1 *Jatropha curcas (Linnaeus)*

Taxa: *Jatropha curcas Linnaeus*

Tribe: *Joannesieae of Crotonoideae*

Family: *Euphorbiaceae*

Synonyms: *Castiglionia lobata* Ruiz and Pav.; *Curcas adansoni* Endl. ex Heynh.; *Curcas curcas* (L.) Britton; *Curcas indica* A. Rich.; *Curcas purgans* Medic; *Jatropha acerifolia* Salisb.; *Jatropha edulis* Cerv.; *Jatropha moluccana* Wall.; *Jatropha yucatanensis* Briq.; *Ricinus americanus* Miller; *Ricinus jarak* Thumb., and *Croton moluccanus* Lour. (Hannan-Jones & Csurhes: 2008).

Pictures 2.1 & 2.2: *Jatropha curcas* in Tamil Nadu, India (right) and Tanzania (left)

Sources:
1) author's picture - India;
2) Envirotrade - Tanzania

From the reports and journals it is found that there are more than 100 tree species occurring in the forests yielding non edible oils. There are nearly 50 to 70 species of non-edible oil species occurring naturally in Karnataka State, India. However, on commercial scale only three to four species namely, Neem (Azadirachta indic, Bevu), Pongamia (Pongamia pinnata, Honge), Hippe (Bassia longifoli, Mahua) and Castor are exploited for the oil purpose. Others species are commercially negligible though they meet the demand of the domestic and indigenous medicinal requirement, substantially (EMPRI: 2003, Widyaswamy: pers. comm.). Table of oil yields (kg oil per ha) for major Indian oil producing crops can be found in Appendix I.

Jatropha curcas (Linnaeus) (Physic Nut, Ratanjyot or Bhagarenda as it is called in the Indian countryside) is a poisonous perennial shrub of Latin American origin that is now widespread throughout arid and semi-arid tropical regions of the world. It grows wildly as a large shrub or as a cluster of number of bushes, packed very closely. The Portuguese imported this plant from tropical countries of Latin and Central America to India in 16th century for its medicinal values (Bhattacharya & Joshi: 2003, Lele: 2004; Heller: 1996; Friends of Earth: 2008).

From the review of many literatures, there were many conceptions, misconceptions and confusions regarding the ecological requirement of *Jatropha* as it has been recorded in areas where rainfall ranges from 250 mm to 3,000 mm per annum and from sea level up to 1,800 m altitude.

Jatropha curcas is a member of the plant tribe *Joannesieae* of *Crotonoideae* in the *Euphorbiaceae* family (Dehgan & Webster: 1979). It is a drought-resistant perennial, living up to 30-50 years and can bear fruits for 25 years (AgroForestryTree Database 2007, Hannan-Jones & Csurhes: 2008). It is classified under a generic name of ERAND. The genus of *Jatropha* containing 176 species (160-175 species - Dehgan: 1984 cited by Hannan-Jones & Csurhes: 2008) of trees, shrubs, rhizomatous sub-shrubs and herbs belongs to the *Euphorbiaceae* family. Nearly 17 species were recorded from India from wild and cultivated strata (Heller: 1996; Lele: 2004; Friends of Earth: 2008; Paramathma, *et. al.*: 2004).

The *Jatropha curcas* bark is pale brown, papery and tends to peel off readily. If damaged, stems exude copious watery latex that is soapy to touch but becomes brittle and brown when dry (AgroForestryTree Database 2007, Hannan-Jones & Csurhes: 2008). Depending on local climatic conditions, these can grow up to 5 meters tall (Friends of Earth: 2008, SCU: no date) which sounds more trustworthy than 7 to 10 meters tall claimed by Lele (2004) and Heller (1996), but in rain-fed areas these grow only 2 to 3 meters tall. In jungle, 3 or 4 plants grow together, as if it is one bush. In case of plantation, it is grown as 1 trunk and 2 branches at every node. In jungle its trunk can be 200 to 250 mm in perimeter, but in plantation it is generally only 100 to 120 mm.

Normally, five roots are formed from *Jatropha* seeds: a deep taproot and four shallow lateral roots. Plants from cuttings develop only lateral roots (Heller: 1996, Achten, *et. al.*: 2008, Devebiotech: no date, Paramathma: pers. comm., Karanth: pers. comm.). The taproot may stabilize the soil against landslides while the shallow roots are alleged to prevent and control soil erosion caused by wind or water, but this potential has not been investigated scientifically. Different crop species have a variety of rooting depths and this aid in distributing organic matter throughout the soil profile. As such, deep-rooting plants are especially useful for increasing carbon storage at depth, where it should be most secure (FAO: 2004).

Jatropha curcas is monoecious with protandry (male function precedes female function). Each inflorescence, once it begins flowering, flowers daily and lasts for 11 days. Flowers are unisexual, occasionally hermaphroditic. Bunches of flowers grow at the end of the branches. The fruit (Picture 2.3) is an ellipsoid capsule 2.5-3.0 cm long, 2-3 cm in diameter, initially yellow then turning black (AgroForestryTree Database 2007, Hannan-Jones & Csurhes: 2008).

Picture 2.3. Jatropha curcas fruit and seeds

Source: Envirotrade: 2006.

The yield of a plant depends mainly on the number of branches and on the genetics of the plant. The number of branches is important, because the inflorescences develop only at the end of branches. To improve the number of branches, the plant has to be pruned. If a branch is cut back, 3 to 5 new shoots will be developed below the cutting (Raina: pers. comm., Karanth: pers. comm., Rijssenbeek, *et. al.*: 2007, Dovebiotech: no date).

Jatropha curcas is pollinated by insects. (Friends of Earth: 2008, Hannan-Jones & Csurhes: 2008). Thus, Dehgan and Webster (1979 cited by Friends of Earth: 2008) believe that it is pollinated by moths because of "its sweet, heavy perfume at night, greenish white flowers, versatile anthers and protruding sexual organs, copious nectar, and absence of visible nectar guides".

In India, Raju and Ezradanam (2002 cited by Hannan-Jones & Csurhes: 2008) observed bees, ants, thrips and flies visiting flowers of *Jatropha curcas*. When insects are excluded from the greenhouse, seed set does not occur without hand pollination. Hand pollination experiments by Raju and Ezradanam (Ibid.) showed 96% fruit set through xenogamy (pollination from flowers on another plant) and 77% fruit set through geitonogamy (pollination from a flower on the same plant) (i.e. *Jatropha curcas* is self compatible). All xenogamous fruit develop to maturity but only 77% of geitonogamous fruit reach maturity (Ibid.).

Picture 2.4: Jatropha curcas non-raped fruit

Source: Envirotrade: 2006

Picture 2.5: Jatropha curcas exposed fruit and seeds

Source: Envirotrade: 2006

In the beginning fruits are green, then ripen to yellow with a golden tinge. On drying, these darken and when fully dry are black. When these dry fruits are peeled, 2 seeds each are found in 3 pockets (Pictures 2.3 & 2.5).

The reported seed weight per 1,000 is variable from ~727 g (Dovebiotech: no date), 400-730 g (Protabase: no date), ~500-800 g (SCU: no date). Final seed size is dependent on moisture availability at the time of seed filling (Aker: 1997 cited by Hannan-Jones & Csurhes: 2008). Seed size is correlated to percentage germination, seeds less than 300 mg, according to Hannan-Jones & Csurhes (2008), failing to germinate (Table 2.1). In moist soil, germination takes 10 days.

Table 2.1: Effect of seed weight on germination of *Jatropha curcas*

Seed size, mg	Average seed weight, mg	Germination, %
100-200	167	0
201-300	241	0
301-400	368	20
401-500	471	30
501-600	560	60
601-700	648	85
701-800	724	100

Source: Daghar, *et. al.*: 2004 cited by Hannan-Jones & Csurhes: 2008

Kumar, *et. al*. (2008) of the National Research Centre for Agroforestry (NRCAF), Jhansi, Uttar Pradesh documented that all morphological traits, viz. plant height, collar diameter, number of branches and branch length are positively correlated. Therefore, exploration can be made to collect the superior plant materials on the basis of the studied morphological traits. The best available practice in India at the moment is recommended to use planting material obtained from the best performing trees of the best performing provenance available in the location of interest. Shrubs with an annual yield above 2 kg dry seeds and seed oil content higher than 30% by weight can be considered a good source (Gour: 2006 cited by Achten, *et. al.*: 2008). Polyphenol oxidase and peroxidase enzymatic activities showed large variation, which will not only help in estimating the genetic relationship between the germplasm, but also in evaluating the capability of drought tolerance and enhancing flowering and fruiting. Thus, quantification of peroxidase and polyphenol oxidase enzymes can be used not only as markers for estimation of genetic variation, but also for screening the breeding lines of *Jatropha curcas* for high yielding potential. They also reported that number of female flowers/inflorescence showed highest variation among the morphological traits. As only female flowers bear fruits and it is a most desirable trait in monoecious species, selection of plants having more female flowers will be crucial for *Jatropha* oilseed and, therefore, oil yield raise (Kumar, *et. al.*: 2008).

Typically, *Jatropha curcas* begins to produce fruits at 4-5 months of age and reaches maximum seed production from the 2nd or 3rd year (Lele: no date, Beerens: 2007, Hannan-Jones & Csurhes: 2008, Paramathma: pers. comm.). Plants raised through vegetative propagation show early establishment, flowering and seed yield and are also relatively more uniform than the plants raised from seeds (Sharma, *et. al.*: 2008, Paramathma, pers. comm., Karanth: pers. comm.).

Both irrigated and rainfed *Jatropha curcas* have alternate bearing. It can not be currently forecasted or predicted, but if *Jatropha* plantation gets a good (high) yield during first harvest, the second one in a year will be much reduced. For now, even specialists can not make any prognoses how it will work for the next year. On moist or irrigated land alternate bearing is taking place annually. However, in dry land areas alternate bearing could happen not during one calendar year, but on bi-annual cycle. Under rainfed conditions just one good crop of *Jatropha* oilseeds per annum could be expected. The second crop is pretty much unlikely to occur, and if happens, it produces a very poor yield (Raina: pers. comm.).

2.1.1 Jatropha seed

Jatropha curcas is a multipurpose species with many attributes and considerable potential. *Jatropha* seed has the composition shown in Table 2.2, and agreed calorific value 20.1 +/- 0.08 GJ/t (Augustus, *et. al.*: 2002, Beerens: 2007) to 25.5 GJ/t (Moisture content: 5%. Ash: 4%) (Openshaw: 2000).

Table 2.2: *Jatropha curcas* (L.) oilseed composition

		per 100 g			**per 100 g**
Moisture	6.2%	6.2 g	**Carbohydrates**	17.0%	33.5 g
Protein	18.0%	18.2 g	**Fiber**	15.5%	15.5 g
Fat	38.0%	38.0 g	**Ash**	5.3%	4.5 g

Sources:
1) Lele: pers. comm.;
2) Duke & Atchley: 1983

Dessication generally improves seed longevity according to Ellis, *et. al.* (1985) cited by Heller (1996) (the only exception being Hevea). *Jatropha* oilseed viabilites are summarized in Tables 2.3 and 2.4.

Table 2.3: Jatropha oilseed germination (1)

Storage duration	Days	0	7	14	21
Germination level	%	90	89	88	86
Storage duration	Days	28	56	84	112
Germination level	%	85	77	55	43

Note: Dry seeds stored under room temperature

Source: Ratree: 2004

Ratree (2004) revealed that seed germination percentage significantly decreased with an increase in storage duration. Kobilke (1989) explains this rapid decrease is that these seeds remained at the site, having been exposed for long periods to extreme changes in levels of humidity and temperature. High levels of viability and low levels of germination shortly after harvest indicate innate or primary dormancy (Ellis, *et. al.*: 1985 cited by Heller: 1996). Pasabutr and Suthiponpaiboon (no date) conclude that it may be of high advantage to store *Jatropha* seeds in a temperature as low as 20°C where high respiration rate could be reduced, thus it may be possible to prevent the rapid deterioration of seeds since oil seeds obviously loses its vigour more rapidly when stored at high temperature.

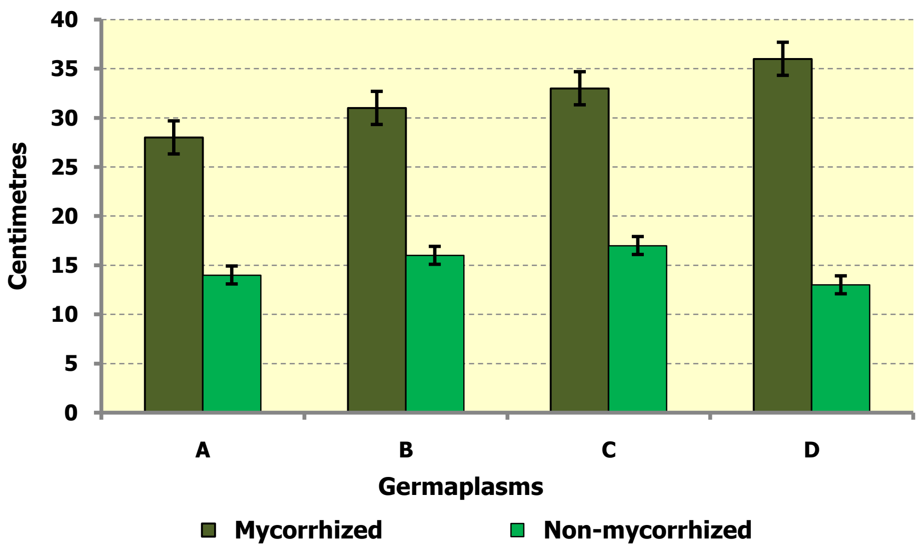
Most recent studies carried out at ICRISAT (2008. Activity 7.2.1.2) showed that inoculation of *Jatropha* seeds with Arbuscular Mycorrhizal cultures at one gram per seed, while dibbling the seed in the nursery bag enhanced seedling height by 34% and stem girth by 10% (Chart 2.1, Table 2.5). Dr. Adholeya (2008) says that as a new biological instrument, Mycorrhiza: a) making available nutrients from marginal soils; b) improving efficiency of water use; c) serve as a disease protection; d) reduced chemical fertilizer needs by efficient use of soil minerals, e) utilize organically bound materials, and, hence, a) reduced input costs up to 30%; b) improves biological health of soil, and c) support productivity increase 5 to 15%.

Table 2.4: Jatropha oilseed germination (2)

Oilseed storage duration	Storage conditions	Germination level	Comments	Reference
5 months	Ambient temperature (~20°C)	62% (ranging 19 to 79%	Stored in unsealed plastic bags	Ellis: 1995 cited by Heller: 1996
7 years	~16°C	47% (ranging 0 to 82%	Stored in unsealed plastic bags. Average mosture - 6.2% after 3 years	Ellis: 1995 cited by Heller: 1996
8 months	Room temperature	80%	-	Pasabutr & Suthiponpaiboon: no date
9 months	Room temperature	42%	-	Pasabutr & Suthiponpaiboon: no date
>15 months	Extreme changes inlevels of humidity and temperature	<50%	-	Kobilke: 1989
47 days DAA[a)]	-	73%	Green/immature	Panwar: 2004
57 days DAA[a)]	-	89%	Yellow/mature	Panwar: 2004
67 days DAA[a)]	-	89%	Black/ripened	Panwar: 2004

Note: DAA - days after anthesis

Chart 2.1: Effect of Mycorrhizal inoculation on Jatropha sapling height



Notes:
a) A - Chhattisgarh, B - Tamil Nadu, C - Karnataka, D - Maharashtra;
b) Age - 80 days

Source: Adholeya: 2008

Table 2.5: Effect of Mycorrhizal inoculation on growth of *Jatropha* seedlings in nursery

Treatment	Plant Height (cm)	Stem Girth (cm)	Number of Leaves
Inoculated	47	6.5	16
Non-inoculated control	5	5.9	12

Source: ICRISAT: 2008. Activity 7.2.1.2

2.1.2 Jatropha seed oil

The oil from the seeds (Tables 2.7, 2.8 & 2.9) is potentially the most valuable end product. It appears as a light yellow (Francis, *et. al.*: 2005) or clear brown (Mehta: 2004) liquid. The seed contains 19.0% oil, 4.7% polyphenol, and 3.9% hydrocarbon (Lele: 2004, Heller: 1996). The survey carried out by National Oil-seeds and Vegetable Oils Development Board (NOVOD) as part of the "National Network on Jatropha" reported variation in 'oil-content' 21-48% (Table 2.6). This semi-drying oil could be an efficient substitute for diesel fuel. The gross heat value for the seed (0% moisture content) was 4,980.3 cal/g (20.85 GJ/t), oil was 9,036.1 cal/g (37.83 GJ/t), and hydrocarbon was 9,704.4 cal/g (40.63 GJ/t) (Lele: 2004, Heller: 1996).

Jartopha oil cetane number is 51 and that of diesel is ~45 (Tables 2.7 & 2.9), which indicates that *Jatropha* oil does not readily ignite as diesel. However, the calorific value of *Jatropha* oil is 39.6 GJ/t, which is almost the same as petrodiesel (a) 43.8 GJ/t - de Castro: 2007 and Vyas: 2009; b) 45.343 GJ/t - Beerens: 2007) and fuel oil (LSHD) (a) 42.462 GJ/t - Dasappa: 2003; b) 44.8 GJ/t - Iyer, *et. al.*: 2002), and twice that of wood (a) 16.0 GJ/t - Ravindranath and Chanakya: 1986; b) average 16.9 GJ/t - oven-dried wood, average 13.5 GJ/t - air-dried wood - Ramachandra, *et. al.*: 2003; c) 16.0 GJ/t - Dasappa, *et. al.*: 2003; d) 15.5 GJ/t - Openshaw: 2000 and Nivitchanyong: 2007). The carbon content of *Jatropha* oil is 76.11 wt% (*-ef* to 80.33 wt% for diesel) , hydrogen content is 10.52 wt% (*-ef* to 12.36 wt% for diesel), and oxygen content is 11.06 wt% (*-ef* to 1.19 wt% for diesel) (Beerens: 2007).

The high viscosity of *Jatropha* oil is a result of the presence of the saturated and unsaturated acids identified in Table 2.8 and Appendix XII. The acids consist of relatively long carbon chains (C14:0-C20:0) when compared to conventional diesel (C12:0-C15:0) (Knothe & Steidley: 2005 cited by Beernes: 2007). High viscosity of *Jatropha* oil are not suitable for its use directly as engine fuel, often results in operational problems such as carbon deposits, oil ring sticking, and thickening and gelling of lubricating oil as a result of contamination by the vegetable oils (Akbar, *et. al.*: 2009).

Table 2.6: Variation in oil content in *Jatropha curcas* oilseeds in different geographical regions of India

Region/Provenance	Oil (%)	Region/Provenance	Oil (%)
Chhattisgarh[1]		**Orissa**[1]	
Pendra Road	48.2	Bhubneshwar	29.7
Bilaspur	44.6	**Thamil Nadu**[1]	
Jagdalpur (Bastar)	42.7	Coimbatore	30.5
Ambikapur (North Hills)	43.5	**Uttaranchal**[1]	
Raigarh	43.3	Dehradun	34.0
Raipur	42.8	**Rajasthan**[1]	
Andhra Pradesh[1]		Jodhpur	43.0
Hyderabad	33.8	**Maharashtra**[2,3]	21.0-42.0
Uttar Pradesh[5]	42.3	**Average oil-content**	30.0-35.0[2] 27.8-38.4[3] 36.8[6]

Notes:
a) N = 50;
b) Seed coat removed;
c) Seed weight = 3 g

Sources:
1) Sunil Puri: 2004;
2) NOVOD: no date;
3) PRAYAS: 2006;
4) ICRISAT: no date;
5) Tewari: 2007 cited by Tomomatsu and Swallow: 2007;
6) Beerens: 2007

Table 2.7: Physical properties of selected plant oils and petrodiesel oil

Oil type	Density @ 20°C	Viscosity @ 20-40°C	Flash point, °C	Cetane value	Energy value, GJ/t
Petroleum diesel	0.836[1] 0.855[7]	1.6-6.0[8] 3.06[7] 7.5[1] 8.0[6] 2.44+/-0.27[c,10]	76[7] 93[1]	50[1,7] 42.8[a,5] 47.0[b,5]	43.8[1,7] 45.343[10]
Cottonseed oil	0.921[1] 0.912[4]	73[1] 50[c,4] 36[8]	243[1] 210[4]	34[1] 35-40[6]	36.8[1] 39.6[4]
Palm oil	0.945[1]	60[1]	280[1]	39[1]	36.9[1]
Jatropha oil	0.920[1] 0.9186[2]	77[1] 53[6] 34-36[8] 35.98+/-1.3[c,10]	236[1]	35[1] 57[2] 38-51[3] 23-41[6]	37.83[9] 38.8[2] 39.6[1] 39.071[10]
Rapseed oil	0.920[1] 0.914[4]	78[1] 39.5[c,4]	285[1] 280[4]	36[1]	37.4[1] 37.6[4]
Rubber seed oil	0.91[4]	66.2[c,4]	198[4]		37.5[4]
Sunflower oil	0.918[4]	43[8] 58[c,4]	220[4]	29-37[6]	39.5[4]
Soybean oil	0.92[4]	31[8] 65[c,4]	230[4]		39.6[4]

Notes:
a) Grade 1-D diesel. ASTM D613-86;
b) Grade 2-D diesel. ASTM D613-86;
c) Viscosity @ 40°C

Sources:
1) de Castro: 2007;
2) Vyas, *et. al.*: 2009;
3) Achten, *et. al.*: 2008;
4) Ramadhas, *et. al.*: 2005;
5) McCormick, *et. al.*: 2003;
6) Vaitilingom & Liennard: 1997 cited by Jongschaap, *et. al.*: 2007;
7) Barnwal, *et. al.*: 2005
8) Knothe & Steidley: 2005 cited by Beerens: 2007;
9) Augustus, *et. al.*: 2002
10) Agarwal & Agarwal: 2007 cited by Beerens: 2007

Table 2.8: *Jatropha curcas* (L.) oil fatty acid composition

		Augustus: 2002	Akintayo: 2003	Kandpal & Madan: 1994	Akbar, *et. al.*: 2009	Raina & Gaikwad: 1987	Sarin, *et. al.*: 2007
Saturated acid							
Myristic	(14:0)				0.1%	0.07%	
Palmitic	(16:0)	14.1%	19.5% +/- 0.8	12.8%	14.2%	16.27%	14.2%
Margaric	(17:0)				0.1%		
Stearic	(18:0)	6.7%	6.8% +/- 0.6	7.3%	7.0%	7.34%	6.9%
Arachidic	(20:0)				0.2%	0.26%	
Total saturated acid						24.0%	21.1%
Unsaturated acid							
Palmitoleic	(16:1)				0.7%	1.16%	1.4%
Oleic	(18:1)	47.0%	41.3% +/- 1.5	44.8%	44.7%	43.87%	43.1%
Linoleic	(18:2)	31.6%	31.4% +/- 1.2	34.0%	32.8%	30.74%	34.4%
Linolenic	(18:3)				0.2%		
Total unsaturated acid						76.0%	78.9%

Notes:
a) Monounsaturated fatty acid (Cn:1) - 45.4%; polyunsaturated fatty acid with two or three double bonds (Cn:2,3) - 33.0%; saturated fatty acid (Cn:0) - 21.6% (Akbar, *et. al.*: 2009);
b) According to the European standard the concentration of linolenic acid and acid containing four double bonds should not exceed the limit of 12.0% and 1.0% respectively (Ibid.)

Sources:
1) Beernes: 2007;
2) Sarin, *et. al.*: 2007;
3) Edem: 2002 cited by Akbar, *et. al.*: 2009;
4) Raina & Gaikwad: 1987

Differrent methods such as preheating, blending, ultrasonically assisted methanol transesterification and supercritical methanol transesterification are being used to reduce the viscosity and make *Jatropha* oil suitable for engine application (Parmanik: 2003 and Banapurmath: 2008 cited by Akbar, *et. al.*: 2009).

Another disadvantage of raw *Jatropha* oil is that it freezes at lower temperatures thereby obstructing the flow to the burner or the engine (Neupane: 2001).

Treatment of plants with growth regulators significantly influenced the production of hydrocarbons. Among the treatments, ethephon and morphactin induced the maximum production of hydrocarbon by 5.0% and 5.4%, respectively (Lele: 2004, Heller: 1996).

The acid composition in Table 2.8 and Appendix XII also hints an acidic nature of *Jatropha* oil, which is harmful to rubber engine components. Poor atomization, low volatility and insufficient fuel-air mixing can lead to combustion chamber deposits, gum formation and unburned fuel in the lubrication oil (Agarwal & Agarwal: 2007 cited by Beernes: 2007).

Table 2.9: *Jatropha curcas* (L.) oil composition and characteristics

	Unit	Range	Mean
Appearance			Light yellow liquid[3]
Caloric value	GJ/t		37.8[3] 38.8[4] 39.6[6] 39.071[8]
Specific gravity	g/cm^3	0.860-0.993[1]	0.914[1] 0.9141[2] 0.92[3),7)] 0.912[4] 0.917[8]
Caloric value	GJ/t	37.83-42.05[1]	39.63[1]
Refrattive index			1.4698[2]
Solidifying/ melting point	°C	8-10[2]	
Pour point	°C		-3[1] 15[4]
Cloud point	°C		2[1] 20[4]
Flash point	°C	210-240[1]	235[1] 125[4] 240[7] 229 ± 4[8]
Fire point	°C		136[4] 274 ± 3[8]
Aniline point	°C		135[4]
Cetane value		38.0-51.0[1]	46.3[1] 57.0[4]
Saponification number	mg/g	102.9-209.0[1]	182.8[1] 185.0[4] 195.98[2] 197.0[3]
Viscosity at 30°C	cSt (mm^2/s)	37.0-54.8[1]	46.82[1] 52.0[7]
Viscosity at 40°C	cSt (mm^2/s)		15.0[4] 35.98 ± 1.3[8]
Free fatty acids	% (kg/kg*100)	0.18-3.4[1]	2.18[1] 5.29[4] 14.9[5]
Unsaponifiable	% (kg/kg*100)	0.79-3.8[1]	2.03[1] 0.5[2] 0.4[3]
Iodine number	mg iodine/g	92-112[1]	101.0[1] 101.8[2] 102.0[3]
Acid number	mg KOH/g	0.92-6.16[1]	1.24[3] 3.71[1] 10.2[2] 10.586[4]
Acetyl number			2.16[2]
Hydroxyl number			2.15[2]
Monoglycerides	% (kg/kg*100)	no data-1.7[1]	not detected[7]
Diglycerides	% (kg/kg*100)	2.5-2.7[1]	2.7[7]
Triglycerides	% (kg/kg*100)	88.2-97.3[1]	97.3[7]
Water	% (kg/kg*100)		0.07[7]
Carbon content	% (kg/kg*100)		76.11[8]
Hydrogen content	% (kg/kg*100)		10.52[8]
Oxygen content	% (kg/kg*100)		11.06[8]
Nitrogen content	% (kg/kg*100)		0.0[8]
Sulphur content	% (kg/kg*100)	0.0-0.13[1]	0.0[8]
Phosphorous	mg/kg		290.0[7]
Calcium	mg/kg		56.0[7]
Magnesium	mg/kg		103.0[7]
Iron	mg/kg		2.4[7]

Sources:
1) Achten, *et. al.*: 2008;
2) Talavera: 2004;
3) Francis, *et. al.*: 2005;
4) Vyas, *et. al.*: 2009;
5) Berchmans & Hirata: 2008;
6) de Castro: 2007;
7) Gübitz, *et. al.*: 1999;
8) Agarwal & Agarwal: 2007 cited by Beerens: 2007

2.1.3 *Jatropha curcas* annual growth cycle

Two major things about time of *Jatropha curcas* flowering and harvest time is an understanding of its interconnection with monsoon season and understanding that *Jatropha curcas* has alternate bearing. Dormancy is induced by fluctuations in rainfall and temperature/light as well. In terms of monsoons: in the South of India monsoons come from May, have peak in June-July, and last until September. So, the first flowering period is in May with first harvest coming in June-July, and second flowering period upon the peak of monsoon rains and harvest in August-September. In the North of India shift is one month further (June instead of May and so on). Also, in dry areas, or without irrigation there is just one harvest a year.

From the field visits it was observed that though the plant can survive in any type of soil, the yield of the seeds and oil content varied and in order to get a good yield of superior quality, proper care is required. The soil should have proper drainage and heavier soil type.

Black (cotton) soil type is not good for its growth as it cannot stand water logging. The soil has to be treated with Farm Yard Manure, chemical fertilizers and pesticides, and proper watering is required in the initial period with pruning being done from 6-8 months old plants age. The Central Soil Salinity Institute studies show that application of at least two crucial irrigations, i.e. during peak summer (May-June) and peak winter (December-January) seasons is essential for optimum survival and productivity of *Jatropha* in the first two years. An additional irrigation during flowering period is helpful, in case rains fall (Sharma, *et. al.*: 2008).

Also, ICRISAT (2008. Activity 7.2.1.2) studies clearly demonstrate that terminal pruning at 45-60 cm in the first year of planting during the dormant period (*Jatropha* normally sheds its leaves after the cessation of monsoon rains and puts forth new flushes towards the onset of the next monsoon) increased the number of flowering branches and similarly continuous light pruning of secondary and tertiary branches during the dormant period is necessary to ensure improvement in the number of flowering branches and maintaining a suitable canopy spread at a height to facilitate manual picking of seeds. Pruning should be done in the dry or winter period after the trees have shed their leaves. This will result in a lower and wider tree shape, induce earlier seed production and facilitate manual harvesting.

Table 2.10: *Jatropha curcas* "early crop" timetable. Karnataka State. India

	Dormancy	Vegetation	Flowers	Fruits	Activities
January	Dormant period				
February					Late February - pruning
March					
April		April - fresh bud break, sprouting. Late April - fresh spurs coming			Late April - fertilizers application
May			Mid-late May - start of first flowering		
June			Full flowering		
July				Fresh fruits	Start of the first fruits harvesting (major harvest)
August			Start of second flowering	Raped/dry fruits	End of the first fruits harvesting
September			Second flowering		
October			Minor number of flowers (if soil contains enough moisture). The number of man flowers are highly prevails.	Fresh fruits	Start of the second fruits harvesting (minor quantity)
November		Late November - shed leaves		Early November - raped/dry fruits	End of the second fruits harvesting
December	Early December - start of dormant period				

Source: Raina: pers. comm.

Once every 10 years, the entire plant has to be cut low, leaving a stump of 45 cm. The re-growth will be quick and the trees will start yielding again within about 1 year. This intervention will induce new growth and help to stabilize the yield (Gour: 2006 cited by Achten, *et. al.*: 2008). Beside trimming hedgerows and pruning plantations annually, periodic thinning of plantations is proposed as well. Starting from 1,600 seedlings per hectare, stand density should be thinned to 400-500 trees per hectare in the final mature stand (Openshaw: 2000). *Jatropha* plant is sensitive for elevation and, therfore is not suitable for frosty and high elevation areas. Author's observations in both Andhra Pradesh and Chhattisgarh led to the conclusion that *Jatropha's* growth and vegetation improvement is very poor if planted in rocky soils, or thin soils with rock bed (Picture 2.6).

Fertilizer applications should be consistent with the time of *Jatropha* flowering. That means it should be at the time when less than 10% flowers occurs, before sprouting (bud break) of flowers and fresh leaves. It also should be noticed that *Jatropha curcas* flowering (as well as harvest time) directly interconnected with monsoon seasons (Raina: pers. comm., Sharma, *et. al*.: 2008). The "early" crop starts flowering in mid-to-late May, just prior to monsoon season, with female to male flowers rate of 1:3. It produces fruits in July-August. Then flowering continues up to August-September, and sometimes even until October. Late flowering is a subject of moisture levels in soil and it's essentially only male flowers. Actual female to male flowers ratio monitored and recorded is 1:20 to 1:40. Due to diminishing female-to-male flowers ratio, the second crop in October is pretty negligible. The "late" crop starts its flowering in late June with the same 1:3 female to male flowers ratio, which is slowly dropping to 1:20, and even 1:30 up to the end of October - turn of November (Raina: pers. comm).

Picture 2.6: Eight months old *Jatropha* planted on rocky soils. Andhra Pradesh. March 2006

Source: author's picture

Early flower initiation (July-August) is a desirable trait in the North Indian conditions as late formed flowers and late flowering varieties face lower high temperatures thus, hampering further seed development and maturity (Sharma, *et. al*.: 2008). In South India, fruits are coming in August-September and sometimes in much less amount in October. Irrigated crop is behaving just as a "late" crop. It gives much longer flowering (June-November) and fruiting (up to December or even around the year) duration, but still with one peak in late July-August.

Some hormones (GA3) induce female flowers and improves male to female ratio up to 1:3 (Raina: pers. comm., Sharma, *et. al.*: 2008).

2.1.4 Climate conditions influence on *Jatropha curcas* oilseed yield

According to UNEP (1992 cited by FAO: 2004), ~47% of the surface of the earth can be classified as dryland. Although there is many various definitions of dryland with pretty ambiguous boundaries, drylands are considered to be areas where average rainfall is less than the potential moisture losses through evaporation and transpiration.

The World Atlas of Desertification (UNEP: 1992) reveals that drylands have a ratio of average annual precipitation (P) to potential evapotranspiration (PET) of less than 0.65. Where the water deficit prevails throughout the year, drylands are classified as extremely arid or hyperarid, whereas when it occurs for most of the year they are arid and semi-arid regions (FAO: 2004).

Table 2.11: Dryland categories according to FAO (1993) classification and extension[1)]

Classification	P/PET[1)]	Rainfall, mm	Area, %	Area, x10^9 ha
Hyperarid	< 0.05	< 200	7.50	1.00
Arid	0.05<P/PET<0.20	<200 (winter or <400 (summer)	12.1	1.62
Semi-arid	0.20<P/PET<0.50	200-500 (winter or 400-600 (summer)	17.1	2.37
Dry subhumid	0.50<P/PET<0.65	500-700 (winter or 600-800 (summer)	9.90	1.32
Total			47.2	6.31

Sources:
1) UNEP: 1992;
2) FAO: 2004

The main characteristic of drylands is deficiency of water. This harshly restrains plant productivity and therefore affects the accumulation of C in soils. The problem is aggravated because rainfall is not only low but also generally inconsistent.

Furthermore, the SOC pool tends to decrease exponentially with temperature (Lal: 2002a cited by FAO: 2004). Hence, soils of drylands contain small amounts of C (between 1% and less than 0.5%) (Lal: 2002b cited by FAO: 2004). The SOC pool of soils is generally going up with the addition of biomass to soils when the pool has been depleted as a result of land uses (Rasmussen & Collins: 1991; Paustian, *et. al.*: 1997; Powlson, *et. al.*: 1998, Lal: 2001a cited by FAO: 2004).

The complexity of agricultural/oilseed cultivation component of this Life Cycle Assessment augmented by the fact that Indian subcontinent has 10 different bio-geographic zones and 26 biotic provinces (Wildlife Institute of India: 2000 cited by Promode: 2005). South India comprises of Andhra Pradesh (AP), Tamil Nadu (TN), Karnataka, Kerala, Goa, and Islands in Bay of Bengal (Andaman and Nicobar) and Arabian Sea (Lakshadweep). It comprises central uplands, Deccan plateau (Karnataka plateau and Telangana plateau of AP), Nilgiri hills of TN, South Sahiailri, Eastern hills (Eastern Ghats, TN, upland) and Coastal Plains. Climate is mainly semi-arid in nature. The rainfall ranges from 400 to 500 mm in AP, 450 to 1300 mm in Karnataka, 500 to 1215 mm in TN, 100 to 450 mm in Kerala (Swarajyalakshmi, *et. al.*: 2003).

Karnataka state included 10 agro-climatic zones per se: 1) North Eastern Transition Zone; 2) North Eastern Dry Zone; 3) Northern Dry Zone; 4) Central Dry Zone; 5) Eastern Dry Zone; 6) Southern Dry Zone; 7) Southern Transition Zone; 8) Northern Transition Zone; 9) Hilly Zone, and 10) Coastal Zone. The climate of Deccan plateau that extends from Andhra Pradesh into Karnataka consists of a mild winter period (*rabi*, November-February), a hot and dry summer (March-May) and the southwest monsoon, when more than 80% of rainfall occurs (*kharif*, June-October). Average rainfall is slightly less than 900 mm. The hottest month is May, just before the onset of rains, when the maximum daytime temperature can reach 40°C. Conversely, night temperatures can drop to 6°C in December. Moisture availability for crop growth ranges from 120 to 150 days after sowing (FAO: 2004).

Village Devardau and village Pendra at Bilaspur District, Marwahi Subdistrict, Gorilla Range, Chhattisgarh is being claimed to produce highest in India *Jatropha* seeds yields and oil content in kernel, as *Jatropha* traditionally growing in the area in hedges (Picture 2.7). This is a humid part of Chhattisgarh, with relatively low temperatures in winter. Temperature in April-May is usually 30-37°C and does not exceed 40°C (unlike 46°C in Rajpur, the capital of Chhattisgharh). Also, this area is experience a high frequency of rains in summer period, which contributes to high humidity/increase of moisture. Finally, these climatic conditions contribute to the high yield of *Jatropha*. Dr. Thakur (pers. comm.) believes that 10 kg of seeds per plant is possible for 15-25 years old *Jatropha* plants in this area.

Most of the literature (Patil & Singh: 1991; Heller: 1996; GOI. Planning Commission: 2003; Becker & Francis: 2003; Paramathma, *et. al.*: 2004; Hegde, *et. al.*: 2004; Lele: 2004; Labland Biotech Pvt. Ltd.: 2005; Amissah-Arthur, *et. al.*: 2007, Singh, *et. al.*: 2008, *etc*) cites *Jatropha* yields of up to 12.0 t/ha for irrigated plantations, but such yields are not realistic on poor soils and without irrigation. Also, GTZ (no date) after several experiments to measure yields have concluded that degraded land yields of 8.0-12.0 t/ha are highly improbable. Moreover, after using pest control measures, Professor Neelakantan, Dean for the Forest College and Research Institute, restricts the yield in rainfed areas to 2.5 t/ha and in irrigated areas to 5.0 t/ha (Friends of Earth: 2008). The same average yield of 5.0 t/ha reported by GOI (2004) and Francis, *et. al*. (2005).

Altenburg, *et. al*. (2009) recited Negi, *et. al*. (2006) opinion that mature *Jatropha* plantations are expected to yield more than 3.5 t/ha. However, to achieve such yields, fertile soil, irrigation or high rainfall and inputs of fertiliser and pesticides are required (Ibid.). Dr. Paramathma, Professor and Nodal Officer for the Center of Excellence in Biofuels, TNAU says that under rainfed condition *Jatropha* oilseed yield recorded never exceeded 0.5-1.5 t/ha even for 10 years old trees. In his opinion, it is very difficult to get more than 1.5 kg per tree under rainfed conditions.

Picture 2.7: Defoliated *Jatropha curcas* shrub in Bilaspur District, Chhattisgarh

Source: author's picture

Under irrigated crop might get seed yield of 4.5 kg per tree (3x2 m spacing) or 6.5 kg (3x3 m spacing). However, the new TNMC 7 (Tamil Nadu Mettupalayam Curcas 7) "plus tree" provides opportunity of getting 7.5 t/ha of Jatropha oilseeds under irrigated, fertilized, pruned and plant protection adopted condition (Paramathma: pers. comm.). Report of the Committee on Development of Bio-fuels (2003) says that the annual seed- yield of *Jatropha* in Maharashtra is highly variable and could be as low as 0.4 t/ha (PRAYAS: 2006).

The German Development Insititute studies also point out that experience made in the past few years by research institutions and practitioners has shown yields in fact remain at the lower end of that stated by the Planning Commission of India (2003) 0.4-12.0 t/ha range (Altenburg, *et. al.*: 2009). Also, according to Mr. Vinayakrao Patil, a Chairman of Maharashtra Agro-forestry Federation, results of *Jatropha* plantation raised on over 20,000 acres of land between 1986 to 1994-1995 were not very encouraging, with yields of 1.0 to 1.5 t/ha in the third and fourth years (NABARD: 2005).

The expectation that oil-bearing trees, especially *Jatropha*, would give good yields even on marginal and dry lands without inputs such as irrigation, fertilisers and pesticides has not materialized (Table 2.12, Pictures 2.6 & 2.8).

Table 2.12: Reported *Jatropha curcas* oilseed yields

Yield, t/ha/yr	Country	Primary reference	Comments
4.5[1)]	Nicaragua	Foidl	After 4 years
1.0[2)]	Tanzania	Coleman	6-year-old plantation
4.0-5.0 (ds.)[1)]	Indonesia	Manurung	2x2 m spacing; precipitation 2000 mm/a; good soil; high organic matter
1.25 (ds.)[1)]	Guatemala	Barrilas, Octagon	Irrigated; fertilizers applied
0.5-0.6 (ds.)[1)]	Guatemala	Barrilas, Octagon	Rainfed; no fertilizers applied; precipitation 4000 mm in 6 month
0.8 (ds.) - prognosis[1)] 0.25 (ds.) - fact[1)]	Brazil	Moller	Fist year plantation; late planting; optimal climate; good soil fertility
1.27[1)]	India	Patolia	After 2 years; 4 x 3 spacing; high nutrient level; precipitation 800 mm/a
1.0-2.8[4)]	India	AEA: 2008	Rainfed
5.0-12.0[4)]	India	AEA: 2008	Irrigated
1.5-7.5 (ds.)	India	Jongschaap, *et. al.*: 2007	
0.67[5)]	India	Prof. Neelakantan, TNAU: no date	Poor rainfed soil
2.5[5)]	India	Prof. Neelakantan, TNAU: no date	Fertile irrigated soil
0.0-5.0[3)]	Thailand	Prueksakorn & Gheewala	On-site data for year 1
0.35-12.5[3)]	Thailand	Prueksakorn & Gheewala	On-site data for year 2
0.88-12.5[3)]	Thailand	Prueksakorn & Gheewala	On-site data for year 3

Note: ds. - dry seed

Sources:
1) Rijssenbeek: 2007;
2) Coleman: pers. comm.;
3) Prueksakorn & Gheewala: 2008;
4) Howarth, *et. al.*: 2009;
5) Burley & Griffiths: 2009

In order to achieve economically viable yields, farmers would have to bear high input and opportunity costs. Current figures presented by NOVOD's Network on *Jatropha*, suggest that in order to reach economic viability, *Jatropha* must yield 2.0 kg of seeds per plant without investments in irrigation and fertilizers, whereas actual yields under these conditions tend to be well below 1.0 kg. Achieving higher yields is a necessary condition to make the industry viable and to increase rural income (NOVOD: 2007 cited by Altenburg, *et. al.*: 2009). High oil content in *Jatropha* seeds harvested in this area occurs as flowering of *Jatropha* occurs during higher humid conditions (Takur: pers. comm.). Another explanation of this phenomenon is given by NRCAF researchers who correlated different enzymes with the percentage of oil in *Jatropha* oilseeds and found that accessions which have greater laccase enzyme activity showed greater oil percentage (Kumar, *et. al.*: 2008).

Picture 2.8: Eight months old rainfed *Jatropha* plantation in Chhattisgarh. February 2006

Source: author's picture

Author's observations in Chhattisgharh come to conclusion that watering and planting of *Jatropha* in areas with high water table is crucial for Chhattisgharh climatic conditions, as in Tamil Nadu, application of fertilizers, especially urea, is a most important factor, as average ambient temperatures in Tamil Nadu not as high as in Chhattisgharh. It is in average

95 rainy days during monsoon period (June-October). In conditions of continuous rains (up to 4-5 days) flowering could be negatively affected. However, if frequency of rains is low (rainy days mixed with sunny days) - flowering will be high for two reasons - increasing humidity and sunshine. Continuous rains are not good for flowering, and therefore yield and oil content. In Chhattisgharh flowering occurs around a year. In addition, direct and intense sunshine during the same period contributes to both high yield and high oil content. Thus, in 2005, in Chhattisgharh, flowering was only 10-15% compare to previous year (2004) due to temperature variations, as continuous rains and cold weather come to pass in July-August 2005 severely affected flowering and, therefore, oilseed yield (Thakur: pers. comm.).

From April to December flowering and all processes up to maturity of fruits could be prolonged (up to 6 times a year harvesting of *Jatropha* seeds) due to pruning and manipulation of flowering by application of some hormones/growth regulators. Also, author's observations, together with the professional opinion of Mr. Chandrakur of the Forest Division Dhamtari led to the conclusion that the quality of ground preparation and the manner of seedling transplantation are amongst the most important factors for the further vegetation development and fruits production.

2.1.5 Indian soils

According to the latest appraisal (Sehgal & Abrol: 1994 cited by Pachauri: no date), most of Indian land is either degraded, is undergoing degradation or runs the risk of being degraded. The main consequences of land degradation are: the chemical degradation of the soil (e.g. lost of significant amounts of C); loss of vegetation cover; loss of topsoil infiltration capacity; reduction in soil water storage; loss of soil organic matter, fertility and structure; loss of soil resilience; loss of natural regeneration; and lowering of the water table (FAO: 2004). Among the different land categories, land under cultivation faces the biggest problem followed by grazing land and pastures, forests, barren lands, and uncultivable land in decreasing order.

Many soils in the sub-humid and semi-arid tropics show some properties which place them in the category of 'fragile soil', notably those with easily erodible surface soils. Nearly 146 million ha land is classified as degraded land in India. Estimates of the cost of soil degradation during 1980s and 1990s ranged from 11 to 26% of GDP. The cost of salinity and waterlogging is estimated at Rs. 120 billion (~2 billion GBP) to Rs. 270 billion (~4.5 billion GBP), and if the cost of environmental damage is taken into account, India's economic growth comes to minus 5.73% per annum as against plus 5.66% estimated otherwise (GOI: 2007).

The Report of the Working Group on Natural Resources Management (GOI: 2007) identified land conservation, soil health and access to land are the main challenges for the Indian agricultural industry.

Due to the poor soil condition, marginal lands cannot support a high plantation density without adversely affecting output per plant. Therefore yield per hectare from such lands is likely to be lower compared to yield from lands of higher quality (Pictures 2.6, 2.8 & 2.9; Rajagopal: 2007). Soil health enhancement holds the key to raising small farm productivity. However, inappropriate management practices in India have made the land suffer from varying degrees and types of degradation.

Picture 2.9: *Jatropha* planted on rocky soil in Andhra Pradesh. February 2006

Source: author's picture

The major soil types of Deccan Plateau that extends from Andhra Pradesh into Karnataka are Alfisols and Vertisols. The former include red lateritic soils comprising loamy sands, sand loams and sandy clay loams and are usually nonsaline. Red soils (Alfisols, Inceptisols, and Entisols) make up about 60-65% and are well drained, blacksoils (Vertisols and Inceptisols) comprise about 20-25% and the rest are coastal sands (Swarajyalakshmi, *et. al.*: 2003). The Vertisols, black cotton soils, are potentially more productive with a higher waterholding capacity, moderately alkaline and with a highly soluble salt content. They comprise clay loams, clays and silty clays (FAO: 2004).

The organic carbon content of soils in the area is usually 0.5-1.0%. The land lies between 500-600 m above sea level, and very little natural vegetation remains. The tropical dry deciduous forest has mainly been felled except on protected government land (Ibid.).

There are four types of soils found in the tracts of Eastern Ghats, namely a) rocky soil (lethosols), b) redloam, c) alluvial, and d) black soil. The major type of soil type in the agency areas is lethosols. The mountains, plateaus and rough hill lands include many areas in which shallow soils overlie their rock formations by only an inch. In other areas up to a foot or two of soil marbles the bed rock (Subramanyam: 2003).

To characterize the fertility status of soils under dryland agriculture in the semi-arid regions of India, Ch Srinivasarao, *et. al*. (ICRISAT: 2008. Activity 9.2.1.9) demonstrate that crops grown under rainfed agriculture in the semi-arid tropical regions of India not only face water shortages and deficiencies of major plant nutrients (N and P), but they also suffer from multi-nutrient deficiencies of S, B and Zn.

An important strategy for restoration of degraded soils is to grow specific species for biofuel production (Sampson, *et. al.*: 1993, Aberlson: 1995; Giampietro, *et. al.*: 1997). Use of appropriate species in different ecoregions can lead to net carbon assimilation of 5 Mg/ha/yr (Lai, *et. al.*: 1998 b). Smith, *et. al.* (1998) reported that afforestation of surplus arable land by appropriate species and using the material as biofuel would lead to carbon off-set for fossil fuel in Europe at 30-40 Tg/yr. Restoration of 100 million ha of degraded soils through conversion to biofuel production could lead to below ground Carbon (C) sequestration of 0.025 PgC/yr as soil organic carbon (SOC) and biofuel for fossil fuel offset of 0.35 PgC/yr.

There is another aspect of cropland degradation, which is important to C sequestration. Salt-affected soils cover about 1/10th of the earth land (Szabolcs: 1998 cited by Lai & Bruce: 1999), and one-third of the arid and semi-arid regions (Rengasamy: 1998 cited by Lai & Bruce: 1999) and 930 Mha worldwide (Summer, *et. al.*: 1998 cited by Lai & Bruce: 1999). High salt level leads to soil structural degradation and changes in soil/plant water potential resulting inreduced biomass productivity. According to Swarajyalakshmi, *et. al.* (2003), soil salinity in Southern India has reduced crop yields up to 50% and consequently cropping has been abandoned in many areas.

The area of salt-affected soils extends to about 0.176 million ha in AP, 0.2 million ha in Karnataka, 0.0427 million ha in TN and about 0.03 million ha in Kerala. Soil salinity observed in South India ranges from hydrometphic saline soils in Kerala to highly saline (20.0-30.0 dS/m) in Karnataka and AP (Ibid.). At present, The Central Soil Salinity Research Institute in Karnal, Haryana conducting research which aims to develop *Jatropha* germaplasm base to promote its economic production in saline agriculture (saline/sodic soils and waters) and found practices for raising *Jatropha* plantations in salt affected soils.

Preliminary results show good salt tolerance of *Jatropha* during establishment period as not much reductions occurred in soil salinity of 10.0-12.0 dS/m and application of saline water (Sharma, *et. al.*: 2008).

In common with other agricultural systems, the cultivation of *Jatropha* without implementation of a properly designed farming system can lead to both short- and long-term problems. These can include erosion, nutrient depletion, lower water table level and pollution. Only within use of farming systems tailored to the area can yields be sustained. The farming system programme should fully utilize indigenous knowledge system and locally available inputs (GOI: 2007, ICRISAT: 2006. Project 8).

2.1.6 Pests and diseases of *Jatropha curcas*

2.1.6.1 Insect Pests

Contrary to popular belief that toxicity and insecticidal properties of *Jatropha curcas* are a sufficient deterrent for insects that cause economic damage in plantations, several groups of insects have overcome this barrier (Shanker & Dhyani: 2006; Adholeya: 2008). Regular irrigation and fertilizer application is expected to enhance these pest and disease infestations in commercial monocultures (Sharma: 2007, Achten: 2008). Thus, Amissah-Arthur, *et. al*. (2007) reported that "bushfires and pests have posed much bigger threat to the cultivation of *Jatropha* in Ghana than initially anticipated". Farmers in Swazilend also reported severe problems with pests (Burley & Griffiths: 2009).

At present, in depth studies on the ecological aspects as well as control measures are being carried out at the National Research Centre for Agroforestry (NRCAF), Jhansi, Uttar Pradesh. Many diseases of TBOS, including 1) Nursery Diseases, 2) Foliar Diseases, 3) Stem Diseases, 4) Root Diseases well described by Professor Prakasam of the Department of Forest Biology, TNAU (Prakasam at Paramathma, *et. al.*: 2004).

In its native range, more than 40 species of insects affect *Jatropa curcas*, including the shield-backed bug *(Pachycoris klugii)* and the leaf-footed bug *Leptoglossus zonatus* (Grimm & Fuhrer: 1998; Grimm & Somarriba: 1999 cited by Hannan-Jones & Csurhes: 2008).

Thus, these authors reported that the millipede *Julus* sp. has caused seedling mortality and the locust *Oedaleus senegalensis* attacks seedlings and leaves (Heller: 1992 cited by Heller: 1996). The cushion scale *Pinnaspis strachani* (known to occur in South Australia (Donaldson & Tsang: 2006) and the wooly mealybug *Ferrisia virgata* cause branch die-back. The blue bug *(Calidea dregei)* and green vegetable bug *(Nezara viridula)* damage fruits (Heller: 1996).

Serious disease symptoms of mosaic from mild to severe, marked reduction in leaf size, rolling of leaf margins and puckering of leaf surface were reported on a large number of *Jatropha* plants in various localities of Balrampur District, Uttar Pradesh during the rainy season of the year 2005. The disease was also transmitted by cleft graft in new shoots and could not be transmitted to any other plant, except *Jatropha curcas* (Tewari, *et. al*.: 2007, Friends of Earth: 2008). Dr. Ganeshkumar, Professor and Head for the Department of Forest Biology, TNAU observed that *Jatropha* suffers badly from the larvae of insect *Spondoptera litura* (Fabricius) Boursin (Defoliator). Its larvae feed on the leaves at night gregariously for a few days and then disperse and cause a heavy damage to the young plant for about 30 days. The incidence of this pest varies from 60-70%. Another reported insect pest is *Scutellera nobilis* (Bug), both nymphys and adult of which cause severe damage. Adults look like metallic green with black spots. Yellowing of leaves and produces crinkled leaves (Ganeshkumar at Paramathma, *et. al.:* 2004, Hannan-Jones & Csurhes: 2008).

Grimm and Maes (1997) identified *Pachycoris klugii (Scutelleridae)* and *Leptoglossus zonatus (Coreidae)* as the key pests in Nicaragua. The insect order Heteroptera that has at least 15 species in Nicaragua, can extract nutrients from physic nut, is predominantly dangerous for *Jatropha* plantations.

Other possible pests are the blister miner *Stomphastis (Acrocercops) thraustica*, the semi-looper *Achaea janata* and the flower beetle *Oxycetonia versicolor*. Shanker and Dhyani (2006) say that insect that caused maximum damage proved to be the seed-feeding Scutelleridae, *Agonosoma trilineatum*. It belongs to the phytophagous insects and was found in Australia.

In reality, even in India where *Jatropha curcas* is grown in continuous stretches as a monocrop, it is devastated by two pests that are emerging as a major problem in *Jatropha* cultivation - the scutellarid bug *Scutellera nobilis* Fabr., which causes flower fall, fruit abortion and malformation of seeds. It was observed to occur at an average of five per bunch, with a maximum of 15 bugs per bunch (Shanker & Dhyani: 2006). The inflorescence and capsule-borer, *Pempelia morosalis* also causes economic damage by webbing and feeding on inflorescences and in later stages boring into the capsules.

Another natural control agent was the spider, *Stegodyphus sp*. (Eresidae: Arachnida), which snared these bugs in its web. Elsewhere, capsule-borer and the barkeating caterpillar have been recorded as key pests for which a spray of endosulfan is advocated. Other pests that have caused noticeable damage (e.g. in India) are *Stomphastis (Acrocercops) thraustica* Meyerick, the blister miner, the semilooper *Achaea janata* and to a small extent, the flower beetle *Oxycetonia versicolor* (Shanker & Dhyani: 2006), and to a small extend the flower beetle *(Oxycetonia versicolor)*, calotropis leaf hopper bug (green-striped leaf hopper bug) *(Eurybrachis tomentosa)*, grape vine thrips *(Rhipiphorothrips cruentatus)* and chilli muranai mite *(Polphagotarsonemus latus)* (Hannan-Jones & Csurhes: 2008).

The following description of virus and fungus affected *Jatropha curcus* plants were found at Hannan-Jones & Csurhes (2008):

2.1.6.2 Virus

Jatropha mosaic virus (JMV) is a potential pest of *Jatropha curcas* and has recently been found in Southern India following the introduction of its vector silverleaf whitefly *(Bemissia tabaci* 'B biotype'*)*. The disease causes reduced leaf size, leaf distortion, blistering and stunting (Narayana, *et. al*.: 2006 cited by Hannan-Jones & Csurhes: 2008).

2.1.6.3 Fungus

Overseas, *Phytophthora*, *Pythium* and *Fusarium* can cause damping off and root rot (Heller: 1992). The leaf spots *Helminthosporium tetramera*, *Pestalotiopis paraguarensis* (Singh: 1983), *Pestalotiopis versicolor* (Phillips: 1975) and *Cercospera jatrophae-curcas* (Kar & Das: 1987) have also been recorded (Hannan-Jones & Csurhes: 2008).

2.1.7 *Jatropha curcas* (L) in Australia

It was repeatedly stated that *Jatropha* is not a weed, and thus not self propagating. It has to be planted (FACT Foundation: 2006). However, according to Peter Johan Schei, Director for the Norwegian Fridtjof Nansen Institute (2007), *Jatropha curcas* shows most of the characteristics of a potential Invasive Alien Species, one of the most serious threats to biodiversity today (Navdanya: no date, Biofuelwatch and FERN: no date, Burley & Griffiths: 2009). Once released from the capsule, the *Jatropha* seeds could potentially be moved by flowing water or perhaps adhere to mud in animal's hooves or on vehicles (Parsons & Cuthbertson: 2001 cited by Hannan-Jones & Csurhes: 2008). Moreover, Holm, *et. al.* (1991 cited by Hannan-Jones & Csurhes: 2008) noted that *Jatropha curcas* has been listed as a weed in Peru, Brazil, Fiji, Honduras, India, Jamaica, Panama, South Africa and Indonesia and, according to Burley and Griffiths (2009), recognized as an "invasive species" in some parts of the world, including United States, South Africa, Australia and Puerto Rico. The Global Invasive Species Programme has recommended that it should not be used for biofuel production (Ibid.).

The unique characteristic of *Jatropha* indicates that the species could be invasive as referred to in Australia (Friends of Earth: 2008, Shanker & Dhyani: 2006, Biofuelwatch and FERN: no date). *Jatropha curcas* is a declared weed under the Northern Territory's *Weed Management Act 2001*, Class A (to be eradicated) and Class C (not to be introduced to the Northern Territory) and in Western Australia. It is an eradication target in the Northern Territory and was declared many years ago due to concern over its toxic seeds. Since *Jatropha curcas* is considered to be under 'official control' in Australia, its import is prohibited by the Australian Quarantine and Inspection Service (AQIS). *Jatropha curcas* and *Jatropha gossypiifolia* are official targets for biological control in Australia, with *Jatropha gossypiifolia* being the main target (Hannan-Jones & Csurhes: 2008).

Jatropha curcas is not known to occur in Western Australia but, as a precaution to prevent its introduction, is a declared plant under the Western Australian *Agriculture and Related Resources Protection Act 1976* ('category P1' for the whole state). This declaration also prohibits movement of the plant or its seeds *within* the state. *Jatropha curcas* is also declared as a 'category P5' plant for the municipal districts of Broome, Derby-West Kimberley, Halls Creek and Wyndham-East Kimberley. This category requires that infestations on public land must be controlled. Australian Quarantine and Inspection Service (AQIS: 2007) also prohibited the importation of *Jatropha curcas* into Australia because the plant is considered to be under 'official control' in jurisdictions within Australia.

At some sites in North Queensland, Australia, *Jatropha curcas* has formed small thickets and these will probably expand slowly over time. As such, it could cause localized problems that might expand over coming decades. The fact that *Jatropha curcas* has not become a major weed in Queensland over more than 100 years suggests that it is a low risk. Csurhes (1998 cited by Hannan-Jones & Csurhes: 2008) suggests that *Jatropha curcas* is not as readily dispersed as a bellyache bush *(Jatropha gossypiifolia)* and appears to be much less vigorous.

While unlikely to have major negative impacts on agriculture, *Jatropha curcas* may act as an alternate host for some plant pests such as the rainbow shield bug *(Calidea dregii)*, a pest of cotton in Tanzania and sorghum and sunflower in South Africa (Parsons & Cuthbertson: 1992 cited by Hannan-Jones & Csurhes: 2008). In addition, *Jatropha curcas* is listed by the Queensland Department of Health as a 'category 2' and 'category 3' poisonous plant. It poses a risk to human health if ingested. *Jatropha curcas* contains a range of toxic compounds, including saponins, lectins, phytates, protease inhibitors, curcalonic acid and irritant diterpene esters (phorbol esters) (Wink, *et. al.*: 1997 cited by Hannan-Jones & Csurhes: 2008).

Apart from Australia, South Africa has also banned the commercial cultivation of *Jatropha* because of uncertainty about its local environmental impacts. Pristilla Sehoole from the Agricultural Department named *Jatropha* as an "environmental and social disaster for South Africa". Besides, environmental concerns were highlited in Swaziland when, in April 2008, the Government suspended all further planting of *Jatropha* until a strategic environmental assessment had been carried out (Burley & Griffiths: 2009).

2.2 Life Cycle Assessment as a tool for simplified Impact Assessment (LCIA)

2.2.1 Introduction

Life Cycle Assessment (LCA) can be defined as an environmental management tool for systematic identification, quantification and analysis of inputs and outputs (i.e. sources of environmental impact) throughout a product's, process or activity life cycle "from cradle to grave" (ISO: 1997, Azapagic: 2006).

Life-Cycle Assessment or LCA is a process of evaluating the effects that a product has on the environment over the entire period of its life thereby increasing resource use efficiency and decreasing liabilities. It can be used to study the environmental impact of either a product or the function the product is designed to perform. LCA's key elements are: 1) identify and quantify the environmental loads involved; e.g. the energy and raw materials consumed, the emissions and wastes generated; 2) evaluate the potential environmental impacts of these loads; and 3) assess the options available for reducing these environmental impacts (ISO: 1997, Azapagic: 2006, Jungbluth & Frischknecht: 2006).

Stokes and Horwath (2005) approach the modern Life Cycle Assessment as a combination of two major techniques: process-based LCA (Pro-LCA) and economic input-output analysis-based LCA (IO-LCA). The traditional process-based LCA methodology has been defined by the Society of Environmental Toxicology and Chemistry (SETAC), the EPA and the International Organization for Standardization (ISO) 14040 series standards, based on system models, where the product under study is described by unit process and input-output flow. Process-based LCA is used to assess the environmental effects of system construction and operation to obtain process-specific results and involves four main steps: goal and scope definition, inventory analysis, impact analysis, and improvement analysis (ISO: 1997). However, Junnila (2008) point out several major drawbacks intrinsic to Pro-LCA such as: 1) the operational concept is disapprovingly laborious which makes it badly fitted to fast and cost-conscious business environment; 2) the system incorporated in the LCA should be determined in terms of energy and mass units, in opposite to the regular business practice when most of material and energy inputs and outputs are primarily expressed in monetary terms; 3) some other inputs, i.e. purchased services and capital goods, are typically expressed in the business records only in monetary terms.

Economic IO-LCA is a matrix-based LCA approach that utilizes the economy's input-output tables as a general interdependency model that maps comprehensively the interactions between all sectors of economy, and identifies product and service supply chains. Economic data are combined with resource consumption, energy use, environmental emission and waste data (Stokes & Horwath: 2005, Jungbluth & Frischknecht: 2006, Junnila: 2008). IO-LCA provides results for the entire material production supply chain, very fast to use which economizing time and data requirements for the analysis and making this approach easier to be adopted for environmental evaluations and ample environmental testing of products in early conceptual design phase (Ibid.).

Other benefits from the standpoint of environmental management of businesses includes: the purchased materials, energy, and services require to be defined only in terms of monetary value; always makes available a full inventory for the production phase of the product or service included into the model; the environmental interventions of goods and services produced are always assessed consistently and, finally, the life-cycle costs of the products are always presented in parallel with environmental information. However, at present the IO-LCA approach is not to be considered as an adequate approach for detailed LCA studies (Junnila: 2008). To allow for most detailed and comprehensive analysis, a hybrid LCA approach incorporating elements from both process-based LCA and IO-LCA was used for biodiesel production systems analysis.

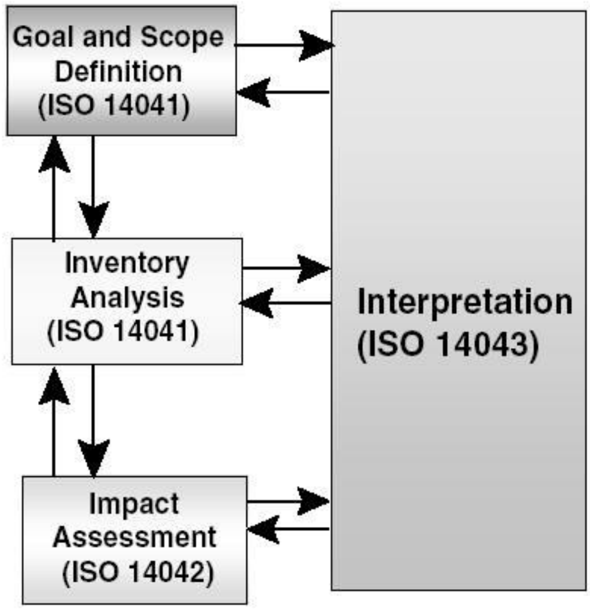
According to Jonasson and Sanden (2004), Life Cycle Assessment (LCA) can be categorized in different ways. One distinction emphasized is between product LCA and technology LCA, where the latter one aims to assess more general technology and the former one seeks to explore the impact of a specific product or production process. They also differentiate on the basis that one is retrospective, looking back at historic environment, versus prospective, looking forward and considering effects of different solutions. As retrospective studies usually use plant-specific or average data to demonstrate life-cycle impact on a product, prospective studies are mostly change-oriented and use marginal data. Kalstrom and Sanden (2004) underline that in change-oriented technology LCA a key methodological problem is to select which cause-effect chains should be included and how to quantify the effects.

The principles and standards for Life Cycle Assessment are laid out by the International Standards Organisation through its ISO 14040 series of standards (ISO: 1997). For example, ISO 14040 (1997) provides the general framework for LCA. ISO 14041 (1998) provides guidance for determining the goal and scope of an LCA study and for conducting a lifecycle inventory (LCI). ISO 14042 (2000) deals with the life-cycle impact assessment (LCIA) step and ISO 14043 (2002) provides statements for the interpretation of results produced by an LCA. Moreover, technical guidelines illustrate how to apply the standards.

The ISO standardized the technical framework for the life-cycle assessment methodology in the 1990s. On this basis, according to ISO 14040 (1997), the process-based LCA consists of the following steps (Figure 2.1):

- ❐ Goal and scope definition;
- ❐ Inventory analysis;
- ❐ Impact assessment;
- ❐ Interpretation.

Figure 2.1: The phases of LCA according to ISO 14040 (1997)



Source: Sonneman, *et. al.*: 2003

The procedure for the goal and scope definition described in the ISO 14041 (ISO: 1998) document. The goal of LCA study should in comprehensible and strict manner describe the intended application, the reason for undertaking the study and the anticipated audience. It should also specify: 1) functions of the system under study; 2) characterization of goods and services as a functional output; 3) the functional measurement unit of the performance of the functional output of the product(s) or service(s) which the system delivers. Once defined, the functional unit will provide a reference, quantified in terms of the reference flow, to which the inputs and outputs of the product system is related. In modern practice, the LCA aims to analyze and juxtapose the different products, processes or services that carry out the same value/functional unit (for example, one ton of biodiesel against one ton of petrodiesel) (ISO: 1998, Jungbluth & Frischknecht: 2006). The goal and scope definition phase should also comprise assessment of data quality with consideration to time, geographical location and technologies covered followed by assumptions and limitations of the study.

The system boundary identifies the unit process to be included in the system to be modeled. It is drawn to cover all phases in the LCA from the raw materials extraction to the final disposal. The analysis of technical processes required to manufacture products and deliver services are based on pure environmental process chain analysis. ISO 14041 (1998) identified a number of criteria for inputs to be studied including mass, energy and environmental relevance. Any exclusion of life cycle stages, processes or inputs/outputs should be clearly declared and justified. Thus, if final or intermediate product has a number of various uses, it might not be appropriate or even possible to include to the LCA all possible utilization scenarios after production phase (ISO: 1998, Jungbluth & Frischknecht: 2006, Azapagic: 2006)

The life cycle inventory analysis is the second stage of life cycle assessment standardized by ISO 14041. It encloses the data collection and calculation procedures to quantify associated inputs and outputs of a product system. The life cycle inventory analysis is an intermediate result of LCA which produces data on the emissions of numerous individual substances and various resources utilizations originated through the entire life cycle of the final product (ISO: 1998, Jungbluth & Frischknecht: 2006).

2.2.2 System delimitation in LCA

When dealing with system delimitation in environmental LCA, two methodologies are usually referred to: attributional LCA (ALCA) and consequential LCA (CLCA). The distinction between consequential and attributional life cycle assessment (LCA) and life cycle inventory (LCI) is one of the most acute issues in modern LCA methodology.

ALCA (mass and economic allocation) describes the pollution and resource flows within a chosen system attributed to the delivery of a specified amount of the functional unit (Thomassen, *et. al.*: 2008, Eriksson, *et. al.*: 2007). The goal of attributional methodology is to describe the environmentally associated physical flows to and from product system and its subsystems. It considers only impact on running processes and not what would have happened if the process had not taken place. Quite often it used to predict environmental improvements, but it has been shown that it is not fully possible to derive conclusions on future changes from the analysis of existing systems (Jungbluth & Frischknecht: 2006). The attributional approach uses average or supplier-specific data and treats co-product allocation by applying allocation factor.

CLCA (system expansion) estimates how pollution and resource flows within a system change in response to a change in output of the functional unit. Outcomes of CLCA are more sensitive to uncertainties compared with ALCA, due to inclusion of market prospects (Thomassen, *et. al.*: 2008, Eriksson, *et. al.*: 2007).

Jungbluth and Frischknecht (2006) describe the consequential LCA methodology aims to account how the environmentally relevant physical flows to and from the technosphere will change in response to possible changes in the life cycle on product and service. The consequential approach uses marginal data and avoids co-product allocation by system expansion. The main idea of this approach is that the system under investigation has to be expanded to take in the consequences due to changing some production patterns outside the life cycle investigated. As a result, the marginal, i.e. actual affected processes are included and that co-product allocation is avoided by system expansion. In authors view, the following option might be evaluated in a consequential LCA and LCIA:

- ❒ Increased or reduced demand for a product or production technology caused by growing the demand for the product under investigation;
- ❒ Alternative use of products, residues, *etc* that are required in the life cycle of product system;
- ❒ Consequences of not using certain products, residues, resources, *etc*;
- ❒ Consequences of emitting more or less of a pollutant in comparison to the today average (Ibid.).

A consequential LCA model can also include economic partial equilibrium models (Eriksson, *et. al.*: 2007) and other tools that are designed to quantify specific types of causal relationships (Ekvall, *et. al.*: 2004, Eriksson, *et. al.*: 2007). Up to date, it is no standardized methodology for consequential LCA and LCIA, i.e. no clear guidelines how to define cut-off rules for consequences to be included or excluded (Jungbluth & Frischknecht: 2006).

The main cause of these differences between ALCA and CLCA is the fact that different systems are modeled. In general, the goal of CLCA is to assess environmental consequences of a change in demand, whereas the goal of ALCA is to assess the environmental burden of a product, assuming a status-quo situation.

Within ALCA, avoiding allocation by using system expansion to handle co-products is optional, while co-product allocation is most frequently used. Avoiding allocation by system expansion, however, is the only way to deal with co-products within CLCA, as it reflects the consequences of a change in production (Thomassen, *et. al.*: 2008). According to Schnidt (2008), the consequential approach providing a more complete and accurate but also less precise result, while attributional approach provides a more precise result but with inherent blind spots, i.e. a less accurate result. As such, in a long term, modeling consequences looks like more promising approach (Ekvall, *et. al.*: 2004, Jungbluth & Frischknecht: 2006).

2.2.3 Life Cycle Impact Assessment (LCIA)

It is possible to use LCA as a tool for simplified impact assessment as the life-cycle impact assessment (LCIA) is introduced as the third step of the life-cycle assessment, described in ISO 14042, 2002 and further outlined in ISO/TR 14047, 2002 (Sonnemann, *et. al.*: 2003, Hirschberg & Dones: 2000, Hirschberg, *et. al.*: 2004). The purpose of LCIA is to assess a product system's lifecycle inventory (LCI) to understand its environmental significance better. Moreover, LCIA provides information for interpretation - the final step of the LCA methodology. For each impact category, impact potentials are selected and category indicator results are calculated.

Life Cycle Impact Assessment goal is to understand and evaluate the magnitude and significance of the potential environmental impacts of a product system (ISO 14040: 1997). The framework of the LCIA phase is composed of several mandatory elements that convert life-cycle inventory results into indicator results. The mandatory LCIA elements are (ISO 14042: 2002):

- ❒ Selection of impact categories, category indicators and LCIA models;
- ❒ Classification of environmental loads within the different categories of environmental impact; and
- ❒ Characterization of environmental loads by means of a reference pollutant typical of each environmental impact category.

In comparative studies, such as biofuel comparisons typically are, it may be found that biofuel A is better than biofuel B with regard to some emissions, but poorer with regard to others. In such cases, the impact assessment phase should be included. Life cycle impact assessment (LCIA) helps to interpret the results of the inventory from the environmental impact point of view. However, a life cycle study does not always need to use impact assessment. In some cases conclusions can be drawn and judgements and valuations are possible just on the basis of the results of the inventory phase (Soimakallio, *et. al.*: 2009).

In addition, there are optional elements for a) normalization; b) grouping; and c) weighting of the indicator results and data quality analysis techniques. Thus, impacts normalization might be implemented with respect to the total emission or extraction in certain area and over given period of time. However, the absence or insufficiency of reliable data for many impacts at both the regional and global scales is the major drawback for the LCA results normalization procedure. Grouping includes qualitative or semi-quantitative sorting and/or ranking of impacts and thereafter broad grading with respect to their significance. Weighting, which involves social, political and ethical value choices considered to be a most divisive step of the methodology in several publications (Finvedeen: 1997 cited by Azapagic: 2006).

Interpretation is the final phase of the life cycle assessment which intends to analyze results, finalize conclusions, and explain limitations and present recommendations on the LCA outcomes. It includes: a) identification of significant issues; b) evaluation of LCA results by examination of completeness, consistency, sensitivity analysis, *etc* followed by c) drawing conclusions, recommendations and writing a final report with accordance with the ISO 14040 (1997). LCA is a repetitive process, so an interpretation of results occurs after each step.

Traditionally Life Cycle Impact Assessment does not consider site-dependent effects. A problem for site-dependent LCIA is the consistent application of impact factors through the full chain. Site-specific factors should be used only where the locations of emissions are identifiable (Hirschberg, *et. al.*: 2004). This approach is reflected at the Table 2.14 adopted from the Paul Scherrer's Institute GaBE Project on "Comprehensive Assessment of Energy Systems" (Hirschberg & Dones: 2000). Sonneman, *et. al.* (2003) recited Udo de Haes, *et. al.* (1999) who have proposed classifying impacts in input and output-related categories (Table 2.13). Input refers to environmental impacts associated with material or energy inputs to the system and output corresponds to damages due to emissions or pollutants, vibrations, or radiation.

Table 2.13: Impact categories and possible indicators

Impact categories	Possible Indicator
Input-related categories	
Extraction of abiotic resources	Resources depletion rate
Extraction of biotic resources	Replenishment rate
Output-related categories	
Climate change	kg CO_2 as equivalence unit for GWP
Stratospheric ozone depletion	kg CFC-11 as equivalence unit for ODP
Human toxicity	HTP
Eco-toxicity	Aquatic eco-toxicity potential (AETP)
Proto-oxidant formation	kg ethane as equivalence unit for photochemical ozone creation potential (POCP)
Acidification	Release of H^+ as equivalence unit for AP
Nutrification	Stoichometric sum of macronutrients as equivalence unit for the nitrification potential (NP)

Sources:
1) Udo de Haes, *et. al.*: 1999;
2) Sonneman, *et. al.*: 2003.

In this study, a hybrid LCA approach, combining elements of process-based and input-output-based LCA was used to compare several biodiesel production pathways: a) irrigated and rainfed oilseeds cultivation; b) various options for organic and chemical fertilizers applications for feedstock cultivation; c) oil extraction with hand-press and oil extraction with electricity-driven press and oilseeds treatment with heat; d) Henkel (one-stage), Lurgi (two-stage) industrial-scale esterification/transestrification processes and small-scale transesterification process. For all options, energy use and emissions associated with feedstock cultivation, vegetable oil extraction and free-fatty methyl esters production were quantified for life-cycle phases and biodiesel production stages (cultivation, production and distribution).

Table 2.14: Criteria, indicators, evaluation basis

1st level	W	2nd level (evaluation basis and unit)	W	3rd level (evaluation basis and unit)	W
Economy	1/3	Financial Requirements	70	Production Costs (Rp./kWh)	50
				Investment (power plant, Rp./kW)	25
				Fuel Price Increase Sensitivity (Increase of Production Costs due to Doubling of Fuel Cost)	25
		Resources	30	Short-Medium Term Potential (Generation potential GWh/year)	40
				Availability (load factors)	15
				Geo-political Factors (estimation)	15
				Long-Term Sustainability (years)	10
				Peak Load Response (relative scale)	20
Health and Environ-ment	1/3	Human Health Impacts	30	Mortality (EIA & LCA, Rp./kWh)	90
				Morbidity (EIA & LCA, Rp./kWh)	10
		Loss of Crop (EIA & LCA, Rp/kWh)	1		
		Impact on Materials (EIA & LCA, Rp/kWh)	4		
		Non Pollutants' Effects	5	Land Use (m^2/kWh)	
		Greenhouse gases (LCA, gCO_2eq/kWh)	30		
		Wastes	15	Volume (LCA, m^3/kWh)	
		Severe Accidents	15	Fatalities (RA, fatalities/kWh)	
Special Aspects	1/3	Employment (jobs per unit of energy)	20		
		Proliferation Risks (yes or not)	.5		
		Local Disturbance (estimation per unit of energy)	25		
		Critical Waste confinement time (years)	25		
		Risk Aversion (maximum fatalities per accident)	25		

Note: W – weight

Source: Hirschberg & Dones: 2000 cited by Hirschberg, *et. al.*: 2004

Discussion on others aspects of LCA will be developed at the Chapter 3: "Well-to-Tank (WTT) Life Cycle Assessment for production of biodiesel from *Jatropha curcas* in Southern India".

2.3 Searchinger-Wang debate (2008)

Presented up to date Life Cycle Assessments of biofuels feedstock cultivation and associated biodiesel production (e.g. Reinhardt & Jungk: 1996, Mortimer, *et. al.*: 2002; Mortimer, *et. al.*: 2003; Elsayed, *et. al.*: 2003; GM & LBST: 2002; Ceuterick & Spirinckx: no date; Van Gerpen: 2000; Van Gerpen, *et. al.*: 2004; Patyk: 2000; Puppan: 2002; Levelton Engineering Ltd. and $(S\&T)^2$ Consultants Inc.: 2002; CONCAWE: 2002; Woods & Bauen: 2003; Bernesson: 2004; Toyota Motor Corporation: 2004, *etc*) circumvented evaluation of changes in land use patterns, as well as infrastructure costs. Even though some studies have acknowledged emissions from land-use change (LUC), they failed to count them simply because these emissions are difficult to quantify (Searchinger, *et. al.*: 2008). Thus, GM and LBST (2002 (a, b)) report says that land use change can also lead to a sequestration of CO_2. The cultivation of energy crop, including TBOS can lead to CO_2-sequestration if grasslands, idle or wastelands were converted for the following reasons:

- The amount of biomass above ground will be increased (from biomass which is not harvested);
- The amount of underground biomass (e.g. roots will be increased);
- The organic content of the soil will therefore probably increase.

The contrasting views of two American researchers, Timothy Searchinger of Princeton University and Michael Wang of Argonne National Laboratory, and their discussion, carried out through prolific scientific papers and letters throughout 2008, has been called the "Searchinger-Wang debate". The validity of including "indirect" impacts of biofuel production, especially indirect land conversion (such as conversion of grasslands to croplands, or forests to plantations), as well as scale of such impacts, to the Life Cycle Analysis (LCA) of biofuels is central to this "net emissions" debate.

Land use change issues associated with biofuels were explored in LCA since early 1990s. Generally speaking, the land use changes that occur as a result of biofuel production can be separated into two categories: direct and indirect. Direct LUC involve direct displacement of land for farming of the feedstocks needed for biofuel production. Indirect LUCs are those made to accommodate farming of food commodities in other places in order to maintain the global food supply and demand balance (Wang & Haq: 2008, Soimakallio, *et. al.*: 2009).

Dr. Searchinger (2008 (b), 2009) explains meaning of "direct" and "indirect" cost of LUCs in following way. When forest is converted to biofuel production, the carbon cost is "direct" and measured as the loss of carbon storage and any ongoing sequestration. When food is diverted and after accounting for the food value of biofuel by-products, biofuels grown on existing croplands results in three possible effects:

- ❒ Some of the food is not replaced because of higher prices.
- ❒ Farmers plow up more forest and grassland, which triggers the same greenhouse gas emissions indirectly and may reduce biodiversity.
- ❒ Farmers will invest more resources to boost yields on existing cropland beyond the yield increases that would already occur (and that too will in part spur additional greenhouse emissions and cause other environmental impacts).

By the basic principles of economics, some of all three effects will occur the net effect on average yields faces a countervailing effect from bringing less productive lands under cultivation.

As far, this debate comprises the following theoretically substantiated positions:

I.

- ❒ In view of Dr. Searchinger (2008 (a)), Dr. Wang's foremost approach appears to repeat the common error that has guided previous greenhouse gas accountings, which is to attribute to biofuels any factor that could improve or hold down the baseline level of LUC. Dr. Searchinger also stressed that it is not proper to attribute benefits to biofuels for changes that would occur with or without biofuels. Moreover, factors that influence the baseline - even factors that could theoretically cause overall crop prices to drop - do not necessarily affect the incremental effect on land use by diverting an acre of cropland to produce biofuels.

Life cycle analyses for biofuels assign a "feedstock credit" to the biofuel for the carbon dioxide taken up by plants incorporated into the fuel. Without this credit, conventional life cycle analyses show that most biofuels would increase greenhouse gases compared to gasoline and diesel. But typical lifecycle analyses ignore the fact that land would already be providing carbon benefits, which are sacrificed when the land is diverted to producing biofuels.

Calculating LUC simply means calculating the carbon storage and annual uptake that is foregone directly or indirectly by using land to produce biofuels. Unless land use change is included, lifecycle accounting assumes that land is a cost-free asset from a carbon perspective (Searchinger: 2008 (b), Searchinger: 2009, Altenburg, *et. al.*: 2009).

❒ Because existing land uses already provide carbon benefits in storage and sequestration (or, in the case of cropland, carbohydrates, proteins, and fats), dedicating land to biofuels can potentially reduce GHGs only if doing so increases the carbon benefit of land (Searchinger, *et. al.*: 2008 (a)).

❒ Any calculation that assigns biofuels the carbon benefits of using land to grow them must also deduct the carbon costs of that land use decision. If not used for biofuels, land would already take carbon out of the atmosphere and continuing to store carbon previously removed, and much of this benefits lost by using the land to produce biofuels (Searchinger: 2008 (a)).

II.

❒ Accounting for the cost of using land to make biofuels as well as the benefit obviously produces a very different result than just counting the benefit. Making biofuels out of waste products avoids these costs. Waste products would cause no LUC emissions. Biomass produced abundantly on otherwise unproductive land would cause small land use change emissions. And feedstocks produced on productive land (whether productive of food, forest or grassland) would cause high land use change emissions (Searchinger: 2008 (a), Searchinger: 2009, Fargione, *et. al.*: 2008).

It may be possible to grow new biofuel grasses and trees productively on otherwise unproductive land, resulting in land use benefits that greatly exceed the costs. But Dr. Wang's position calls for ignoring the cost of using land altogether (Searchinger: 2008 (a), Fargione, *et. al.*: 2008). The basic principle, particularly in an age of climate change that values carbon storage by land, is that productive land provides valuable benefits, and the world cannot use such land for biofuels without sacrificing some other benefits (Searchinger: 2009).

❒ If biofuels are to help mitigate global climate change, they need to be produced with little reduction of the storehouses of organic carbon in the soils and vegetation of natural and managed ecosystems. Degraded and abandoned agricultural lands could be used to grow native perennials for biofuel production, which could spare the destruction of native ecosystems and reduce GHG emissions. Diverse mixtures of native grassland perennials growing on degraded soils, particularly mixtures containing both warm-season grasses and legumes, have yield advantages over monocultures, provide GHG advantages from high rates of carbon storage in degraded soils, and offer wildlife benefits. Monocultures of perennial grasses and woody species also can offer GHG advantages over food-based crops, especially if they are sufficiently productive on degraded soils, as can slash and thinning from sustainable forestry, animal and municipal wastes, and crop residue (Fargione, *et. al.*: 2008).

III.

- The amount of land used to produce a gallon of gasoline is extremely small, according to some energy experts, is less than 1% of the amount of land used to produce a gallon-equivalent of ethanol. Because the effect of oil production on emissions from land use change is small, it is reasonable to omit it (Searchinger: 2008 (a)).

The following assumptions and observations should be mentioned as well:

- The most important lesson of the 1990's is that conversion occurs in a wide variety of habitat types, some richer in carbon than others, but all with high carbon losses. Study by no means predicts that land conversion will typically come from the most carbon-rich lands, and while future results could be better than the 1990's, they could also be worse (Searchinger: 2008 (a)).
- Additional efforts by farmers to boost yields, would be balanced out by the need to rely on more marginal land, but different scenario were analyzed as a part of the sensitivity analysis that assumed additional yield increases (Searchinger: 2008 (a)).
- Study assumes that yields in each country would continue to increase according to present growth trends. If the world can dramatically improves agricultural yields beyond existing trends, less additional forest and grassland will be converted to cropland, and therefore, would decrease the total amount of land conversion. Future yield increases above recent trends could alter the incremental affects of biofuels but only in more modest ways (Searchinger: 2008 (a)).
- Also, there is no evidence that deforestation rates are declining worldwide. Today's record high crop prices, in significant part a reflection of biofuels, increases the likelihood of the kind of government and private investments that lead to agricultural conversion in more remote, carbon-rich lands (Searchinger: 2008 (a)).

Limiting the focus to climate change, the basic question is whether the use of biofuels, and thus use of land for feedstock production, saves more GHG emissions by displacing fossil fuel than that saved by leaving land in its existing use even while continuing to use fossil fuels (Searchinger: 2009).

According to FAO World Soil Resources Report (2004), in dryland environments, SOC in the first 100 cm soil amounts to ~4 t/ha (Batjes: 1999 cited by FAO: 2004). This is noticeably lower than in other environments. Batjes (1999) estimates for current SOC are: 7-10 t/ha in the tropics; 7-13 t/ha in the subtropics; 11-13 t/ha in temperate regions; and 21-24 t/ha in boreal, polar and alpine areas. In the semi-arid savannahs of Sahel and dry forests in Senegal (West-Central agricultural region) as SOC estimated by Tiessen and Feller (1998), Ringius (2002) and Tschakert and Senè (2004), is ranging from 4.5 tC/ha for continuously cultivated areas without manure input to 18 tC/ha for non-degraded savannahs (top 20 cm soil) (Ibid.).

FAO (2004) accounts that land-use change and soil degradation are major processes for the release of carbon dioxide to the atmosphere. Thus, LUC is responsible for 33% of CO_2 raise in the atmosphere from late nineteenth century to late 1990s. According to the World Bank (2008), 20% of global CO_2 emissions are generated through land use change and the conversion and degradation of forests. Such as, tropical forests are the richest carbon stocks and the most effective carbon sinks in the world store around 46% of the world's living terrestrial carbon (Soepadmo: 1993 cited by Danielsen, *et. al.*: 2008, Philips, *et. al.*: 1998). Estimates run as high as 418 tC/ha in carbon stock, and 5 to 10 tC/ha/yr sequestered, 40% of which is in soil organic carbon. The carbon stock in old growth forests would be even greater, and according to a new study in southeast China, soil organic carbon just in the top 20 centimeters of such old growth forests (Ho: 2007, Giardina, *et. al.*: 2004) increased on average at a rate of 0.62 tC/ha each year between 1979 and 2003. When tropical forests are cut down at the rate of more than 14 million ha a year, some 5.8 Gt of carbon is released to the atmosphere, only a fraction of which would be sequestered back in plantations (Ho: 2007).

The World Bank/ESMAP studies (2007) stated that ramped-up biofuel production would have a major impact on land use and ecosystem. The land requirement for biodiesel quintupled if global use of other vegetable oils was made (Kojima, *et. al.*: 2007). The annex to the "An EU Strategy for Biofuels" in February 2006 (European Commission: 2006 cited by Kojima, *et. al.*: 2007) points out that additional production using, for example, virgin savanna in Brazil could cancel out GHG benefits for decades. It also highlights increased pressure on rain forests as the main general negative effect of biofuel feedstock expansion. The decision of the government of the Netherlands to cut the subsidy for "green electricity" produced from palm oil (all of which is imported) has been reported to be driven in part by the negative publicity on the sustainability of palm production in Indonesia and Malaysia (USDA: 2006 cited by Kojima, *et. al.*: 2007, Biofuelwatch & FERN: no date). The Committee on Industry, Research, and Energy of the European Parliament in October 2006 called for an EU-wide ban on the use of biofuels derived from palm oil (ESMAP: 2007).

Until more data specific for *Jatropha curcas* plantations become available, the following calculations completed by Fargione, *et. al*. (2008) and lately reported in SCOPE International Biofuels Project Rapid Assessment (Ravindranath, *et. al.*: 2009) can be used for the LUC impact calculations. CO_2 emission from conversion of abandoned cropland to *Jatropha* can be used at the same rate as emissions from conversion of abandoned cropland to maize of 145 tCO_2/ha estimated by Fargione, *et. al*. (2008 cited by Ravindranath, *et al.*: 2009), assuming that land has been abandoned for 15 years on average, and will stay abandoned for more than 30 additional years, resulting in emissions of 0.69 tCO_2/ha annually when converted back to cropland. The same estimates of CO_2 emissions were applied by authors in case of conversion of grassland to cropland for both sugarcane and *Jatropha* resulted in total emissions of 93 tCO_2/ha. Emission factors considered for the 30 year period as well as on a mean annual basis are as follows:

- Grassland to *Jatropha* (93.0 tCO_2/ha over 30 years period) = 3.1 tCO_2/ha/yr.
- Abandoned crop land to *Jatropha* (145 tCO_2/ha over 30 years period) = 4.1 tCO_2/ha/yr.
- Tropical forest to Oil Palm (535 tCO_2/ha over 30 years period) = 17.4 tCO_2/ha/yr (Ravindranath, *et. al.*: 2009).

Using an allocation period of 25 years for emissions from deforestation, preceding cultivation of oil palm on tropical peatlands, Rieley presents an annual emission estimate of as much as 170 tCO_2/ha/yr for the combined emissions from deforestation and drainage of peat swamp forests, and 100 tCO_2/ha/yr, if only drainage is considered (Carbopeat: 2007, JRC: 2008 cited by Soimakallio, *et. al.*: 2009).

Current scientific evidence suggests that managed and mature old-growth forests act as active carbon sinks sequestering C at rates of up to 6.0 t/ha/yr (for boreal and temperate forests) (Valentini, *et. al.*: 2000 cited by FAO: 2004). At the same time, Dr. Paul Varghese, the TERI Research Fellow (January 2008. Online, visited 12 May, 2009) says that *Jatropha curcas* is not a nitrogen fixer and effective sequestration from *Jatropha* plantations would be as low as 1.05 tCO_2/ha/yr.

As such, by excluding emissions from land-use change, most previous accountings were one-sided because they counted the carbon benefits of using land for biofuels but not the carbon costs, the carbon storage and sequestration sacrificed by diverting land from its existing uses (Searchinger, *et. al.*: 2008). According to Fargione, *et. al*. (2008) analyses, biofuels, if produced on converted land, could, for long periods of time, be much greater net emitters of greenhouse greenhouse gases than the fossil fuels that they typically displace. Therefore, at least for current or developing biofuel technologies, any strategy to reduce GHG emissions that causes land conversion from native ecosystems to cropland is likely to be counterproductive (Fargione, *et. al.*: 2008). Most significantly, the potential emissions per hectare of land conversion greatly exceed the annual greenhouse reductions per hectare of biofuels (Searchinger, *et. al.*: 2008). One of the controversies surrounding bioenergy regards the effect that the feedstock cultivation, biofuels production and use has on the Earth's climate. For example, if peat land is burned to clear a rainforest to plant palm oil for biodiesel manufacture, there could easily be a net increase, rather than decrease, in life-cycle GHG emissions (Fargione, *et. al.*; 2008, Searchinger: 2008 (b), Kojima, *et. al.*: 2007; Ho: 2007). Thus, Danielsen, *et. al*. (2008) demonstrate it would take between 75 and 93 years for the carbon emissions saved through use of biofuel to compensate for the carbon lost through initial forest conversion, depending on how the forest was cleared. If the original habitat was peatland, carbon balance would take 692 years. These results are very similar to Fargione, *et. al.* (2008) who estimate of compensation points for forest and peat 86 and 840 years, respectively.

In order to generate greenhouse benefits, the carbon generated on land to displace fossil fuels (the carbon uptake credit) must exceed the carbon storage and sequestration given up directly or indirectly by changing land uses (the emissions from land-use change). An effective system would have to guarantee that biofuels use a feedstock, such as a waste product, or carbon-poor lands that will not trigger large emissions from land-use change (Searchinger, *et. al.*: 2008).

Even though the Searchinger-Wang Debate reaches its peak when this LCA Model for *Jatropha* cultivation and associated biodiesel production in India has been already completed, the author made additional efforts to investigate land use change impact on the Model performance. It was estimated that LUC emission factors per hectare for both grassland conversion to *Jatropha* and abandoned crop land conversion to *Jatropha* plantation (Fargione, *et. al.*: 2008 cited by Ravindranath, *et al.*: 2009) added only 2.6-14.0% (Large scale scenario) and 4.2-17.7% (Small-scale scenario) to the Total CO_2 farming emissions per hectare.

As such, this raise has no significant influence on final results for the CO_2eq emissions from farming, Total CO_2eq emissions and Total CO_2eq avoided and at this stage could be excluded from the Model until more reliable data for LUC will be available.

Currently, the sustainability of biomass and biofuels is an open question (GBEP: 2008 cited by Soimakallio, *et. al.*: 2009). A recent survey commissioned by the UK government found that 4 out of 5 litres of biofuel supplied at British pumps failed to meet basic industry standards for sustainability. Biofuel manufacturers could not prove that their biofuel feedstock had not been grown by destroying rainforests or by harming the livelihoods of poor farmers. Additionally, the origin of half of the biofuels in UK fuel tanks was unknown (Anon: 2008 cited by Soimakallio, *et. al.*: 2009).

2.4 Biodiesel production process

Biodiesel is the name of the mono-alkyl esters of fatty acids derived from vegetable oils or animal fats. It is considered to be a renewable fuel because its agricultural production and processing have a positive energy balance of roughly 2.5:1 (Ahmed, *et. al.*: 1994).

Currently, biodiesel is used predominately in transportation. It is typically blended into 20% biodiesel and 80% petroleum diesel. This is referred to as B20. Pure blends of 100% biodiesel are referred to as B100 or as "neat" biodiesel. Biodiesel production pathways can be classified into conventional (lipid esterification products) and non-conventional (potential new products from SuperCetane, lipid catalytic hydrotreating synthesis and Fischer-Tropsch synthesis from low-lipid biomass-derived synthesis gas). Holbein, *et. al.* (2003) differentiate three chemical pathways relate to two distinct types of feedstock; those rich in lipids, such as canola oil and animal rendering fats, and those low in lipid content, such as agricultural waste residues or municipal wastes. The two distinct feedstock types require fundamentally different processing and chemical synthesis to obtain biodiesel and related products. Only esterification products are currently recognized as biodiesel under industry specifications. However, the petroleum industry has experience in utilizing Fischer-Tropsch hydrocarbons and they can act as blending stocks for current petroleum derived fuels (NRCan: 2003).

There are three basic routes to methyl ester production from oils and fats: 1) Base catalyst transesterification of the oil with methanol; 2) Directed acid catalyzed esterification of the oil with methanol; 3) Conversion of the oil to fatty acids, and then to methyl esters with acid catalysis (IAG Ltd./Enerquest: 2002, Van Gerpen, *et. al.*: 2004, Schmidt: 2004).

Conventional production of biodiesel, or alkyl esters, is a reesterification of glycerol esters of fatty acids into methyl esters of fatty acids. The target for this procedure is the reduction of molecule mass and by that a reduction of viscosity and boiling point. This enables biodiesel to replace mineral diesel in diesel engines without any changes (BDT Technologies: 2002). The chemical conditions of a base catalyzed transesterification is low temperature (60-66^{o}C), low pressure (20 psi) and high conversion factor (98%) with minimal side reactions and reaction time (Puppan: 2002, (S&T)^{2}: 2002, Sharma, *et. al.*: 2010). However, a drying of oil at 105^{o}C is considered optimum to remove the moisture content from crude *Karanj* and *Jatropha* oils before transesterification (Sharma, *et. al.*: 2010).

Biodiesel feedstock can be classified based on their free fatty acid content as follows:

- Refined oils contain less than 1.5% of free fatty acids (e.g. soybean or canola).
- Low free fatty acids contain less than 5% of fatty acids (i.e. yellow greases and animal fats).
- High free fatty acids contain 20% or more of free fatty acids (e.g. greases and animal fats) (IAG Ltd./Enerquest: 2002).

Methyl esters of fatty acids can be made either by esterification of the fatty acids or transesterification of the triglycerides using methanol (Gervajio: no date).

Esterification. Esterification is the reaction of an acid with an alcohol in the presence of a catalyst to form an ester. The reaction is expressed by the general equation:

$$\underset{\text{Acid}}{RCOOH} + \underset{\text{Alcohol}}{R'OH} \underset{\text{Catalyst}}{\overset{\text{Acid}}{\rightleftharpoons}} \underset{\text{Ester}}{RCOOR'} + \underset{\text{Water}}{H_2O} \qquad (1)$$

Generally, acid catalysts like sulfuric acid are employed. As esterification is an equilibrium/reversible reaction, the water must be removed continuously to drive the reaction to the right and obtain a high-ester yield. There are two general methods used for esterification: the batch process and the continuous process (IAG Ltd.: 2002). Esterification can be done batchwise under pressure at a temperature of 200-250^{o}C (Gervajio: no date).

Transesterification. Transesterification, on the other hand, is the displacement of the alcohol from an ester by another alcohol in a process similar to hydrolysis, except that an alcohol is used instead of water. This reaction, cleavage of an ester by an alcohol, is more specifically called alcoholysis and is represented by the general equation:

$$\underset{\text{Easter}}{RCOOR'} + \underset{\text{Alcohol}}{R''OH} \underset{\text{Catalyst}}{\overset{NaOCH_3}{\rightleftharpoons}} \underset{\text{Ester}}{RCOOR''} + \underset{\text{Alcohol}}{R'OH} \qquad (2)$$

The long and branched chain triglycerides molecules are transformed to monoesters and glycerine. Transesterification process consists on a sequesnce of three consecutive reactions. That is, conversion of triglycerides to diglycerides, followed by the conversion of diglycerides to monoglycerides. The glycerides are converted into glycerol and yielding one ester molecule in each step (Ramadhas, *et. al.*: 2005).

Transesterification is an equilibrium reaction. Stoichometrically, three moles of alcohol are required for each mole of triglyceride (Ramadhas, *et. al.*: 2005, Sharma, *et. al.*: 2010). However, to shift the reaction to the right, it is necessary to use a large excess of alcohol (15:1-35:1 (Canakci & Van Gerpan: 2001 cited by Ramadhas, *et. al.*: 2005)) or to remove one of the products from the reaction mixture. The second option is preferred where feasible, as in this way, the reaction can be driven to completion.

Transesterification is a general term. More specifically, if methanol is used, the reaction is termed methanolysis (Gervajio: no date). The reaction with fats and oils and using methanol is represented by the general equation.

$$\underset{\text{Fat or oil}}{\begin{matrix} RCOOCH_2 \\ | \\ RCOOCH \\ | \\ RCOOCH_2 \end{matrix}} + \underset{\text{Methanol}}{3CH_3OH} \underset{\text{Catalyst}}{\overset{NaOCH_3}{\rightleftharpoons}} \underset{\text{Methyl ester}}{3RCOOCH_3} + \underset{\text{Glycerine}}{\begin{matrix} CH_2OH \\ | \\ CHOH \\ | \\ CH_2OH \end{matrix}} \qquad (3)$$

As crude *Karanj* and *Jatropha* oils has a high free fatty acids (FFA) content, a two-stage transesterification process showed higher methyl ester yield than single stage or direct transesterification process (Berchmans & Hirata: 2008, Sharma, *et. al.*: 2010).

The first stage, called acid esterification reaction, is required to lower the FFA in the oil to the desired limit (i.e., <2%). After acid pretreatment/acid catalyst esterification, FFA in the oil moved into methanol phase. In the second stage, alkaline transesterification should be performed for conversion of oil with lowered acid value to fatty acid methyl esters. A moderate molar ratio of 6:1 (methanol/oil) is efficient for acid esterification. For alkaline transesterification with 1 wt% of the calalyst, 8:1 (methanol/oil) molar ratio resulted in optimized yield (90-95%) and high conversion (96-100%). Generally, alkaline catalysts are used with sodium methylate (CH_3ONa) said to be the most effective, although sodium hydroxide (NaOH) can also be used (Ibid).

Summary of reported alternative transesterification processes presented in Tables 2.15 and 2.16.

Physico-chemical parameters of Methyl and Ethyl Esters of Jatropha curcas oil summarized in Tables 2.17 and 2.18.

Flowchart 2.1: Industrial scale biodiesel production pathway (1)

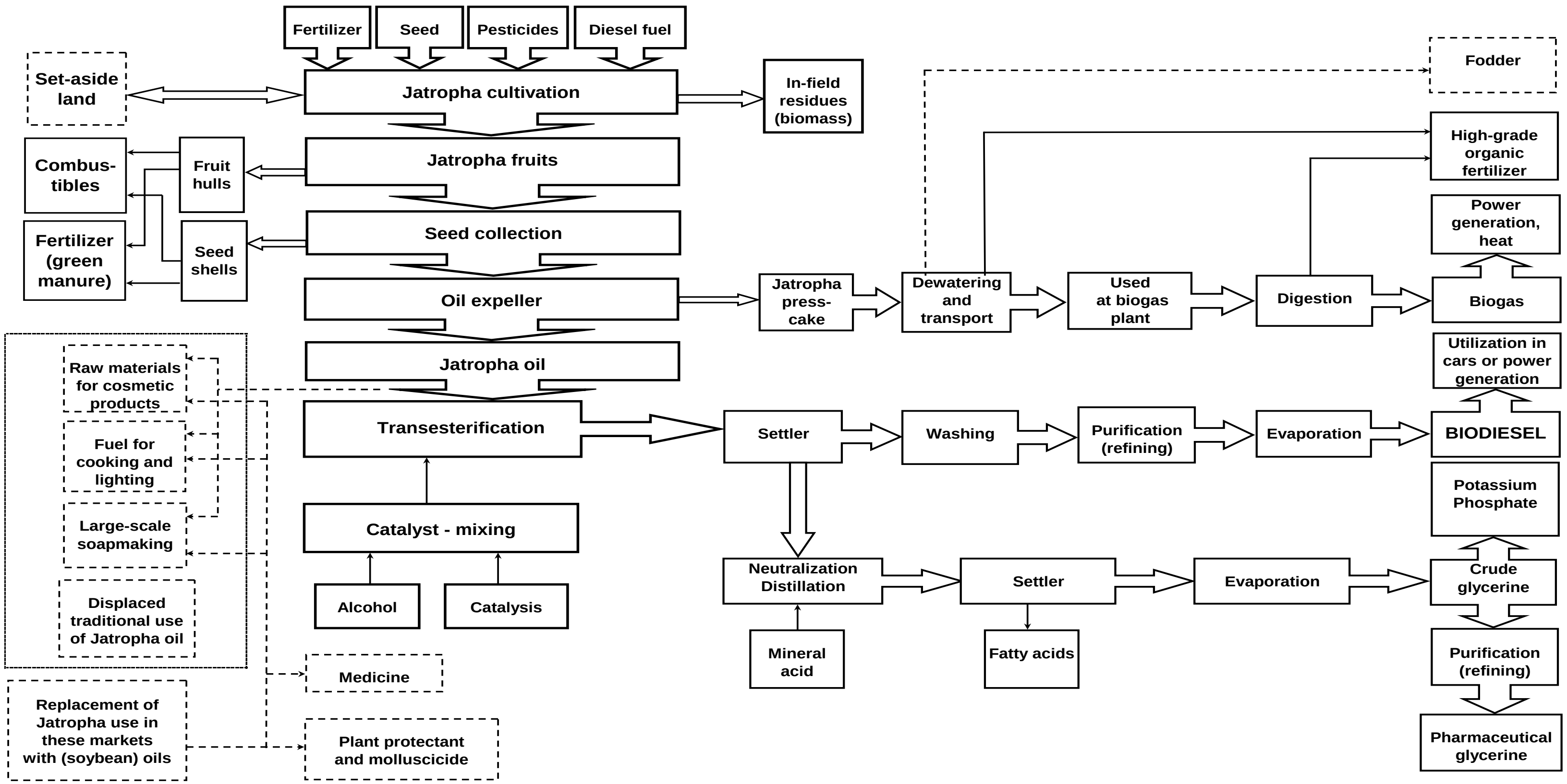


Table 2.15: Various biodiesel production processes

	Homogeneous catalytic process	Heterogeneous catalytic process	Enzymatic process	Supercritical methanol process
Catalyst	Alkali or acid	Metal oxide or carbonate	Immobilized lipase methyl ester	None
Reaction conditions	0.1 MPa, 30-65°C	0.1-5.0 MPa, 30-200°C	0.1 MPa, 35-40°C	>8.09 MPa, >239.4°C
Reaction time	0.5-4.0 h	0.5-3.0 h	1.0-8.0 h	120-240 s
Yield	Normal to high	Normal	Low to high	High
Removal for purification	Methanol, catalyst, and saponified product	Methanol	Methanol or methyl acetate	Methanol
Waste	Waste water	None	None	None
Glycerin purity	Low	Low to normal	Normal or triacetyl-glycerol as byproduct	High
Free fatty acids	Saponified product	Methyl esthers	Methyl esthers	Methyl esthers

Source: Kiwjaroun, *et. al.*: 2009

Table 2.16: Alternative transesterification procedures

Conversion method	Maximal conversion, %	Catalyst, %	Temperature, °C	Time, min.	Alcohol:oil molar ratio
Transesterification using a solid super base catalyst	93	1.5	70	150	Methanol:oil 9:1
***In situ* transesterification (skipping the oil extraction step)**	87	1.0	60	60	100 ml (m)ethanol for 20 g whole seeds
Transesterification in supercritical alcohols	95-99	0	200-250	40	Supercritical (m)ethanol: oil 50:1
Bio-diesel synthesized enzymatically in the presence of supercritical CO_2	60-70	0	45	480	(m)ethanol: oil 5:1

Source: Achten, *et. al.*: 2008

Table 2.17: *Jatropha* methyl ester and ethyl ester composition and characteristics with the corresponding values of the European (EN 14214:2003), German (DIN V 51606) and the USA Standards (ASTM D6751)

		***Jatropha* Methyl Esther**		***Jatropha* Ethyl Esther**	**EN 14214:2003[1)]**	**DIN V 51601[1)]**	**ASTM D6751[1)]**
		Range	Mean				
Density	g/cm^3	0.864-0.88[1)]	0.875[1)] 0.879[2),5)] 0.884[3)]	0.89[1)] (0.886)[2),5)]	0.86-0.90	0.87-0.90	
Caloric value	GJ/t	38.45-41.00[1)]	39.65[1)]				
Flash point	°C	179-192[1)]	186[1)] 169[3)] 163[4)] 191[5)]	190[1),5)]	min 120	min 110	min 130
Cetane value		50.0-56.1[1)] 58-52[3)]	52.3[1)] 51.0[2),5)] 57.1[4)]	59.0[1),5)]	min 51	min 49	min 47
Saponification number	mg/g	202.6[1)]					
Viscosity at 30°C	cSt	4.84-5.65[1)]	5.11[1)] 4.84[2),5)] 4.40[4)]	5.54[1),2),5)]	3.5-5.0	3.5-5.0	1.9-6.0
Iodine number	mg iodine/g	93-106[1)]	98[3)]		max 120	max 115	max 115
Acid number	mg KOH/g	0.06-0.5[1)]	0.27[1)] 0.24[2)]	0.08[1),2)]	max 0.5	max 0.5	max 0.5
Monoglycerides	% (kg/kg*100)	0.24[1)]		0.55	max 0.8	max 0.8	
Diglycerides	% (kg/kg*100)	0.07[1),5)]		0.19[1),5)]	max 0.2	max 0.4	
Triglycerides	% (kg/kg*100)	no data[1)]	not detected[5)]	no data[1)] not detected[5)]	max 0.2	max 0.4	
Carbon residue	% (kg/kg*100)	0.02-0.50[1)]	0.18[1)] 0.004[4)] 0.025[5)]	0.0018[5)]	max 0.3	max 0.3	max 0.05
Sulphur content	% (kg/kg*100)	0.0036[1)]			max 0.01	max 0.01	max 0.015
Sulphated ash	% (kg/kg*100)	0.005-0.010[1)]	0.013[1)] 0.014[2),5)] 0.002[4)]	0.08[2)] 0.10[5)]	max 0.02	max 0.03	max 0.02
(M)ethyl esther content	% (kg/kg*100)	99.6[1),5)]		99.3[1),5)]	min 96.5		
Methanol	% (kg/kg*100)	0.06-0.09[1)]	0.06[5)]	0.05[1),5)]	max 0.2	max 0.3	
Water	% (kg/kg*100)	0.07-0.10[1)]	0.05[4)] 0.16[1),5)]	0.16[1),5)]	max 0.5	max 0.3	max 0.5
Free glycerol	% (kg/kg*100)	0.015-0.030[1)]	0.015[2),5)] 0.01[4)]	no data[1)] not detected[2),5)]	max 0.02	max 0.02	max 0.02
Total glycerol	% (kg/kg*100)	0.088-0.100[1)]	0.088[2),5)] 0.02[4)]	0.17[1),2),5)]	max 0.25	max 0.25	max 0.24

Sources: 1) Achten, *et. al.*: 2008; 2) Foidn: 1996 cited by Singhal, *et. al.*: 2005; 3) Francis, *et. al.*: 2005; 4) Sarin, *et. al.*: 2007; 5) Gübitz, *et. al.*: 1999

Table 2.18: Analysis of methyl ester of *Jatropha* oil

			DIN value	Product prepared by Acid Catalysis	Product prepared by Base Catalysis
Appearance				Clear brownish liquid	Clear brown
Density at 15°C	ISO 3675	kg/m^3	860-900	881.1	880.0
Oxidation stability	prEN 14112	hour	>6	7.8	2.8
Viscosity at 40°C	ISO 3104	mm^2/s	3.5-5.0	4.43	4.34
Iodine number	DIN 53241-1	$gJ_2/100g$	<120	94	96
Ash	ISO 3987	g/100g	<0.02	<0.01	<0.01
Water content	EN ISO 12037	mg/kg	<500	600	450
Flash point	DIN EN 22719	°C	>101	173	160
Cetane number			>51	58	N/A
Methanol	prEN 14110	g/100g	<0.2	<0.02	<0.02
Ester-content	prEN 14103	g/100g	-	98.7	98.5

Source: Mehta. Winrock International India conference: 2004

Unlike ethanol, biodiesel is a mixture of different size molecules with varying levels of unsaturation. The composition of a given biodiesel fuel, and the molecular structure of each ester comprising the fuel, depends on the feedstock (and the process conditions to a lesser extent); the amounts of contaminants left in the biodiesel fuel depend on the production process.

The seed oils of plants are structurally similar to long chain hydrocarbons derived from petroleum, and thus represent excellent renewable resources for oleochemical production. Oils produced in oil seed plants include a wide range of fatty acids with five dominating ones: palmitic, stearic, oleic, linoleic and linolenic acids, which are present in most food oils (described in more details in subchapter 2.1.2: "Jatropha seed oil", Table 2.8 and Appendix XII). In addition to these common fatty acids, there are a great number of other fatty acids occurring in high amounts in seed oils from various wild plant species. These unusual fatty acids include functional side groups, such as epoxy and hydroxy groups, conjugated or acetylenic bonds, unusual mono-unsaturated fatty acids, and medium and very long chain fatty acids. Other unusual plant oils are the ones made up of wax esters instead of trialcylglycerols (Carlsson, *et. al.*: 2007 cited by Soimakallio, *et. al.*: 2009).

It is relatively easy to make biodiesel, but it is difficult to make on-spec biodiesel. Only biodiesel made largely from rapeseed oil meets the biodiesel standard EN 14214. Rapeseed biodiesel complies with the standard even if blended with a small amount, for example, 25% of biodiesel made from other oils such as soybean or palm (European Commission: 2005 cited by Kojima, *et. al.*: 2007). Close cooperation between Cummins and the American Society of Testing Materials has resulted in an improved B100 specification (ASTM D6751) that now requires a cold soak test and a new B20 specification (ASTM D7467) that includes an oxidation stability requirement (PEI: April, 2009).

Ensuring fuel quality consistency presents a much greater challenge for biodiesel than ethanol, especially for biodiesel made at small-scale, simple technology facilities. The United States and the European Union have issued biodiesel specifications and associated test methods, but more work is needed. The existing specifications and test methods are inadequate even for biodiesel fuels made from domestic feedstocks (for which these specifications are intended). Some test methods cannot be used for biodiesel fuels made from certain feedstocks (ESMAP: 2007). The equipment and procedures for testing biofuel products are still being perfected. Thus, there have been persistent difficulties obtaining reliable measurements of the Cold Filter Plugging Point (CFPP) of biodiesel - the critical temperature at which a fuel will cause a fuel filter to plug due to components crystallizing or gelling (Feeney: 2009).

Benefits of FAME esters are good cetane numbers, low sulfur content, no aromatics, and good lubricity. However, the FAME biodiesel has also drawbacks: e.g. high viscosity, poor cold properties, problematic distillation characteristics (dilution of engine oil), difficult impurities (triglycerides, glycerol and alcohols), problems with materials, and poor storage stability (Graboski & McCormick: 1998, WWFC: 2006 cited by Soimakallio, *et. al.*: 2009).

2.4.1 Alkoxides as low-temperature transesterification catalysts

Transesterification reactions can be catalytic and non-catalytic, and those involving catalysts can be catalyzed by alkali, acid or enzymes. Among these three catalyst-based approaches, the conventional or widely used method in industry is alkali-catalyzed reactions mediated typically by sodium or potassium hydroxide, sodium or potassium methoxide and ethoxide since the reaction rate is fast (Kiwjaroun, *et. al.*: 2009).

The solid Methoxides such as Sodium Methoxides (Sodium Methylate) $NaOCH_3$ and Potassium Methoxides (Potassium Methylate) $KOCH_3$ are not used as transesterification catalysts, the MeOH ($NaOCH_3$, 30% in MeOH; and $KOCH_3$, 32% in MeOH) solutions are preferred since they are ready to use and allow for fast and safe catalyst handling in commercial processes.

The requirements for the catalysts are somewhat different due to the difference in molecular weight, but more important it depends on the quality of the oil, in particular the content in free fatty acids (ffa).

The following formulas represent calculations for the catalysts requirements:

- If free fatty acids (ffa) is given in % - the quantity of Potassium Methoxide 32% in MeOH loading per tonne (kg) = (% ffa x 7.8 kg) + 21 kg;
- Sodium Methoxide 30% in MeOH loading per tonne (kg) = (% ffa x 6.4 kg) + 17 kg;
- If free fatty acids (ffa) is given in (mg NaOH/g) - quantity of Sodium Methoxide 30% in MeOH per tonne raw material = (acid number x 3.2 kg) + 17kg.

In other words, with good oil quality ~2% of the catalysts by weight (calculated) is needed. The potassium catalyst (Potassium Methoxide 32% in MeOH) is chosen when oils with high free fatty acids are processed. For cost reasons Sodium Methoxide (Sodium Methoxide 30% in MeOH) appears to be the Catalyst of Choice - even for the Ethyl Ester Production.

All data related to Sodium Methoxides (Sodium Methylate) ($NaOCH_3$, 30% in MeOH) based on personal communication with Mr. Nirav Kothari, Degussa India Pvt. Ltd. - Building Blocks (Mumbai, India) and Dr. Johannes Ruwwe, Degussa AG - Building Blocks (Niederkassel-Luelsdorf, Germany) in 2006.

2.5 Biodiesel costs of production

None of the biofuels options addressed to the recent or present-day studies are currently cost competitive with petrol or diesel on a pre-tax £/GJ basis (AEA Technology: 2003). Thus, US Department of Energy has announced the one rule of thumb that biodiesel costs about one cent more per percentage point increase in concentration. Under this formula, B20 would cost twenty cents more per gallon compared to diesel and B100 would cost USD 1.00 per gallon more. However, with higher blends there is some economy that allows a little savings in some cases. Thus, "a 2% blend currently sells for ~2 cents per gallon more than diesel; a 20% blend sells for ~18 cents per gallon more than diesel."

"The economics of biodiesel is volatile due to the large effects of feedstock cost and meal credit. The next two important factors were capital costs and electricity (the latter constituting roughly one-third to one-half of the operating costs for oilseeds mainly for expelling the oil). As currently for gasohol in the gasoline market, tax credits would be needed to make biodiesel competitive with diesel fuel at this time." Cost of operation does not reflect economy of scale because scale-dependent expenses such as labour are only a small part of the operating cost.

Currently, the production of methyl or ethyl esters from edible oils is much more expensive than that of diesel fuels due to the relatively high cost of vegetable oils (about three times the cost of diesel in India). Methyl esters produced from such oils cannot compete economically with diesel fuels unless they are granted protection from tax levies (Bender: 1999 cited by Pegu & Bagla: 2006).

According to Weber of the University of Missouri (1993), economic feasibility of cooperative biodiesel facilities should be most successful for farmers who are diversified in both crop and livestock, especially in regions where a large spread exists between the price that farmers receive for their oilseed and the price they pay for protein meal. Also, due to the energy demands of the electrically-driven extruder and press, electricity costs should be carefully examined in the decision to invest in a biodiesel facility. Published estimates for biodiesel produced from vegetable oil feedstock generally fall in the range of the higher estimates for biodiesel from oilseed (Bender: 1999).

BIOCAP Canada studies on biodiesel production from canola oilseeds in Western Canada (2006) declare that the biodiesel from oilseeds grown for traditional markets may prove too expensive for use as fuel, but there are significant opportunities for mitigating oilseed input costs for profitable production of biodiesel.

Land area under crop in Canada is finite and increased biodiesel production will inevitably lead to decreased production of other crops (Reaney, *et. al.*: 2006). AEA Technology (2003) investigation of the international resource costs for biofuels come to the point that estimated resource costs are based on current availability of land for growing energy crops and current markets for by-products. If biofuel production is increased then this will put additional pressures on land availability, which could force prices up. Markets for co-products such as animal feeds could also become less valuable as a result of additional biofuel production.

Seed adds significantly to the overall cost of biodiesel. The income and value of the seed to the industry is highly dependent on the approach taken. Thus, in Western Canada seed for a crop such as canola annual seed are a significant industry with seeding costs of 50.0-75.0 CAD/ha (~24.0-36.0 GBP/ha, 2006 Canadian Dollars) being common. Canola seed is amongst the most expensive used in prairie agriculture. Current canola seed costs in Saskatchewan Crop Production Guide are given as 54.12 CAD/ha (26.0 GBP/ha) while wheat costs just 22.17 CAD/ha (10.6 GBP/ha). The BIOCAP Canada research (2006) has found that seed contribution to costs for canola produced biodiesel in Saskatchewan of 0.07 CAD (0.034 GBP) per liter of biodiesel while seed for solin flax produced biodiesel contributes just 0.03 CAD (0.014 GBP) per liter of biodiesel. The known pedigreed of the oilseeds is important in establishing its relative value in the marketplace (Reaney, *et. al.*: 2006).

Oilseed often loses value due to conditions encountered during the growing season, during harvesting and storage. The damaged or degraded seed is either sold at a discount or not sold at all. Farmers may significantly benefit from the establishment of a biodiesel industry that consumes lower grades of oilseed (Reaney, *et. al.*: 2006).

The cost of farming in Canada is tightly linked to the costs of fuel, chemicals and seed and the potential benefits of biodiesel are unlikely to change these input cost quickly. Fertilization costs constitute a major portion of the total costs of crop production and hence biodiesel production. The use of herbicide resistant crops for biodiesel production will require increased associated farm chemical costs.

The cost of nutrients N and P are closely tied to the cost of natural gas as is the major input in fertilizer production. With a projected yield of 1,490 kg/ha a fertilized consumption will be similar to that of current canola (68.0 CAD/ha (32.6 GBP/ha, 2006 Canadian Dollars), 14.0 CAD/ha (6.7 GBP/ha) and 11.0 CAD/ha (5.3 GBP/ha) for N, P and S respectively). For this example the cost of fertilizer will contribute 0.13 CAD (0.062 GBP) per litre of biodiesel for crops such as canola and flax. Farm chemicals, particularly herbicides, are also a major input cost in canola crop production and are greater than the cost of chemicals used in cereal production. Canola direct seeded on dark brown soil attracted approximately 77.04 CAD/ha (36.9 GBP/ha) and 58.83 CAD/ha (28.2 GBP/ha) - canola seeded on stubble. (Reaney, *et. al.*: 2006).

Levelton Engineering Ltd. and $(S\&T)^2$ Consultants Inc. (2002) study conclude that the vegetable oil biodiesel will have a negative return to the investor even if both federal and provincial taxes are waived. It was assumed that the oil companies will not pay a premium for the biodiesel. In fact, they may pay less than the equivalent cost of the diesel fuel if they also have to add additives to improve the cold weather properties of the fuel and account for the blending costs. Tax incentives of ~0.40 Canadian (2002) Dollars (~0.164 GBP) per litre will be required to make these fuels economic to produce at the current feedstock costs and diesel fuel prices (LevNRCan: 2002).

The studies also warned that the situation is different for the tallow biodiesel due to the lower cost of the feedstock and the lower capital cost of the plants. The two scenarios that have some tax relief produce a blended cost that is less than diesel. According to authors, these costs do not provide a return on capital for the owner of a plant, however, nor do they include any costs for cold flow additives or blending costs (LevNRCan: 2002).

It is noteworthy that IAG Ltd./Enerquest (2002) estimated Alberta (Canada) biodiesel production cost based on canola, yellow grease and animal fat to range between 0.49-0.53 Canadian (2002) Dollars (0.20-0.22 GBP) per litre, compared to the 0.36-0.63 Canadian (2002) Dollars (0.15-0.26 GBP) per litre range from Levelton/NRCan (LevNRCan: 2002, Schmidt: 2004). These differences are due to different feedstock cost assumptions and production processes (e.g., IAG did not assume BIOX process and IAG Ltd. used off-grade canola prices). IAG Ltd. concluded that the net result is that economic factors are not apparently favourable in today's market (IAG Ltd./Enerquest: 2002, Schmidt: 2004).

Table 2.19: Biodiesel after tax cost in Canada (2002)

	Diesel only	Fuel taxes included	Federal tax exempt	Both taxes exempt
Vegetable biodiesel	Cents/litre	Cents/litre	Cents/litre	Cents/litre
Diesel component	35.0	28.0	28.0	28.0
Biodiesel component	0.0	12.6	12.6	12.6
Taxes	19.0	19.0	18.2	15.2
Total, pre GST	54.0	59.6	54.8	55.8
Animal biodiesel	Cents/litre	Cents/litre	Cents/litre	Cents/litre
Diesel component	35.0	28.0	28.0	28.0
Biodiesel component	0.0	7.2	12.6	12.6
Taxes	19.0	19.0	18.4	16.15
Total, pre GST	54.0	54.2	54.6	51.35

Note: All costs presented in Canadian (2002) cents

Source: LevNRCan: 2002

The BIOCAP studies conclude that production of biodiesel crop that displace cereals will significantly decrease demand for transportation and storage of grain. Oilseed crops have considerably lower yield than cereal crops and will require significantly less storage space and fuel for transport. Oilseed crops used in biodiesel production will be processed locally and not transported to ports by rail and then shipped overseas. The lower mass yield is a property of oilseed crops and thus it is expected that any crop grown for biodiesel will produce a low mass yield when compare to a cereal. Transport costs are more related to mass than volume and thus the production of a lowed mass crop will significantly decrease the mass of material transported. The cost of gathering grain in terminals and pooling the grain for shipment will be decreased due to lesser mass and volume of the oilseed crop. Oil extraction facilities for separation of oil and meal will be significantly closer to agriculture land than ports used for export (Reaney, *et. al.*: 2006).

The transportation of methanol and catalyst used in production of biodiesel are relatively small in total volume and mass. Catalyst represents just 1% of the biodiesel mass or 0.4% of the oilseed mass; glycerine and methanol are 4% of the seed mass. Shipping biodiesel to the blending plants will contribute 0.058-0.076 Canadian (2006) Dollars (0.028-0.036 GBP) per liter of biodiesel (Reaney, *et. al.*: 2006).

A principal characteristic of biodiesel is that it has problems with viscosity which require its temperature to be maintained during carriage. The result is that biodiesel tend to be carried in relatively small quantities and relatively expensively, in tankers with stainless steel cargo tanks, which were typically built to carry acids and other chemicals. But then, similar care is taken with transportation of aviation fuel, which must comply with strict quality specifications, such as Defence Standard 91-91 (Feeney: 2009).

The current large scale crushers can produce large volumes of oil at the lowest costs from canola oil. However, these are significant limitations if special non-food oilseed crops are utilized in biodiesel production they may be processed in existing crushing plants operating below capacity. The large scale plants are producing food products that should not be contaminated with non-food streams. The large plants do not easily switch between feed materials and must be cleaned in the transition from food to non-food operations and vice versa. The combined transition would result in one day of production. Larger crushers with volumes smaller than at least 10 days of full production may not be economically processed. Moreover, the design of larger facilities does not allow for the optimization of processes to the needs of specific materials. As such, processes that require low temperature processes cannot be conducted in existing extraction large scale facilities (Reaney, *et. al.*: 2006).

Sampattagul, *et. al*. (no date) says that in Thailand agricultural process for *Jatropha* biodiesel production occupies 62.62%, most expending is the operation costs such as fertilizers, insecticide and electricity for water pumping system, especially in the dry season. Cost of biodiesel production process is ~25.27% while the external cost or environmental cost at use phase is ~12.12%. Thus the total cost of *Jatropha* bio-diesel without externalities is ~0.6 €/liter (0.47 GBP/liter, EUR/GBP = 0.788 - April, 2008. www.xe.com/ucc/convert.cgi). And the total cost included the environmental cost is 0.7 €/liter (0.55 GBP/liter). This makes the production cost of *Jatropha* bio-diesel is higher than the retail selling price of diesel in present market which is ~0.5 €/liter (0.39 GBP/liter), by means of this price is not included the environmental cost.

According to this study, the bio-diesel from *Jatropha* oil is still not suitable for being the alternative fuel in this time as the cost and the environmental impacts at present are pretty high.

It is estimated that cost of biodiesel produced by transesterification of oil obtained from *Jatropha curcas* oil seeds in India shall be approximately same as that of petrodiesel. Satish Lele (no date) reports the cost of biodiesel varies between 14.98-16.59 Rs./litre

(0.19-0.21 GBP/litre, GBP/INR = 79.23 - 02 April 2008. www.xe.com/ucc/convert.cgi). Assumptions are that the seed contains 35% oil, oil extraction will be 91-92%, 1.05 kg of oil will be required to produce 1 kg of biodiesel, and recovery from sale of glycerol will be at the rate of 40.0-60.0 Rs./kg (0.50-0.76 GBP/kg) (Ibid.), which is consistent with 50.0 Rs./kg (0.63 GBP/kg) (Altenburg, *et. al.*: 2009). However, most importantly, the oils from which biodiesel are made have become expensive, and are likely to remain so (Sperling: 2008).

The economic effects of increasing the production of biofuels in Finland have been studied in a framework of the Environmental and economic implications of second generation biofuels for transport (BIOVAIKU) project with the aid of a dynamic general equilibrium model of the Finnish economy. The main conclusions of this project completed at the end of October 2008 as following. Biofuel production is imposed on the economy with blending standards regardless of the cost of biofuels, and the increased use of domestic sources for biofuels is likewise imposed on the refining industry. This has both negative and positive effects on the economy. Agriculture and forestry face increased demand from the refining industry, which increases their output. At the same time, however, production costs increase in the refining industry, and fuel costs in the economy increase overall. This rise in costs has several effects. For the consumers, the immediate effect of rising prices is lower purchasing power, thus reducing consumption and demand. In the industries, the rental price of capital is affected by rising costs, tending to decrease investments. Finally, in the labour markets, decreased profitability initially leads to a fall in demand for labour (Soimakallio, *et. al.*: 2009).

Effects of increased use of biofuels on Finnish macro-economy (e.g. GDP, private consumption, investment, and employment) are unveiled as following. As biofuels expansion has the effect of raising both consumer prices and costs of production, it tends to drive down consumption and production in most sectors of the economy, and also makes investment less attractive. Thus, in the short run, the cost of biofuels has mostly negative effects at the aggregate level. The reason for the continued negative GDP effect stems from the effect of higher costs on competitiveness. While the effects of increased domestic biofuel production are to some extent negative at the level of the whole economy, the increased demand for crops and wood obviously increase activity in agriculture and in particular, in forestry (Soimakallio, *et. al.*: 2009).

Besides, numerous reports emphasize the importance of creating a certification system that avoids excessive costs. The Cramer Commission estimated the potential costs of a certification scheme focused on land management at 20% of production costs. Moreover, traditional certification criteria that focus on direct production processes are probably uncapable of protecting biodiversity, guaranteeing overall greenhouse gas benefits, or avoiding at least some additional contributions to the burdens on the world's water availability and quality (UNCTAD: 2008 cited by Searchinger: 2009).

In the context of total energy consumption, liquid biofuels supplied only 0.4% in 2006 (IEA: 2008, OECD/FAO: 2008, REN_{21}: 2008 cited by Searchinger: 2009). In terms of liquid fuels for transport, biofuels contributed only 1.8% globally and, considering utilization for heating and industrial uses, made up just over 1.0% of total liquid fuel use globally (IEA: 2008, OECD/FAO: 2008, Jank: 2008 cited by Searchinger: 2009). By comparison, solid biofuels supplied approximately 10% to 13% of total global energy consumption, or some 30-fold more energy than liquid biofuels (Howarth & Bringezu: 2009). For the foreseeable future, biofuel production will remain a small fraction of total petroleum fuel production.

As the production of biofuel feedstocks increases, the marginal cost of supply increases as well because of limitations of suitable lands and available water, among other causes. As such, biofuels are unlikely to become the answer to high crude oil prices (ESMAP: 2007).

Chapter 3: Well-to-Tank (WTT) Life Cycle Assessment for production of biodiesel from *Jatropha curcas* in Southern India

3.1 Introduction

There are a vast number of studies on energy balance and GHG balance of oilseed cultivation and biodiesel production (e.g. Reinhardt & Jungk: 1996, Mortimer, *et. al.*: 2002; Mortimer, *et. al.*: 2003; Elsayed, *et. al.*: 2003; GM & LBST: 2002; Ceuterick & Spirinckx: no date; Van Gerpen: 2000; Van Gerpen, *et. al.*: 2004; Patyk: 2000; Puppan: 2002; Levelton Engineering Ltd. and $(S\&T)^2$ Consultants Inc.: 2002; CONCAWE: 2002; Woods & Bauen: 2003; Bernesson: 2004; Toyota Motor Corporation: 2004; Zah, *et. al.*: 2007, Achten, *et. al.*: 2008, *etc*) were conducted and their results published since an alternative fuels development become booming in both European Union and North America. However, all above listed as well as many other studies based on evaluation of the annual oilseed crops such as rape seeds in EU, canola in Canada, or soya beans in USA.

It is also important to make a note that none of the mentioned above LCA studies considered neither changes in land use patterns, nor infrastructure costs. One of the controversies surrounding bioenergy regards the effect that the feedstock cultivation, biofuels production and use has on the Earth's climate. The validity of including "indirect" impacts of biofuel production, especially indirect land conversion (such as conversion of grasslands to croplands, or forests to plantations), as well as scale of such impacts, to the Life Cycle Analysis (LCA) of biofuels is central to this "net emissions" debate. Besides the energy balance and GHG balance, other environmental impacts need to be carefully understood when discussing the possibility of using biofuel. Thus, impacts on soil degradation, resource depletion, biodiversity loss, ecotoxicity, air pollution and water contamination have been included in a research study using the Life Cycle Analysis framework by Zah, *et. al.* (2007). According to this report, to date almost all biofuels are beyond the environmental benchmark for fossil fuels. If the environmental integrity of the Convention (FRCCC (AE)) is to be maintained, a better understanding of the real potential impacts of biofuels needs to be ensured before promoting large biofuel programmes for mitigation (Robledo & Blaser: 2008).

In various studies Life Cycle Assessment (LCA) is termed as Well-to-Wheel (WTW) studies (MacLean & Lave: 2003, Jonasson & Sanden: 2004). As such, WTW analyses usually consider energy use and emissions during fuel productions and vehicle use, while not including the production of vehicles and production facilities. In this case, Well-to-Tank

(WTT) studies do not include vehicle use either. Well-to-Tank (WTT) LCA covers the full production conversion part of the biofuel chain up to delivery of the end-fuel. This is notionally to the 'tank' of a vehicle but is often simplified to encompass delivery only to a point where the renewable fuel is treated in exactly the same manner as the reference fuel (e.g. diesel).

The Well-to-Tank (WTT) studies relate emissions with respect to a megajoule (MJ) of fuel (gCO_2eq/MJ), but in order to compare fossil and alternative fuels, they also include the direct emissions of gasoline or diesel during the use phase in the motor combustion (i.e. well-to-wheel). The Well-to-Wheel (WTW) studies express results per kilometre (km), calculated as the sum of the Tank-to-Wheel (TTW) direct emissions (in gCO_2eq/km) plus the indirect emissions calculated as the product of the WTT emissions (gCO_2eq/MJ) and the TTW energy consumed by the vehicle per unit of distance covered (MJ/km). In most approaches the percentage improvement calculated by dividing the biofuel emissions by the corresponding fossil fuels (gasoline and diesel) emissions, and in a few cases results have been expressed in other units (e.g. per tonne of fuel) (Menichetti & Otto: 2009).

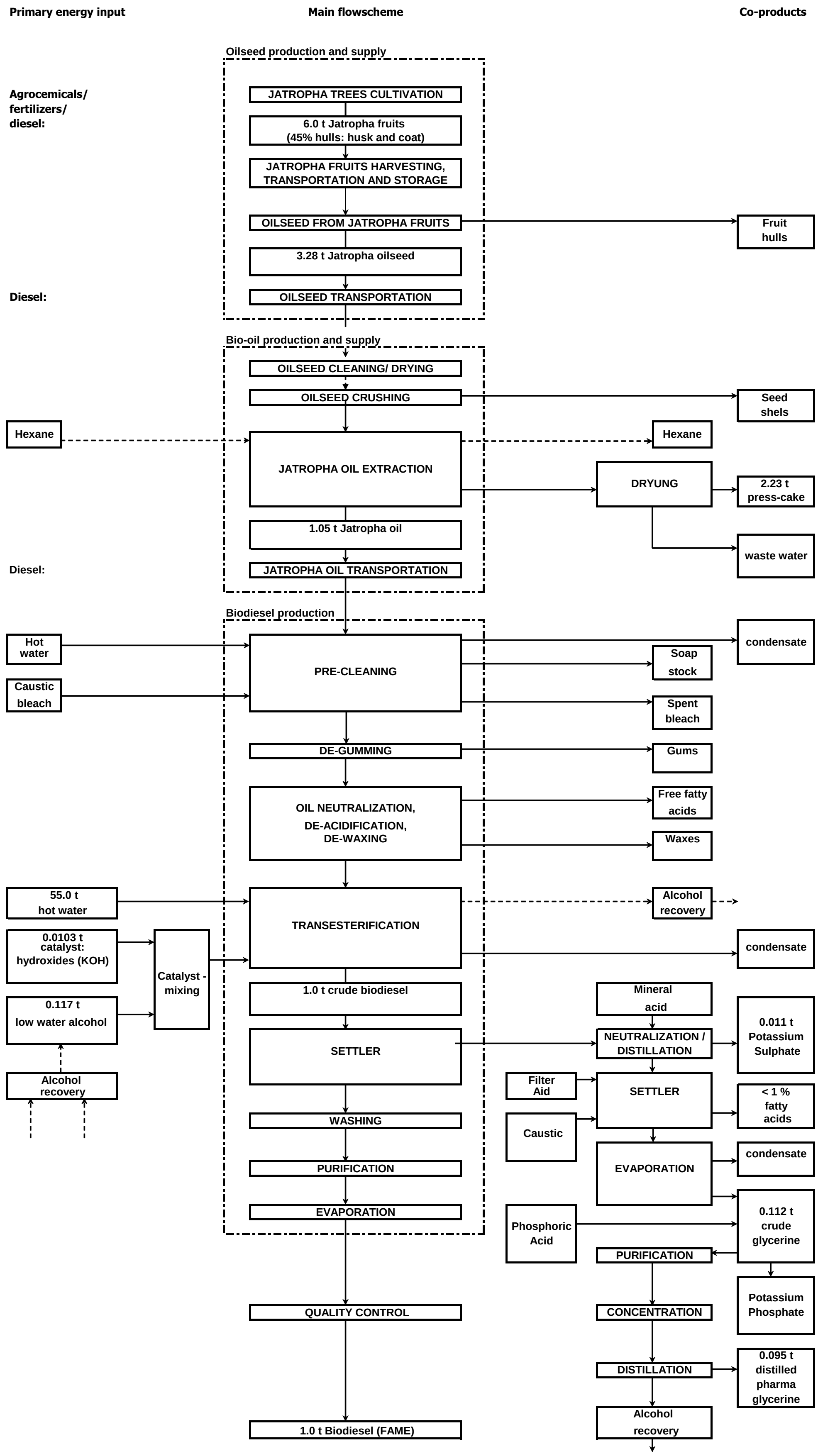
3.2 Basic Jatropha oilseeds-to-biodiesel pathway

It is assumed that biodiesel is produced from *Jatropha curcas* oilseeds (vegetable oil) via industrial scale one-stage transesterification process; two-stage process: fat-splitting and esterification process; or small-scale transesterification process.

Various inputs are required for the cultivation and biodiesel production process. This research and analysis has concentrated on a case where *Jatropha curcas* plantations are grown in the waste/fallow lands in Karnataka State, Southern India. There are numerous by-products with various utilization options during both feedstock cultivation and biodiesel production chain that will be discussed in this chapter later on. It is assumed that the biodiesel produced is either blended into petrodiesel to produce a fuel meeting EN1421112 and/or proposed BIS standard, or use as a neat (B100) biodeisel for standard diesel engines for road and railroad transportation, as well as in gensets for the small-scale local electricity generation.

The basic process for industrial production of biodiesel from *Jatropha curcas* oilseeds is shown in Flowchart 3.1, and basic process for a small-scale production of biodiesel in Flowchart 3.2.

Flowchart 3.1: Industrial scale biodiesel production pathway (2)



The process chain for industrial scale biodiesel production consists on *Jatropha curcas* shrubs cultivation; *Jatropha* fruits harvesting, transportation and storage; *Jatropha* oilseed cleaning, drying, and crushing; *Jatropha* oil extraction using screw press and, at the second stage, hexane solvent to extract the rest of the oil from the press-cake; *Jatropha* oil pre-cleaning, de-gumming, neutralization, de-acidification and de-waxing; transesterification; then biodiesel produced settling, washing, purification, evaporation; and transportation to points of storage, distribution or sale (Flowchart 3.1).

However, for small-scale local production this biodiesel production pathway will be restricted only to the following steps: *Jatropha curcas* shrubs cultivation; *Jatropha* fruits harvesting, transportation and storage; *Jatropha* oilseed cleaning, drying, and crushing; *Jatropha* oil extraction using hand press or screw press; transesterification; biodiesel produced settling, purification/refining; and, finally, transportation to points of distribution or sale (Flowchart 3.2).

Flowchart 3.3 is drawing boundaries for biodiesel Life Cycle Assessment. Energy and emissions from the following processes are included to the current LCA:

I. Upstream:

- *Jatropha* oilseeds cultivation;
- *Jatropha* oilseeds harvesting, handling, drying and storage; and
- petrodiesel fuel upstream energy and emissions.

II. Downstream:

- *Jatropha* oilseeds, *Jatropha* oil, fruit hulls, seed shells and biomass transportation;
- methanol transportation;
- catalyst, H_2SO_4, H_3PO_4 transportation;
- fuel use at *Jatropha* oil extraction facilities;
- fuel use at biodiesel production facilities;
- biodiesel distribution/transportation; and
- glycerine transportation.

At the same time, energy and emissions from the following operations are excluded from current LCA:

I. Upstream:

- energy and emissions from land use and land use change (direct and indirect);

II. Downstream:

- crude glycerine purification, concentration and distillation;
- potassium phosphate recovery;
- potassium sulphate recovery; and
- free fatty acids (ffa) recovery.

III. Vehicle:

- tailpipe emissions; and
- evaporative emissions.

The calculations in this study mainly concerned with Well-to-Tank (consideration of *Jatropha* cultivation and associated biodiesel production from planting oilseed bearing trees to vehicle fuel tank, energy consumption) greenhouse gas (GHG) emissions and energy efficiency of biodiesel in Southern India. At present, the results of WTT analysis one not combined with the results of Tank-to-Wheel (TTW) studies, for several reasons. First of all, there is a lack of data and background information for TTW analysis in specific Indian conditions. Also, the major goal of the Indian Bio-fuels Development Program is promotion of *Jatropha curcas* cultivation biodiesel production for electricity generation rather then for its usage as a substitution of petrodiesel as transportation fuel (Ravindranath: pers. comm.). The study adopted a calculation method used in LowCVP Well-to-Wheel Evaluation for Production of Ethanol from Wheat study (LowCVP: 2004) to calculate energy and GHG emissions balances.

Low Carbon Vehicle Partnership (LowCVP: 2004) LCA Model is an Excel worksheet tool designed and implemented by the Fuels Working Sub-group headed by David Rickeard of ExxonMobil and Gary Punter of British Sugar. The study describes the energy and greenhouse gas emissions associated with producing bioethanol from wheat, using technology currently feasible for the UK.

The basic wheat-to-ethanol pathway describes standard processes including wheat farming and ethanol production via hydrolysis and fermentation. Within the framework of the generic pathway, there are three main factors that can have a profound impact on the outcome of the pathway have been considered:

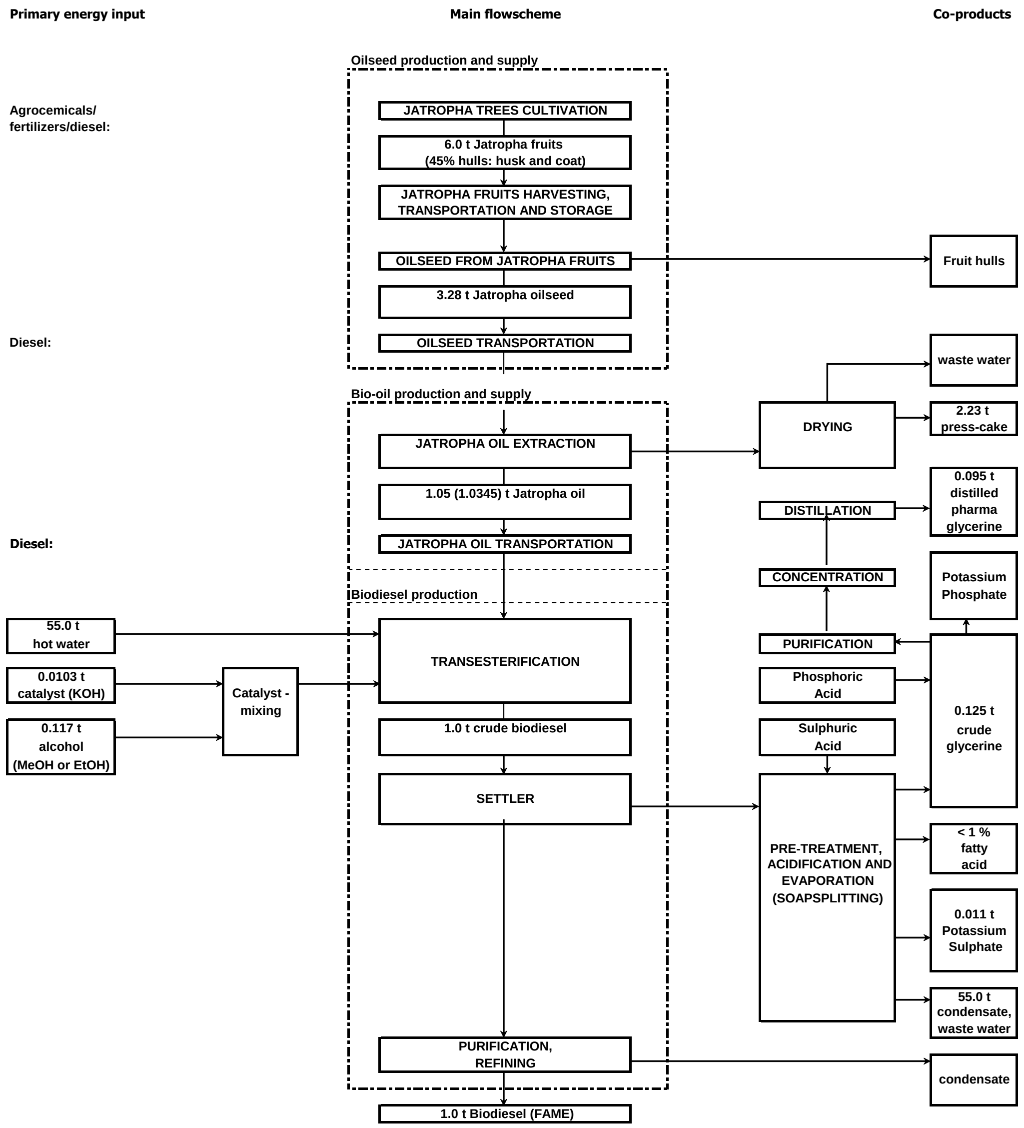
- The heat & power generation scheme used in the ethanol plant;
- The fate of straw: ploughed back into the field or use as fuel for the ethanol plant;
- The fate of Distillers' Dark Grains and Solubles (DDGS) used as an animal feed or energy source.

The study highlights that the way in which fuels are produced has a significant impact on energy balance, GHG emissions and costs. Regulators should consider fuel production processes as well as final fuel properties when deciding policy for future fuels. In particular:

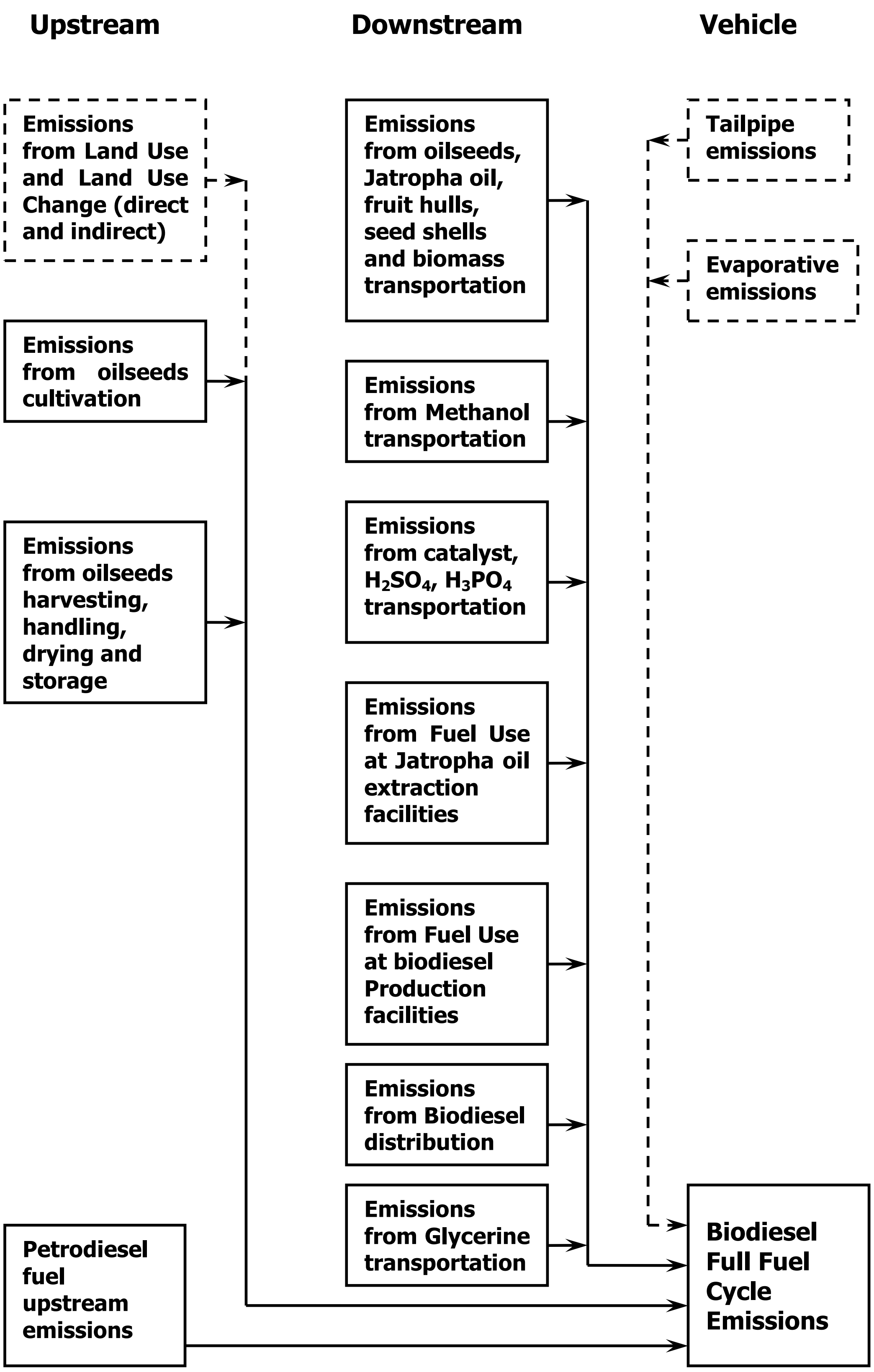
- Incorporation of CHP into the ethanol plant significantly improves energy and GHG balances;
- Use of straw as an energy source further improves energy and GHG savings;
- Use of DDGS as energy for power generation rather than as animal feed gives much greater energy and GHG savings (although it is unlikely to be the most economic option).

To show the potential savings, the energy use and GHG emissions for each model have been compared with the Well-to-Tank (WTT) energy and GHG emissions for gasoline. The results show that all the bioethanol Models give lower WTT greenhouse gas emissions when compared with gasoline, but that the process models and how the by-products are used strongly affect the results (LowCVP: 2004).

Flowchart 3.2: Small-scale biodiesel production pathway



Flowchart 3.3: Biodiesel emissions model



3.3 Scenarios

Personal communications, semi-structured and informal interviews with various stakeholders in India in November 2005 - March 2006, augmented by inputs from secondary sources, resulted in the design of the range of configurations for oilseed feedstock cultivation and new biodiesel production plant which is deemed to be realistic for conditions of Karnataka and Southern India at large. Due to root competition for water the optimal spacing is believed to be a function of rainfall, where wider spacing should be used in semi-arid environments and denser plantations can be appropriate for sub-humid environments (Achten, *et. al.*: 2008).

Expert meeting on the recent developments in *Jatropha* (Brussels, 07 December 2007) substantiates that the optimal tree density is close to 1,300 plants per ha (2.5x2 m spacing). A density of 2,500 plants per ha (2x2 m spacing), as mentioned very often, seems to be too high as grown-up plants (3 years and older) don't allow people to pass between the plants to harvest the fruits. A distance between the rows of 3 m seems very important, which gives a number of plants per ha of 1,700 (3x2 m spacing), if the distance within a row is 2 m (Rijssenbeek, *et. al.*: 2007). Heller (1996) and Achten, *et. al.* (2008) notify as a common practice the populations of 1,111 plants per ha (3x3 m spacing), 1,700 plants per ha (3x2 m spacing) or 1,600 plants per ha (2.5x2.5 m spacing) for Irrigated or Partially Irrigated conditions and 2,500 plants per ha (2x2 m or 3x1.5 m spacing) for Rainfed conditions. Kaushik and Kumar cited by Achten, *et. al.* (2008) and Raina (pers. comm.) propose to use wider spacing patterns (4x2 m and 4x3 m spacing) and agroforestry systems (5x2 m and 6x6 m spacing) to optimize the yield of individual *Jatropha* plants. Opposite of this view, the Resources and Livelihoods Group PRAYAS (Pune, Maharashtra), reffering to the National Oil-seeds and Vegetable Oils Development (NOVOD) Board, considers that the higher plantation density 2,500 plants per ha (2x2 m spacing) is possible only if the soil is not poor and some irrigation is vailable. In rainfed plantations on marginal land also called wasteland, which are going to be the conditions for most plantations (in Maharashtra), the appropriate density would be 1,660-1,700 plants per ha (3x2 m spacing) (PRAYAS: 2006; Rajagopal: 2007). However, Dr. Paramathma, Professor and Nodal Officer for the Center of Excellence in Biofuels, TNAU after experiments with spacing varieties of 1x0.5 m, 1x1 m, 2x1 m, 3x2 m, 3x3 m, and 4x4 m, recommends density of 1,660-1,700 trees per ha (3x2 m spacing) under rainfed conditions and either 1,660-1,700 trees per ha (3x2 m spacing) or 1,111 trees per ha (3x3 m spacing) under irrigated condition (Paramathma: pers. comm.). Professor Neelakantan, Dean for the Forest College & Research Institute, TNAU recommended planting density for poor soil/Rainfed conditions 3,330 trees/ha (2x1.5 m spacing), for normal soil/Irrigated conditions 2x2 m (2,500 trees/ha spacing), for fertile soil/Irrigated conditions 1,660-1,700 trees/ha (2x3 m spacing) (TNAU website. Visited 27 June, 2006). Most recent ICRISAT on-station trials revealed that the planting of *Jatropha* at 3x3 m spacing recorded better growth characteristics compared to 4x2 m and 3x2 m spacing on Vertisols under rainfed conditions (ICRISAT: 2008. Activity 7.2.1.2). Chikara, *et. al*. (2007) observed that in 2.5-year-old plantations with increasing spacing, seed yield per tree increased significantly, while the seed yield per ha decreased (Achten, *et. al*.: 2008).

Three major configurations for *Jatropha curcas* cultivation as an oilseeds feedstock were considered and included into '*Jatropha* to biodiesel pathway' spreadsheet (Table 3.2):

- ❒ Irrigated *Jatropha* plantation. Spacing 3x3 m. 1,111 trees/ha. Organic, chemical fertilizers and agro-chemicals applied;
- ❒ Rainfed *Jatropha* plantation. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied;
- ❒ Rainfed *Jatropha* plantation. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used.

Biodiesel production technologies and processes recently introduced to India by Lurgi India Company Limited (New Delhi office), De Smet Chemfood Engineering Pvt. Ltd. of Belgium (Mumbai and Bangalore representative offices), and locally designed and manufactured by Maland Extraction Industries, Shimoga, Karnataka were scrutinized as well as vast number of secondary sources, e.g. Patyk, *et. al.* (2000), Gervajio (2005), BDT Biodiesel Technologies (2002), Austrian Biofuels Institute (2002), Lele (no date), Woods & Bauen (2003), Lee, *et. al*. (2006). As a result of rigorous analysis of commercially available technological processes for trans/esterification, three following processes were chosen for further evaluation and estimations (Table 3.2):

- ❒ One-stage Henkel Transesterification process (90 bar, 240^{o}C);
- ❒ Two-stages Lurgi process: a) Fat-splitting (60 bar, 260^{o}C) and
  b) Esterification (10 bar, 240^{o}C);
- ❒ Small-scale Transesterification process (1.4 bar, 60^{o}C).

The generic flowcharts for both Irrigated and Rainfed biodiesel production pathways makes it possible to consider numerous options in the following areas:

- ❒ Heat and Power generation scheme used in the biodiesel plant (Tables 3.3 & 3.11);
- ❒ Utilization of *Jatropha* fruit hulls and seed shells: used as fertilizer (compost) or used as combustibles (Table 3.1);
- ❒ Utilization of *Jatropha* press-cake used as fertilizer (green manure) or energy production (Table 3.2).

Every one of these options has a significant impact on the final energy and Greenhouse Gas (GHG) balance of each pathway.

Table 3.1: Scenarios for *Jatropha* oilseed production and supply

	Fruit hulls and seed shells used as compost	**Fruit hulls and seed shells used as combustibles**
Irrigated Jatropha plantation. Spacing 3x3 m. 1,111 trees/ha	**x**	**x**
Rainfed Jatropha plantation. Spacing 2x2 m. 2,500 trees/ha	**x**	**x**

Table 3.2: Scenarios for overall balance credits

	Irrigated Jatropha plantation. Organic, chemical fertilizers and agro-chemicals applied		**Rainfed Jatropha plantation. Organic, chemical fertilizers and agro-chemicals applied**		**Rainfed Jatropha plantation. No fertilizers and agro-chemicals used**	
	Press-cake used as fertilizer (green manure)	Press-cake used for energy production	Press-cake used as fertilizer (green manure)	Press-cake used for energy production	Press-cake used as fertilizer (green manure)	Press-cake used for energy production
One-stage Transesterification process (90 bar, 240°C)	**x**	**x**				
Two-stages process: a) Fat-splitting (60 bar, 260°C) and b) Esterification (10 bar, 240°C)	**x**	**x**				
Small-scale Transesterification process (1.4 bar, 60°C)			**x**	**x**	**x**	**x**

3.4 Biodiesel plant utility generation models

The energy (electricity and heat) supply scenarios for trans/esterification plant were identified during intensive consultations with Dr. Bhatt, Joint Director, Energy Conservation and Development Division, Central Power Research Institute in Bangalore. Tables 3.3 (Irrigated, large scale scenarios) and 3.10 (Rainfed, small-scale scenarios) are summarizing considered energy supply scenarios.

3.5 Irrigated scenario

Table 3.3: Energy supply scenarios. Irrigated

Fruit hulls and seed shells	Energy generation scheme	
Used as fertilizer	a11	Conventional oil boiler
	a12	Conventional coal boiler
	a21	Conventional NG boiler
	b11	Conventional oil boiler, backpressure turbogenerator
	b12	Conventional coal boiler, backpressure turbogenerator
	b21	Conventional NG boiler, backpressure turbogenerator
	c11	NG GT + unfired HRSG
	c12	NG GT + co-firing HRSG
	c21	NG GT + unfired HRSG, backpressure turbogenerator
	c21	NG GT + co-fired HRSG, backpressure turbogenerator
Used as fuel	d1	Biomass boiler + CHP
	d2	Biomass boiler + CHP and combined cycle
	e	Biomass gasification + GT + unfired HRSG + BP/cond STG

3.5.1 Basic configuration: conventional oil-, coal- or natural gas-fired boiler and imported electricity.

Models a11, a12 and a21 were considered as the basically simplest and required minimum investment configurations (Table 3.4). Heat, required for the process in the form of steam, is generated by an on-site boiler. Electricity is purchased from the Indian National Grid.

Table 3.4: Basic configuration

Models:	
Oil boiler	a11
Coal boiler	a12
NG boiler	a21

3.5.2 Optimized fossil fuelled plant: combined heat and power (CHP)

These models embracing configurations that able to provide heat technological process of trans/esterification with 1.0 MPa to 9.0 MPa heat at 240^{o}C to 260^{o}C for industrial scale (Table 3.8), or 0.14 MPa heat at 60°C for small-scale local production and electricity as required for the production process (Table 3.13).

Models b11, b12 and b22, the oil, coal and natural gas boilers consequently are supplemented by a backpressure steam turbo-generator. This allows producing electricity by using the surplus energy from the exhaust steam utilized for the biodiesel production process.

India initially started implementing 6.7 MPa steaming cycle cogeneration plants. Later, in 2002-2003, several 8.7 MPa sugar cogeneration systems were installed employing experiences gained from the operation of those plants. Most recently, the industry is using very high pressure systems of up to 11.0 MPa (Balasankari & Arul: 2009).

Supercritical pulverized-coal power plants first came to operation in early 1960s. The majority of existing coal-fired power plants are based on subcritical technology. More recently, in the 1990s, ultrasupercritical facilities have been constructed and operated (Table 3.5). For a comparably sized plant the engineering, procurement and construction cost for a supercritical unit is 2-5% higher than a subcritical unit. Operation and maintenance costs are about the same for the two designs. Supercritical units have additional costs for the condensate polisher and more sophisticated maintenance requirements, but lower costs for consumables such as limestone, ammonia and coal due to higher efficiencies (Nalbandian: 2008). Presently, large and fuel-efficient super-critical equipment equipment for new power projects, are not manufactured in India (PEI: April 2009).

Table 3.5: Approximate pressure, temperature and efficiency range for subcritical, supercritical and ultrasupercritical pulverized coal power plant.

Pulverized coal power plant	Main stream pressure, MPa	Main stream temperature, °C	Reheat stream temperature, °C	Efficiency, %, net, HHV basis (Inland bituminous coal)
Subcritical	<22.1	Up to 565	Up to 565	33-39
Supercritical	22.1-25	540-580	540-580	38-42
Ultrasupercritical	>25	>580	>580	>42

Source: Nalbandian: 2008

In this case the following assumptions could be made for estimations of steam and electricity generation using oil, coal and natural gas boilers consequently supplemented by backpressure steam turbo-generator:

- Efficiency of modern coal power plant 34-36%, efficiency of old power plant 20-30% (Sharma, February 2004. Available at: www.iea.org/Textbase/work/2004/zets/apec/ presentations/sharma.pdf);
- Coal-fired plants run at a delivered efficiency of 34%, oil-fired plants at 25%, and gas-fired plants at 42% including CCGT and conventional plants running on natural gas (United Kingdom: 2000. www.oxfordenergy.org/comment.php? 0303);
- Clean coal-fired power plant: net efficiency 45%, CO_2 emissions 770 g/kWh, (www.e8.org/index.jsp?numPage=138), 46-47% in a modern hard coal fired steam power plant vs. standard process design efficiency of 36-37% (PEI: May 2009), >43% (Germany. PEI: October 2007);
- Old brown coal/lignite fired power plant efficiency 33%, new supercritical steam power plant 42% (Poland. PEI: September 2008);
- An old steam plant efficiency 37-39%, compared to a new combined-cycle power plant efficiency ~52-58% (PEI: May 2007). Basic CCGT plant efficiency 58.6%, full CHP mode 72.6% (E.ON. PEI: October 2007);
- Super-critical thermal cycles (245 atm, 540°C/565°C) are technological options for improving generation efficiency of coal-based power generation from 37% sub-critical thermal cycles (170 atm, 540°C/540°C) to 39% (TERI/TEDDY: 2003);
- Coal generations results in CO_2 emissions of 0.9 t/MWh, while gas generation produces only <0.4 t/MWh of CO_2 (PEI: June 2007);
- Coal-fired grid electricity emits 1.06 t/MWh, while on-site gas-fired cogeneration plant is 0.55 t/MWh (NSW, Australia. COSPP: May-June 2009);
- Oil-fired power plant (300 MW): efficiency 38%, CO_2 emissions 740 g/kWh (www.e8.org/index.jsp?numPage=138);
- NG-fired combined cycle plant (300 MW): efficiency 56%, CO_2 emissions 360 g/kWh (www.e8.org/ index.jsp? numPage=138);
- NG's thermal/electricity conversion efficiency 48-52% vs. coal's 35-43% (Pearson: no date, www.cleancoaltrm.gc.ca, www.nrcan.gc.ca);
- Central power plant had emissions of CO_2 at 880 kg/MWh, SO_2 at 4 kg/MWh,
  NOx at 2 kg/MWh. The new CHP plant has reduced the emissions to CO_2 at 280 kg/MWh, SO_2 at 1.4 g/MWh, NOx at 20 g/MWh (USA. COSPP: November-December 2008);
- Biomass combustion efficiency: ~33-37% (PEI: May 2009).

Characteristics of cogeneration technologies presented in Tables 3.6 and 3.7.

However, some other options of energy supply are possible (Models c11, c21, c12, c22). They might consist of:

- A natural gas-fired gas turbine for electricity production;
- A heat-recovery steam generator (HRSG) using the exhaust from the gas turbine to produce high pressure steam through additional gas firing;
- A back-pressure steam turbine producing more electricity and low pressure steam suitable to drive biodiesel production process (LowCVP: 2004).

Table 3.6: Heat-to-power ratios of cogeneration plants

Cogeneration systems	Heat-to-power ratio (kWth/kWe)	Power output (as percent of fuel input)	Overall efficiency (%)
Back-pressure steam turbine	4-15	14-28	84-92
Extraction-condensing steam turbine	2-10	22-40	60-80
Gas turbine	1-2	24-35	70-85
Combined cycle	1-2	34-40	69-83
Reciprocative engine	1-3	33-53	75-85

Sources:
1) UNESCAP: 2000;
2) Uddin: 2004

Table 3.7: Characteristics of cogeneration technologies

Capacity	Efficiency (%, HHV basis)			Power-to-	Emissions (g/KWh)		
	Electrical	Overall	Marginal	heat ratio	NOx	CO	Hydrocarbones
Microturbines							
30 kW	23	67	44	0.52	0.23	0.63	< 0.08
70 kW	25	61	41	0.70	0.20	0.12	< 0.08
80 kW	24	63	42	0.63	0.57	0.69	< 0.08
100 kW	26	62	43	0.73	0.33	0.2	< 0.08
Reciprocating engines							
100 kW	30	78	63	0.61	20.9	16.8	1.0
300 kW	31	77	62	0.67	2.8	2.8	1.4
1 MW	34	71	57	0.92	1.4	2.8	1.4
3 MW	35	69	56	1.04	1.0	3.5	1.8
5 MW	37	73	61	1.02	0.7	3.4	0.7
Gas turbines (simple-cycle cogeneration)							
1 MW	22	65	41	0.51	1.09	0.32	2.0 - 3.0
5 MW	27	67	48	0.68	0.5	0.27	2.0 - 3.0
10 MW	29	69	51	0.73	0.5	0.23	2.0 - 3.0
25 MW	34	70	56	0.95	0.41	0.18	2.0 - 3.0
40 MW	37	72	60	1.07	0.36	0.18	2.0 - 3.0
Gas and steam turbines (combined-cycle cogeneration)							
20-50 MW	47	90	88	1.09	0.33	0.15	1.0 - 2.0
50-100 MW	49	90	88	1.20	0.3	0.15	1.0 - 2.0
>100 MW	55	90	90	1.57	0.13	0.08	1.0 - 2.0

Source: Lemar: 2001 and Goldshtein, *et. al.*: 2003 cited by COSPP: October 2006

The progress in the area of steam turbines has, however, been slower. The conventional turbine technology (in the sugar industry) has been back-pressure systems, in the range of

1-5 MW operating at low to medium steam throttle pressures. These turbines, usually single or multistage axial types, have poor conversion efficiencies, in the range of 55-65%. The average steam consumption per kWh in Indian mills is 10-12 kg/kWh, *-ef* to 7-9 kg/kWh in Hawaii (Winrock International: no date) and 4.2-4.6 kg/kWh - condensing steam (condensing turbine).

Table 3.8: Optimized fossil fuelled plant

Models	Unfired HRSG	Co-fired HRSG
Oil boiler + backpressure turbo-generator	b11	
Coal boiler + backpressure turbo-generator	b12	
NG boiler + backpressure turbo-generator	b22	
NG gas turbine	c11	c12
NG gas turbine + backpressure turbo-generator	c21	c22

General Electric Energy Combined Cycle: GE LM 6000 C.C gas turbine (Power: 56.4 MW, Efficiency: 52.5%) has been used for energy (electricity and heat) supply estimations for the large scale (plant capacity: 1,000.0 t of Jatropha oilseed per day, ~100,000.0 t of biodiesel per annum) biodiesel plant in Irrigated I and Irrigared II scenarios (Table 3.9).

In all other configurations it's assumed that the surplus electricity can be exported to the Indian National Grid and get additional credits.

Table 3.9: GE LM 6000 C. C. turbine basic data

GE LM 6000 C. C. Turbine			**Estimate for HP steam production**	
Power	MWe	56.4	Delta Tsat 125-60 bara	52.0
Operating hours	khr/a	8	Efficiency loss	3%
Power production	GWhe/a	451.2		
	TJe/a	1,624		
Steam (60 bar, 450^{o}C)			Steam (125 bar, 565^{o}C)	
Enthalpy	MJ/t	3,220.63		3,267.09
Unfired	t/hr	44.3		
	kt/a	354		
	TJ/a	1,141.39		1,107.15
NG consumption	TJ/a	3168		
GT elec eff		51%		
GT+HRSG		87%		
Co-fired	t/hr	148.32		3,706.82
	kt/a	1,186.56		
	TJ/a	3,821		
NG consumption	TJ/a	8,303		
GT+HRSG		66%		

Sources:
1) 2004 Gas Turbine World Handbook;

2) www.nem.nl;
3) Wei: 2002. Technologies for Next Geenration Turbine System. Rolls-Royce;
4) Aalborg Engineering. Denmark. www.aalborg-engineering.com/products/sg6;
5) www.energysolutioncenter.org/distgen/AppGuide.

It is also worth mentioning, that according to The International Energy Agency's International CHP/DHC collaborative project report, a lack of governmental emphasis on CHP, the absence of a clear methodology for calculating carbon dioxide emissions from CHP/DHC, and a tax and duty structure for CHP equipment that is not attractive as for other renewable energy technologies (RETs) have been considered as a present barriers to meeting India's energy efficiency targets and expansion of CEP/DHC projects (Hodgson: 2009).

3.5.3 Combined Heat and Power (CHP) plant fuelled by biomass

Utilization of biomass by-products of *Jatropha* cultivation such as fruit hulls, seed shells and pruning material is one more option for fuelling the trans/esterification plant (Models d1 and d2). In this case configuration will include biomass-fired boiler producing high pressure steam, extraction steam turbine producing both electricity and low pressure steam for the process (Table 3.10). The surplus electricity can be exported to the Indian National Grid (LowCVP: 2004).

Table 3.10: CHP fuelled by biomass

Models:	
Biomass boiler + backpressure turbo-generator	d1
Biomass boiler + backpressure turbo-generator + condensing turbine	d2
Integrated biomass gasifier with gas turbine + unfired HRSG + BP/cond STG	e

The steam turbine can either be a back-pressure or extraction-condensing type. In a back-pressure system, all of the steam expanded in the steam turbine is used for the heat application. The extraction-condensing steam turbine system is a mixture between a condensing and a back-pressure system, and only part of the steam is used for the heat application. The extraction-condensing system allows the operation from cogeneration to condensing to be highly flexible, although the investment costs are higher than in a pure back-pressure turbine. When the condensing mode is used, the power-to-heat ratio will increase while overall efficiency will decrease (Stahl: 2005).

Even though old-fashioned oil-fired boilers were replaced by modern biomass-fired CHP power plant, consisting of a bubbling fluidized bed steam boiler and also equipped with a flue gas condensation unit, it still requires at least 5% of fuel oil for peak production. A small part of fuel oil is also used when boilers are shut down and started up again for maintenance and service work (Bjorklund, *et. al.*: 2008).

The biomass total moisture content may vary up to ~60%. Dried biomass is hydrophilic and has a tendency to absorb moisture from atmosphere, even in covered storage. The long-term storage of wet biomass can be problematic because with moisture contents above 20%, relatively rapid microbial respiration activity can cause heating of the storage pile, loss of dry matter and significant deterioration in the physical quality of the fuel (Flin: 2009). The humidity of various fuels may vary a lot, but the quality of the fed fuel is evened out through mixing the different fuel loads that arrive in the plant. The boiler is designed for a fuel humidity range of 35-60%, as for the most part of the year humidity varies from 48-52%, and good quality fuels contribute to good boiler efficiency (ibid.).

In biofuel firing with steam temperature above 500^{o}C, there is a risk of high temperature corrosion of the low-alloyed steel materials of the final super-heaters. For this reason, austenitic steel (AC66), which has proven to withstand any corrosion, was selected as the material for the bubbling fluidized bed (BFB) biomass-fired boiler's final super heaters (Ibid.).

Biomass materials generally have lower ash contents than most power station coals, but the nature of biomass ashes is very different from that of most coal ashes. In general, biomass ashes have relatively low fusion temperatures and have relatively high levels of the alkali metals, particularly potassium. They have a greater propensity towards the formation of both slagging and fouling deposits than the majority of coal ashes. Hence, additional cost may be imposed to mitigate environmental impacts of biomass-fuelled CHP by installing a highly efficient flue gas cleaning unit and the recycling of the by-products and slag (Flin: 2009).

Adapting advances in gasification technology to the utilization of biomass waste or by-products is also very promising. The use of the biomass integrated gasifier (Model e) allows yielding high quality producer gas with little tar and particulates that feed gas turbine to produce electricity and low pressure steam for the process (Table 3.10).

The modern gasifier, for example the Skive gasification demonstration project in Jutland, Nothern Denmark, is based on low pressure bubbling fluidized bed (BFB) gasifier and used to produce gas from wood-based biomass which is initially wood pellets. It operated at the maximum of 2 bar over pressure and 850^{o}C temperature. Air is used as gasification medium and dolomite is used as fluidized bed material. The product gas generated in the gasifier contains carbon monoxide ~22% (CO), 20% hydrogen (H_2), and 5% of methane (CH_4) by volume as the major combustible components, and has a heating value of ~5 GJ/t. The gasification technology enables the power plant to produce ~30% more electricity than a conventional steam process, from the same amount of biomass (Salo & Horvath: 2009).

The biomass integrated gasifier combined cycle (BIGCC) at 45% efficiency replacing conventional pulverized coal plant at 36% efficiency will save around 0.5 GJ of primary energy for every one GJ of electricity generated (Planning Commission of India website. Visited 25 May, 2009).

3.6 Rainfed scenario

Table 3.11: Energy supply scenarios. Rainfed

Fruit hulls and seed shells	**Energy generation scheme**
Used as fertilizer	a11 Conventional oil boiler
	a12 Conventional coal boiler
	a21 Conventional NG boiler
	f11 Diesel genset with heat utilization block
	f12 NG genset with heat utilization block
	g NG CHP Microturbine
Used as fuel	h11 Anaerobic digester + CHP externally fired micro gas turbine
	h12 Integrated biomass gasifier + CHP gas engine genset

3.6.1 Basic configuration: conventional oil-, coal- or natural gas-fired boiler and imported electricity.

Models a11, a12 and a21 (Table 3.12) were considered as the basically simplest and required minimum investment configurations. Heat, required for the process in the form of steam, is generated by an on-site boiler. Electricity is purchased from the Indian National Grid.

Table 3.12: Basic configuration

Models:	
Oil boiler	a11
Coal boiler	a12
NG boiler	a21

3.6.2 Optimized fossil fuelled plant: combined heat and power (CHP)

Table 3.13: Optimized fossil fuelled plant

Models:	
Diesel genset with heat utilization block (HUB)	f11
NG genset with heat utilization block (HUB)	f12
NG CHP Microturbine	g

Gas, diesel and dual-fuel (DF) powered reciprocating engines are all used in cogeneration plants (Table 3.13). However, gas engines are generally preferred due to considerably lower exhaust emissions, good performance with CHP applications, and high efficiency of fuel utilization. Gas engines also produce nearly none particulates, so in CHP applications, exhaust heat boilers and HRSGs are not sooted up. Sooting can compromise plant termal efficiency and be a significant maintenance problem when diesel (heavy fuel oil) engines are utilized (Hunt: 2009).

Medium-speed diesel and gas reciprocating engines can achieve electrical efficiency of up to 47% for engines larger than 3 MWe. However, the utilization factor for a CHP plant might be only 50-60% as exhaust heat might not always be required. Also, generators driven by large reciprocating engines can reach a net fuel efficiency for electricity generations equal or more than 44% simple cycle, and 80-90% for CHP, depending on temperature of the heat used (approximately 38% of fuel energy should preferably used for district heating or industrial processes) (Ibid.).

Cummins Spark-Ignited Generator Set, Model GGHH equipped with Ford Heavy-Duty - Rugged 4-cycle industrial spark-ignited engine WSG-1068 has been used as a Natural Gas genset for energy (electricity and heat) supply estimations for the small-scale (plant capacity: 10.0 t of *Jatropha* oilseed per day, ~1,000.0 t of biodiesel per annum) biodiesel plant in Rainfed I and Rainfed II scenarios in Model f12. Technical characteristics for Cummins GGHH genset presented at the Table 3.14.

Table 3.14: Technical characteristics for Cummins Spark-Ignited Generator Set. Model GGHH. Base engine: Ford WSG-1068, Turbocharged[1)]

Power	MWe	0.105
Net thermal output	MWth	0.163
Operating hours	khr/a	8
Power production	GWhe/a	0.84
	TJe/a	3.0
Hot water (70^{o}C)	TJ/a	4.69
NG consumption	TJ/a	10.08
Microturbine elec. efficiency		30%
Microturbine total efficiency		78%
Elec/heat ratio		0.64

Notes:
a) Standard Fuel: Natural Gas or Propane[1)];
b) Efficiency: US DOE Advanced Reciprocating Engine Systems (ARES) programme Original equipment manufacturers (OEMs) Waukesha, Caterpillar and Cummins: thermal ~45-47%, 2010 target is 50%[2)];
c) In case of biogas usage in a gas engine, installed at the biogas plant with 500 kWe - electrical efficiency of 37.5%, thermal efficiency of 42.5%, and methane loses of 0.5%[3)]

Sources:
1) www.cummins.com;
2) COSPP: January-February 2007;
3) COSPP: July-August 2009

Volvo Penta Genset equipped with TD720GE engine has been used as a Diesel genset for energy (electricity and heat) supply estimations for the small-scale (plant capacity: 10.0 t of Jatropha oilseed per day, ~1,000.0 t of biodiesel per annum) biodiesel plant in Rainfed I and Rainfed II scenarios in Model f11. Technical characteristics for Volvo Penta Genset presented at the Table 3.15.

Table 3.15: Technical characteristics for Volvo Penta Genset. Base engine: TD720GE

Power	MWe	0.117
Operating hours	khr/a	8
Power production	GWhe/a	0.94
	TJe/a	3.4
Hot water after HUB	TJ/a	4.09
Diesel consumption	TJ/a	8.46
Genset elec. efficiency		40%
Genset total efficiency		84%
Elec/heat ratio		0.82

Note: Fuel: diesel with caloric value 42.7 GJ/t and a density of 0.84 kg/liter

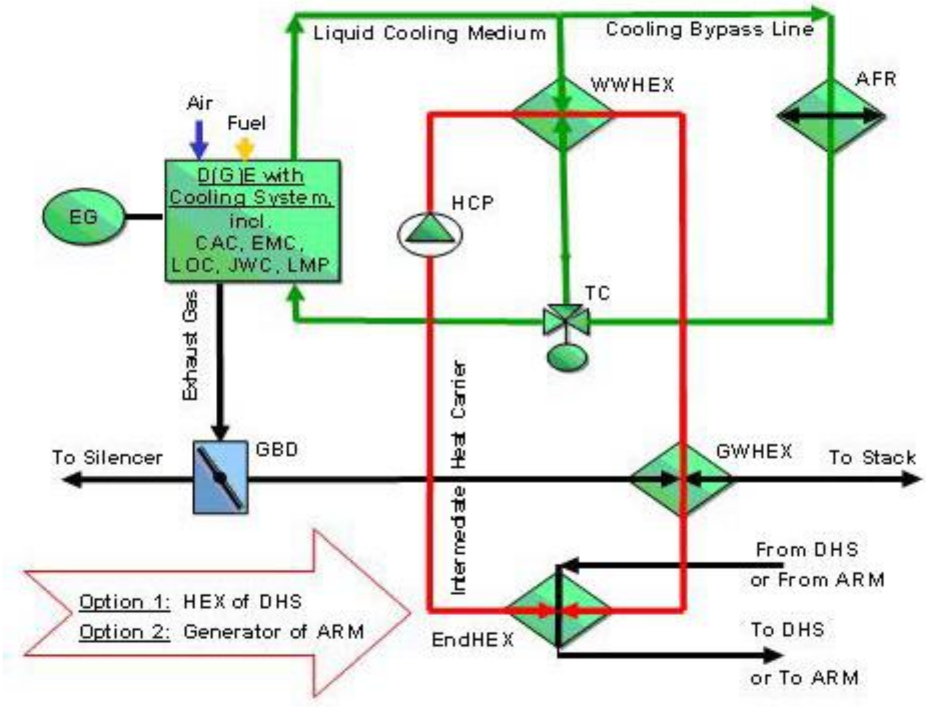
Source: www.volvopenta.com

A Heat Transfer System (HTS) allows utilization of the waste heat of the gas and diesel engines through heating the intermediate liquid heat carrier up to 95-98°C. In the cogeneration plants this intermediate carrier is used for production of hot water in the end heat exchanger (EndHEX) of district heating system (DHS), whereas in the trigeneration plants it is used as heating medium in the generator of absorption refrigerating machine (ARM).

The HTS described above is the main part of the Heat Utilization Blocks (HUB), which also contains system of control, instrumentation, protection and indication, and can be installed using the special supporting structures inside of cogeneration and trigeneration plants or inside of the transportable containers.

A typical scheme of the HTS for a reciprocating diesel or gas engine of small-to-medium size is presented in Figure 3.4. Usually such a diesel (DE) or gas engine (GE) is delivered together with the electric generator (EG) and equipped with the cooling system, consisting of: combustion air cooler (CAC) - for engines with enhanced turbocharging pressure, exhaust manifold cooler (EMC), lube oil cooler (LOC), jacket water cooler (JWC), as well as of liquid cooling medium pump (LMP), providing circulation of cooling medium between the mentioned coolers and air fan radiator (AFR). In the regime of diesel engine or gas engine operation without heat recovery or with a partial use of this heat, radiator provides dissipation of waste heat from the full or a partial stream of cooling medium respectively into surrounding. At the same time the exhaust gas is removed to atmosphere through a silencer.

Figure 3.4: The Heat Transfer System (HTS) for a reciprocating diesel or gas engine



Source: MEEC: 2007. Available at: http://meec.kangu.ru/service/epc_services_3.html

The HTS consists of of water-to-water heat exchanger (WWHEX) installed parallel to the AFR and equipped with temperature controller (TC), gas-to-water heat exchanger (GWHEX) installed in the HTS downstream of the WWHEX, exhaust gas bypass damper (GBD) providing release of exhaust gas from the diesel engine or gas engine through the GWHEX to stack or to silencer, and electric motor-driven heat carrier pump (HCP) providing circulation of the intermediate heat carrier through the mentioned heat exchangers of the Heat Transfer System (HTS) to and from the end heat exchanger (EndHEX). In the most cases the existing heat transfer equipment of the boiler house as the EndHEX is utilised. Optionally, the special heat exchanger (HEX) for district heating system or supply a generator of the ARM with intermediate heat carrier as its heating medium could be manufactures and installed as well (Sinatov: pers. comm.).

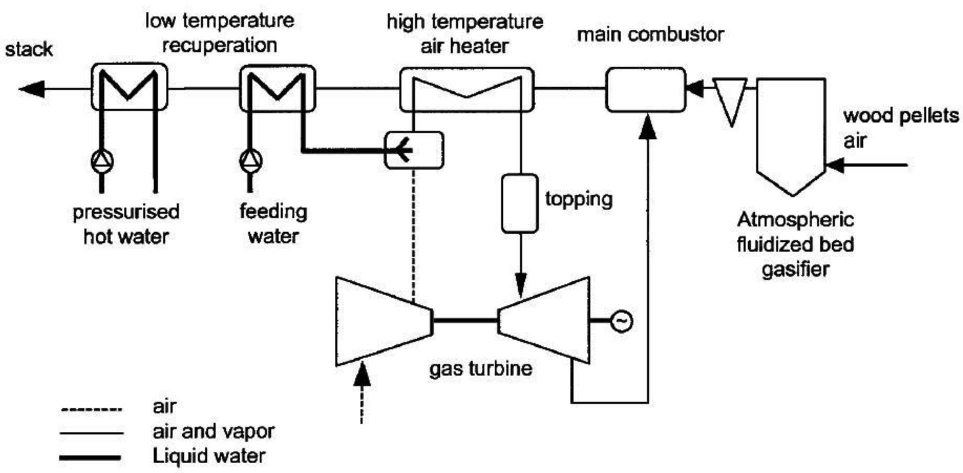
3.6.3 Combined Heat and Power (CHP) plant fuelled by biomass

Table 3.16: CHP fuelled by biomass

Models:	
Anaerobic digester + CHP externally fired micro gas turbine	h11
Integrated biomass gasifier + CHP gas engine genset	h12

The externally fired micro gas turbine (EFmGT) process and plant layout presented at Figures 3.5 and 3.6. EFmGT (or in another terms IFGT - Indirectly-fired microturbine) is based on a gas turbine cycle, where the traditional direct combustion is replaced with a heat exchanger that heats up the working media, usually air (Savola, *et. al.*: no date, Bram, *et. al.*: 2004, Ferreira & Pilidis: 2001, Kautz & Hansen: no date).

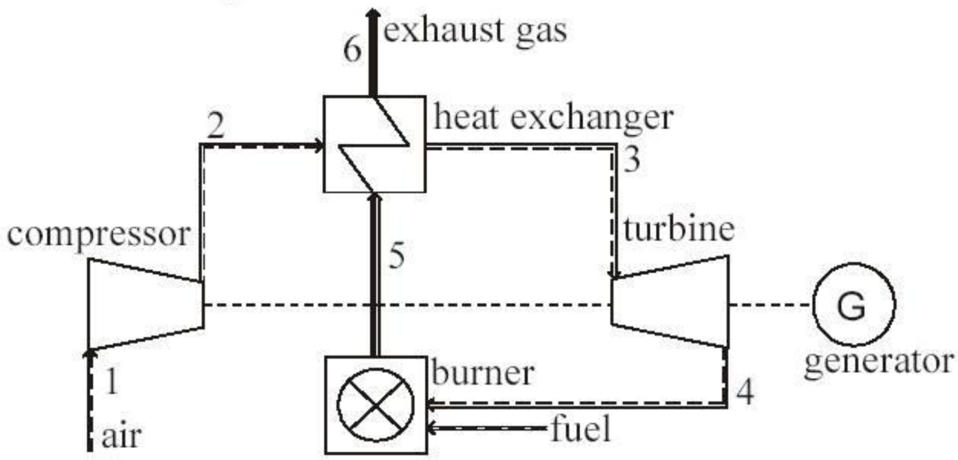
Figure 3.5: The externally fired micro gas turbine (EFmGT) plant layout[a)]



Note: The IFGT demonstration plant at the Vrija Univeriteit in Brussels

Sources:
1) Bram, *et. al.*: 2004;
2) Savola, *et. al.*: no date

Figure 3.6: The externally fired gas turbine process



Source: Kautz & Hansen: no date

ABB/Volvo Turbec T100 micro gas turbine design data and technical characteristics (Tables 3.17 & 3.18) has been used for energy (electricity and heat) supply estimations for the small-scale biodiesel plant in Rainfed I and Rainfed II scenarios in Models g and h11.

Table 3.17: Design data for Turbec T100 micro gas turbine (ABB/Volvo)

Net electric output	100	kW
Thermal power input	333	kJ/s
Turbine power	281.89	kW
Compressor power	158.97	kW
Net electric efficiency, ISO	30.0	
Fuel type	Natural gas	
Exhaust gas temperature	650	°C
Air temperature compressor outlet	214	°C
Gas temperature turbine inlet	950	°C
Gas temperature after recuperator	270	°C
Mass flow air	0.7833	kg/s
Mass flow natural gas	0.0067	kg/s
Mass flow exhaust gas	0.79	kg/s
Pressure ratio	4,5	
Efficiency compressor	0.768	
Efficiency turbine	0.8261	
Heat exchanger area in the recuperator	164	m^2

Note: The T100 unit includes a heat recovery system for hot water production

Source: Kautz & Hansen (no date).

Table 3.18: Technical characteristics for Microturbine Turbec T100 CHP system

Power	MWe	0.105	
Net thermal output	MWth	0.163	
Operating hours	khr/a	8	
Power production	GWhe/a	0.84	
	TJe/a	3.0	
Hot water (70°C)1)	TJ/a	4.69	
NG consumption	TJ/a	10.08	350 KW (1,194,111 Btu/hr) - www.turbec.com
Microturbine elec. efficiency		30%	
Microturbine total efficiency		78%	www.turbec.com
Elec/heat ratio		0.64	0.64 - www.turbec.com; 0.62 - Energy Nexus Group. 2002

Notes:
a) The T100 unit includes a heat recovery system for hot water production:
1) 163 F (77.7°C) - Energy Nexus Group;
180-220 F (82.2-104.4°C) - www.energysolutionscenter.org;

2) 167 kW (570,000 Btu/hr) - www.turbec.com;
163 kW (0.555 MMBtu/hr) - Energy Nexus Group. 2002

Sources:
1) Kautz & Hansen (no date). The Externally Fired Gas Turbine (EFGT Cycle) and Simulation of Key Components;
2) www.turbec.com;
3) EcoPoly Best Practice Sheet "OMES". DONG Energy. Gentofte: Denmark. OMES. 2007;
4) Energy Solutions Center Inc. (no date). Microturbine CHP Systems. Washington, D.C.
5) Energy Nexus Group. (March 2002). Technology Characterization: Microturbines, Virginia: USA;
6) Ferreira & Pilidis: 2001

Quite staggering is the emergence of renewable CHP facilities. Novel models of used in CHP applications reciprocating engines can burn biofuels. Thus, in recently designed Belgian Greenpower-owned CHP project a 9.0 MW Wärtsilä 20V32 engine, equipped also with selective catalytic reduction (SCR), will be the first to burn crude Jatropha oil (Hunt: 2009). Recently established in California the Self-Generation Incentive Program (SGIP), administred by the California Public Utilities Program (CPUP), already represents about 60 facilities, approximately 30 MW of the CHP capacity, powered by renewable fuel sources, such as biogas (COSPP: March-April 2009). Besides, a UK-based enterprise Dalkia, announced a new eco2synergy service, which offers to customers an installation of CHP units range from 30 kW to 3 MW capable to operate using biogas, biomass, bio-diesel, landfill gas and conventional fuels (Ibid.).

3.7 Agricultural input data and assumptions

Rigorous review of the literature and personal communications with government officials, entrepreneurs, researchers and farmers completed during research trip to India in November 2005 - March 2006 highlighted the potential ranges of input data for the agricultural model that may exist under both Irrigated and Rainfed conditions.

Jatropha curcas yields assumptions

The following yields for *Jatropha curcas* oilseeds were used for the LCA model of feedstock cultivation (agricultural) scenarios: a) Irrigated scenario - 5.2 t/ha for mature trees (6-30 years) (Neelakantan: pers. comm., GOI: 2004, Francis, *et. al.*: 2005, Friends of Earth: 2008); b) Rainfed scenario - 1.0 to 1.5 t/ha in the third and fourth years (NABARD: 2005, ICORE: 2006), and 3.45 t/ha - at mature stage (6-30 years) (Openshaw: 2000) (Table 3.19).

Table 3.19: *Jatropha* oilseed yields

Year	Jatropha oilseed yield			
	Irrigated		Rainfed	
	t/ha	%	t/ha	%
6-30	5.2	100%	3.45	100%
5	4.1	79%	2.75	73%
4	3.25	63%	2.0	53%
3	2.5	48%	1.3	35%
2	1.2	23%	0.5	13%

Note: Reported *Jatropha curcas* oilseed yields also available at the Table 2.12

Sources:
1) Openshaw: 2000;
2) GOI: 2004;
3) Francis, *et. al.*: 2005;
4) Friends of Earth: 2008;
5) NABARD: 2005;
6) Neelakantan: pers. comm.;
7) Paramathma: pers. comm.

In Irrigated scenario the capsulate yield of 7.5 t/ha of *Jatropha* oilseed collected of which 5.2 t/ha of oilseed or 4.13 t/ha of kernel supplied to the oil extraction and trans/esterification plant. In addition, 2.33 tonnes of fruits hulls (husk and coat), 1.1 tonnes seed shells and 4.0 tonnes of dry pruning material produced per hectare (Tables 3.19 & 3.27).

In Rainfed scenario the capsulate yield of 5.3 t/ha of *Jatropha* fruits collected of which 3.45 t/ha of oilseed or 2.9 t/ha of kernel supplied to the oil extraction and trans/esterification plant. In addition, 1.9 tonnes of fruits hulls (husk and coat), 0.5 tonnes seed shells and 0.8 tonnes of dry pruning material produced per hectare (Tables 3.19 & 3.28).

Hydrocarbon energy requirements assumptions

For the Irrigated scenario, the 6 kW electric waterpump powered by the diesel-generator is considered for the *Jatropha* plantation irrigation. It is assumed that this waterpump has 84% efficiency and consumed 0.42 l of diesel per hour for 3 hours per day, 100 days per hectare per annum (Bhatt: pers. comm.). Therefore, the total annual diesel (LHV 42.65 GJ/t) requirement for plantation calculated as 4.51 GJ/ha/yr (Table 3.26).

In both Irrigated and Rainfed cases the *Jatropha* oilseeds are assumed to be sundried with no additional energy inputs. Harvesting, handling and storage of oilseeds in conditions of Indian cheap and abundant labour force will not required additional hydrocarbon energy carriers or electricity inputs.

Fertilizers applications assumptions

In literature the values stated for the amount of fertilizers required for the *Jatropha curcas* plantations are vary in a wide range. *Jatropha curcas* fertilizers requirements are presented in Table 3.35.

Based on data collected during field work in India and secondary sources (GOI: 2003; Vinayak & Kanwarjit: 1991, Heller: 1996; Lele: no date; Lele: 2004; Openshaw: 2000; Rao & Korwar: 2003; Euler & Gorriz: 2004; Farooqui and Srinivasappa: 2004; Paramathma: 2004; Labland Biotechs Pvt. Ltd.: pers. comm., Murphy: pers. comm.) the following scenario for fertilizers applications was considered for both Irrigated and Rainfed scenarios for *Jatropha curcas* oilseed cultivation (agricultural) model as a most energy intensive and least favorable in terms of GHG emissions:

a) Organic fertilizers:
Top dressing: 3,430 kg/ha/yr of *Jatropha* fruits hulls and shells started from 5th year of plantation - for Irrigated plantation. Spacing 3x3 m. 1,111 trees/ha, and 2,400 kg/ha/yr of *Jatropha* fruits hulls and shells started from 5th year of plantation - for Rainfed plantation. Spacing 2x2 m. 2,500 trees/ha.

b) Chemical fertilizers:
Basal dressing (Chativerdi: pers. comm.): Di-ammonium phosphate (DAP) - 15 g per plant; and NPK 17:17:17 - 15 g per plant.

Top dressing (Faroqui & Srinivasappa: 2004): Single Super Phosphate - 150 kg/ha, applied on biannual basis with 10% increase from year 4 onwards; and NPK 40:100:40 on biannual basis. As a result, phosphorous application applied as much as 254 kg/ha/yr in years 1-3, and 259.4 kg/ha/yr from year 4 onwards.

Energy factors for fertilizers are presented in Table 3.38 and GHG emission factors for the same - in Table 3.39 and Appendix III.

Biomass utilization assumptions

There are two cases assumed: a) the fruit hulls and seed shells used as fertilizer (green manure) or b) the fruit hulls and seed shells used as combustibles. In earlier case the crop residues are ploughed in and as a result reduce the demand of synthetic fertilizer, and in latest case it is assumed that all by products produced after extraction of oil is used as combustibles for energy production.

Nitrogen returned to the soil by *Jatropha* leaf fall calculated based on the leaf fall volume of 2,431 kg/ha/yr, nitrogen percentage of 0.81, nitrogen returned - 19 kg/ha/yr (Rao & Korwar: 2003), and LHV: 14.3 GJ/t (Nivitchanyong: 2007) as 1,230.2 kgN/ha per Life Cycle for Irrigated I and Irrigated II Scenarios 1,659.4 kgN/ha per Life Cycle for Rainfed I and Rainfed II Scenarios.

The inputs of N, P and K fertilizers are considerably larger when the fruits hulls and seed shells are used as a fertilizer (green manure) rather than used as combustibles as co-fuel for power plant, eventually resulting in 2.50 to 7.25 times increase in GHG emissions from agriculture.

Seeds and agrochemicals application assumptions

The recommendations for the fungicides and insecticides applications (Table 3.43) used for energy inputs and GHG emissions calculations discussed and agreed with Dr. Ashok K. Raina of the Phytotron Research Center, Yehalanka, Karnataka and Mr. Lakshman of the Renu Lakshmi Agro Industries (India) Ltd., Coimbatore, Tamil Nadu.

Jatropha curcas agrochemicals requirements are presented in Table 3.35. Energy factors for seeds and pesticides are presented in Table 3.38 and GHG emission factors for the same - in Table 3.39 and Appendix III.

Results of the agricultural model

The results for the agricultural model summarized in Tables 4.1 "Cumulative emissions of nitrogen (N_2O_N) and total farming emissions from perennial *Jatropha curcas* under three different irrigation and fertilization regimes", and Tables 4.6, 4.7 & 4.8 "*Jatropha* oilseed production and supply. Irrigated/Rainfed scenarios. Best".

3.8 By-products

At present, *Jatropha curcas* is still only a recently established agricultural crop with no well documented uses for by-products. There is a large areas of uncertainties surrounding cultivation of *Jatropha* and associated biodiesel production. This is because of the vast number of co-products, by-products and waste products generated on this pathway of biodiesel production. In addition to *Jatropha* oilseeds harvested from shrubs, fruit hulls, seed shells, and pruning material are also produced. Though these hulls, shells and pruning material might be treated as a waste product, they could be used in as organic fertilizer or as combustibles, replacing energy derived from fossil fuels. During the extraction of crude *Jatropha* oil from sun dried oilseed, *Jatropha* press-cake is produced.

This is another marketable by-product which might be used as organic fertilizer (green manure), be fermented in a biogas plant and subsequently used in heat and electricity generation, or be directly combusted for energy production. Therefore, the crude *Jatropha* oil and the press-cake have two different and distinct uses with some shared properties. Crude glycerine is also obtained during trans/esterification of strait vegetable oils, e.g. *Jatropha* oil. Potassium phosphate (monobasic: KH_2PO_4; dibasic: KH_2PO_4; and tribasic: K_3PO_4) derives as a by-product of the crude glycerine reaction with phosphoric acid followed by its purification to the pharma grade glycerine.

Currently, after chemical reaction, it washed out with wastewater, as process of its separation from wastewater is still complicated and expensive. However, if recovered, potassium phosphate could be used as a valuable chemical fertilizer, and be credited towards total energy balance and GHG emissions balance of the biodiesel production. Free fatty acids (FFA) can be burned as a process heat source, sold as ingredient for animal feed, or composted.

In life cycle assessment, the term "allocation" means distribution of environmental loads (Sonneman, *et. al.*: 2003). The LCA Goal and Scope Definition and Inventory Analysis (ISO 14041: 1998) suggests three methods for dealing with allocation:

- ❒ If possible, allocation should be avoided by disaggregating the given process into different sub-processes or by system expansion.

As ISO standard does not stipulate methods of system expansion, Jungbluth and Frischknecht (2006) identified two possible methods: a) subtraction of avoided burdens for the co-products which are not of interest for the study at hand (avoided burden approach) or b) expansion of the functional unit in order to include more benefits of the system under investigation into the analysis (basket of benefits approach).

- ❒ If it is not possible to avoid allocation problem must be solved by using system modeling which reflects the underlying physical relationships among the functional units (i.e. partitioning of inputs and outputs);

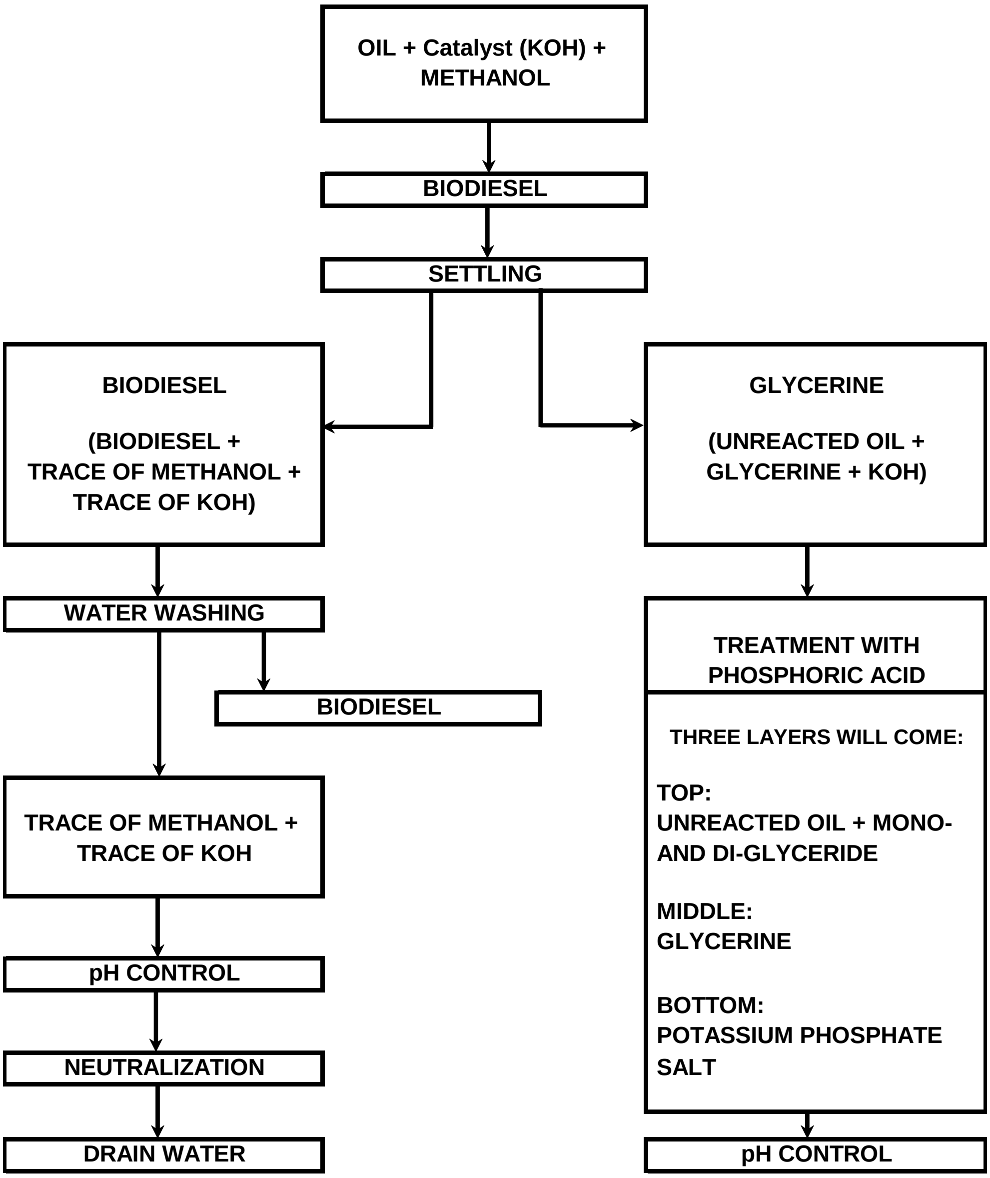
- Where physical relationships cannot be established, other relationships, including economic value of the functional outputs, can be used (Azapagic: 2006, Jungbluth & Frischknecht: 2006, Menichetti & Otto: 2009).

The accurate selection of the allocation method is critical, as method applied is generally influence results of LCA study. In case when different allocation methods might be conceded, an influence of the different allocation methods on result should be established by sensitivity analysis. At present, there is not a single method considered of performing this allocation (Woods, *et. al.*: 2005). As such, allocation by substitution recommended by LowCVP studies (2004) and Woods, *et. al.* (2005) is used in this study. In this method, the primary product is assigned the total GHG emissions minus credits equal to the GHG emissions avoided as a result of co-product displacement of alternative products elsewhere (Ibid.).

In terms of allocation, soya meal or rape meal were considered as a substitute for press-cake but this approach could be challenged by the possible use of both soya beans and rape seeds as a source of biodiesel. Finally, crude glycerine is also obtained during trans/esterification of strait vegetable oils, e.g. *Jatropha* oil. About 10-13 wt% of vegetable oil is converted into glycerol during the transesterification process. At present, the glycerine from esterification plants is exported as product and displaces conventionally produced glycerine. Utilization of crude glycerine as a co-product of biodiesel production and allocation will be discussed a bit further.

Flowchart 3.7 demonstrates allocation of co- and by-products resulted from biodiesel production by esterification of the fatty acids or transesterification of the triglycerides using methanol.

Flowchart 3.7: Biodiesel production pathway and by-products allocations



3.8.1 Glycerine

Glycerine, which is a major by-product of the reaction, utilized in worldwide production of 0.7-0.8 million tonnes for pharmaceutical, cosmetic, food and plastics (Lee, *et. al.*: 2006). About 10-13 wt% of vegetable oil is converted into glycerol during the transesterification process. At present, the glycerine from esterification plants is exported as product and displaces conventionally produced glycerine. The resulting raw glycerol from this esterification process is contaminated with alcohols and inorganic salts. Currently, biodiesel producers are purifying the glycerol so that it is acceptable as either food-grade or pharmaceutical grade. As large quantities of biodiesel are produced an excess of glycerine and related marketing issues become a problem to solve. In this case the glycerine should be used as fuel or part of animal diet, and therefore the credit for by-product glycerine would be different. As a result the total GHG emissions and energy balance of biodiesel production and supply is being different.

Nowadays novel steam gasification and aqueous-phase reforming (APR) energy technologies emerged enabling production of hydrogen or syn gas from glycerol. Experiments on steam gasification of crude glycerol were conducted at the University of Saskatchewan, Canada by Dr. Thiruchitrambalam Valliyappan (2004). This steam gasification can be performed after distilling methanol from the crude because methanol can be reused for the transesterification process. During these experiments glycerine was completely converted to gas which was mostly syn gas of 93 mol% and a small amount of char when 50:50 weight ratio of steam to glycerol was used with the quartz packing of particle diameter of 0.21-0.35 mm at 800^{o}C. The addition of steam enhanced the gasification of glycerine process to produce large volume of gas and hydrogen yield.

Another advanced usage of glycerine appears as generating hydrogen from biomass derived glycerol utilizing Virent Energy System's aqueous-phase reforming (APR) process. Virent has developed the novel APR process and has shown that it is effective for generating hydrogen from aqueous solutions of glycerol. The key breakthrough of the APR process is hydrogen can be generated from oxygenated hydrocarbons such as glucose, sorbitol, glycerol, and ethylene glycol via liquid-phase reforming (Cortright, *et. al.*: 2002 cited by Virent Energy System's: no date). The resulting hydrogen can be purified and utilized as a renewable chemical reagent necessary to produce ammonia, methanol and hydrogenated food oils as well as a fuel for current internal combustion engines and future hydrogen fuel cells.

As above mentioned technological innovations will be reaching commercial scale of production - the commercial value of the crude glycerol might face a drastic boost.

However, evaluation of glycerol to hydrogen and syn gas pathways, credits for by-product glycerine and consequent adjustment to the total GHG emissions and energy balance of biodiesel supply is far beyond of this study.

3.8.2 Jatropha fruit husks and oilseed shells

The impact of utilization of *Jatropha* fruit husks and oilseed shells is covered by multifaceted approach. Primarily, this impact is reflected at the *Jatropha* oilseed production and supply calculations and presented for both Irrigated and Rainfed scenarios in Tables 4.2, 4.3 and 4.4. These results unambiguously demonstrate that in case of a use of the biomass by-products as a fertilizer (green manure), both Total primarily energy requirements and GHG emissions are significantly larger than in case of use them as co-fuel for power plant. Secondly, it is covered by Models d1, d2, and e in industrial scale biodiesel production plant (Irrigated I and Irrigated II scenarios) and Models h11 and h12 in small-scale biodiesel production plant (Rainfed I and Rainfed II scenarios). In Models a, b and c (Irrigated I and Irrigated II scenarios) and Models a, f11, f12 and g (Rainfed I and Rainfed II scenarios), fruit husks and oilseed shells is considered to be left in the field and ploughed back in, which leads to reduction in the amount of chemical fertilizers needed (LowCVP: 2004). Both husks and shells are not suitable as substrates in biogas digesters because of very low digestibility renounce (Becker & Makkar: 2008).

3.8.3 Pruning material

Similar to *Jatropha* fruit husks and oilseed shells, impact of the pruning material utilization as co-fuel for power plant for electricity and technological heat production is covered by Models d1, d2, and e in the biodiesel production plant in Irrigated I and Irrigated II scenarios and by Model h12 in Rainfed I and Rainfed II scenarios. In Models a, b, and c in Irrigated I and Irrigated II scenarios and Models a, f11, f12, h11 and g in Rainfed I and Rainfed II scenarios, utilization of pruning material is considered to be sold elsewhere as a valuable commodity (LowCVP: 2004).

For the biomass burning in the biomass boiler (Models d1 and d2) and used in the integrated biomass gasifier (Models e and h12), it is assumed that the quantity of biomass (*Jatropha* fruit hulls, *Jatropha* seed shells and dry pruning material) available for fuel is equal to the total biomass co-produced, with the *Jatropha* oilseeds converted into biodiesel. Therefore, 4.86 t of biomass is burnt per tonne of biodiesel produced in Irrigated scenario and 3.37 t of biomass per tonne of biodiesel produced in Rainfed scenario. It is also assumed that the biomass is transported by road in diesel-fuelled trucks, and average distance of 55 km (with ranges of 0-55 km one way for Rainfed scenario and 35-100 km one way for Irrigated scenario) from the plantation to the biodiesel plant (Balachandra: pers. comm.). It worth mentioning that a number of studies (Rajagopal.: 2007, Jodha: no date, and Negi, *et. al.*: 2006 cited by Nagar: no date) claim that *Jatropha curcas* yields insignificant amount of wood per tree. Also, *Jatropha* pruning material has a low density of 0.22-0.37 g/cm^3 (TERI: 2005), and its densification into pellets or cubes increases burning feedstock cost significantly adding 50-75% to initial cost of dry pruning material. Although the transport costs for pellets and cubes are lower that for bulk biomass, the cost of densification is far in excess of the cost savings (Alberici: 2007).

3.8.4 Jatropha press-cake

Two options of using press-cake were considered for this Life Cycle Assessment based on interviews and secondary sources. *Jatropha* oilseed production is leading to a rise of innovative uses for by-products such as the fermentation of press-cake to generate biogas. Instead of using *Jatropha* press-cake as an organic fertilizer (green manure), which appears to be the most common use, it can also be fermented in a biogas plant and subsequently used in energy generation. This application is considered in the current study in addition to the press-cake application as a green manure. As such, a number of different scenarios of press cake usage are possible. After extraction of the oil, the residual press-cake can be fermented in a biogas plant. For that purpose a co-fermentation process with liquid manure can be used, yielding biogas, which is converted to electrical energy and heat by small CHP plant (Gartner & Reinhardt: 2003).

Ghosh, *et. al*. (2007) says that *Jatropha curcas* press-cake, as an organic fertilizer application of 3.0 t/ha resulted in yield of 1.27 t_{seed}/ha (4x3 m spacing, 833 trees/ha; control 0.57 t_{seed}/ha) and 1.45 t_{seed}/ha (3x2 m spacing, 1,667 trees/ha; control 0.75 t_{seed}/ha) on poor soil. Openshaw (2000) says that 1.0 kg of seed cake is equivalent to 0.15 kg of N:P:K (40:20:10) chemical fertilizer.

NRCAF (Jhansi, Uttar Pradesh) researchers conducted principal component analysis (PCA) of 27 germaplasm of *Jatropha curcas* determined that major nutritional compounds such as acid detergent fibre (ADF), neutral detergent fible (NDF), crude protein (CP), lignin and hemicellulose content represent the nutritive value of *Jatropha curcas* (Kumar, *et. al.*: 2008). Furthermore, ICRISAT analysis of the cake of *Pongamia* and *Jatropha* indicated the presence of all the essential elements required for plant growth. It was particularly rich in nitrogen (4-6%) and sulphur (0.24-0.36) (ICRISAT: 2008. Activity 7.2.1.4). Properties of *Jatropha curcas* press-cake summarises in Table 3.20.

Table 3.20: Properties of press-cake as fertilizer

Parameters	Jatropha press-cake	Cow dung	Relation
N (%)	5.7-6.48	2	280-320 %
P_2O_5 (%)	2.6-3.1	1.5	170-200 %
K_2O (%)	0.9-1.0	2	43-50 %
CaO (%)	0.6-0.7	4	15-17 %
MgO (%)	1.26-1.34	1	126-134 %

Source: GTZ Jatropha Energy Project. October 1995

The presence of the aforementioned bio-degradable toxins, mainly phorbol esters, makes the fertilizing press-cake at the same time serve as biopesticide/insecticide and molluscicide (Francis, *et. al.*: 2005, Achten, *et. al.*: 2008). Although the phorbol esters decompose completely within 6 days it is advisable to check the absence of phorbol esters in the crops grown on *Jatropha* press-cake fertilized land, certainly crops for human consumption (Heller: 1996, Achten, *et. al.*: 2008).

ICRISAT (2008) conducted a pilot scale study to enrich and improve the availability of nutrients in deoiled press-cake by earthworms. The multiplication rate of earthworms in the heap at 28-30°C was quantified at the end of the composting period, which revealed it ranged from 157-218 in the combination of *Jatropha* deoiled cake with grass; 117-223 in *Jatropha* deoiled cake with millet husk. The period of 50-55 days of initial decomposition was found to be suitable for releasing earthworms for further composting (ICRISAT: 2008. Activity 7.2.1.5). The nutrient composition of vericompost reported by ICRISAT as the following: Organic carbon (OC) - 9.8-13.4%, Nitrogen (N) - 0.51-1.61%, Phosphorous (P) - 0.19-1.02%, Potassium (K) - 0.15-0.73%, Calcium (Ca) - 1.18-7.61%, Magnezium (Mg) - 0.093-0.568%, Sodium (Na) - 0.058-0.158%, Zink (Zn) - 0.0042-0.110%, Copper (Cu) - 0.0026-0.0048%, Iron (Fe) - 0.2050-1.3313, Manganeze (Mn) - 0.0105-0.2038% (World Bank: 2008).

The option of using *Jatropha* press-cake for energy generation might have a number of different scenarios. In the case of press-cake fermentation and usage in a biogas plant, the biogas might be converted into electrical energy and heat by a small combined heat and power plant. Three options might be considered and calculated in this case:

- Direct combustion of *Jatropha* press-cake substituting fuel oil;
- Biogas generation without heat utilization: surplus of heat is not used;
- Biogas generation, heat from fuel oil or biogas generation, heat from natural gas respectively (Gartner & Reinhardt: 2003).

In our case the option of *Jatropha* press-cake utilization for biogas production substituting fuel oil were adopted for further estimations.

The results of energy and GHG balances calculations presented as the Charts 3.1-3.4:

Chart 3.1: Best scenario. Energy balance (GJp/t$_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**

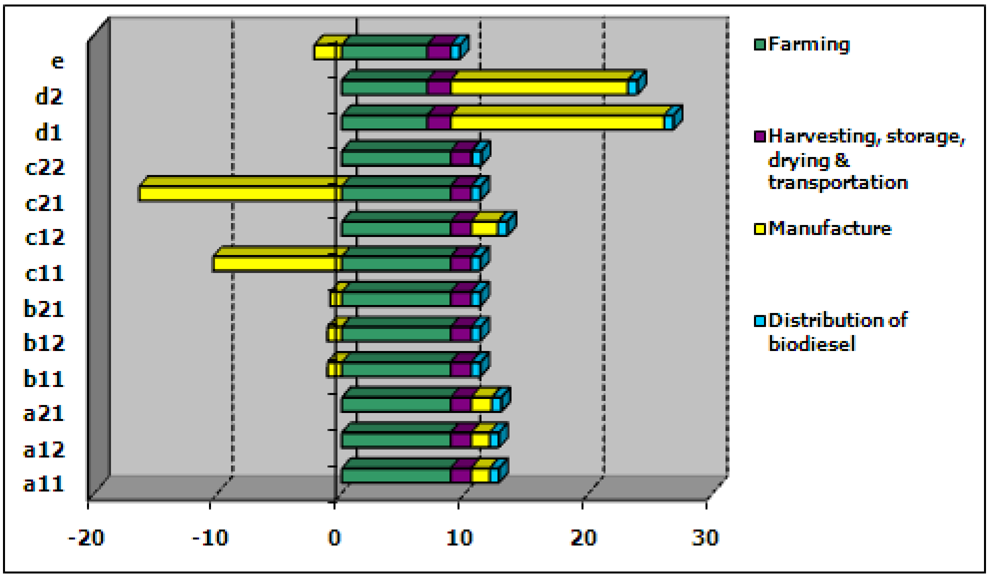


Chart 3.2: Best scenario. Energy balance (GJp/t$_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**

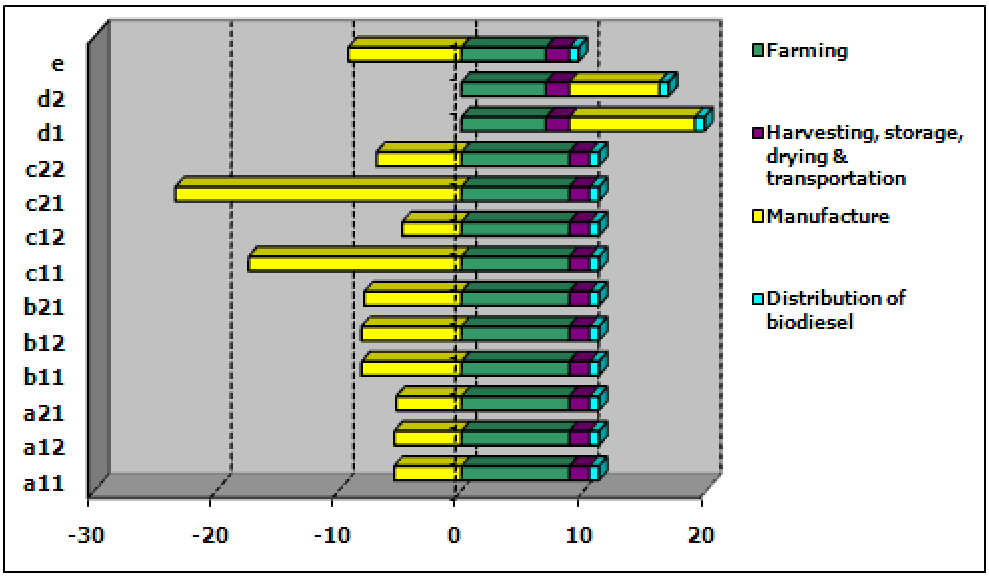


Chart 3.3: Best scenario. GHG balance (kgCO_2eq/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**

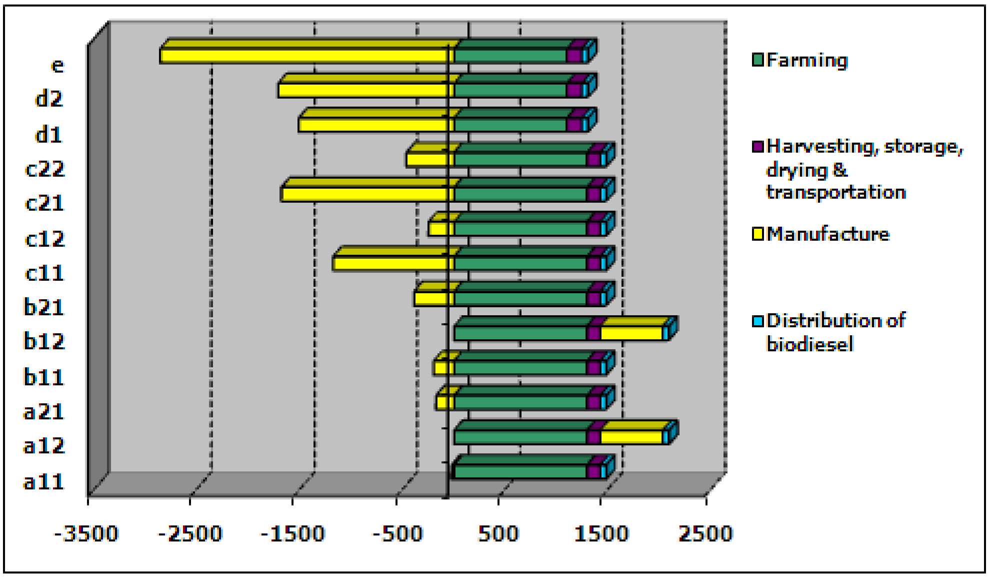
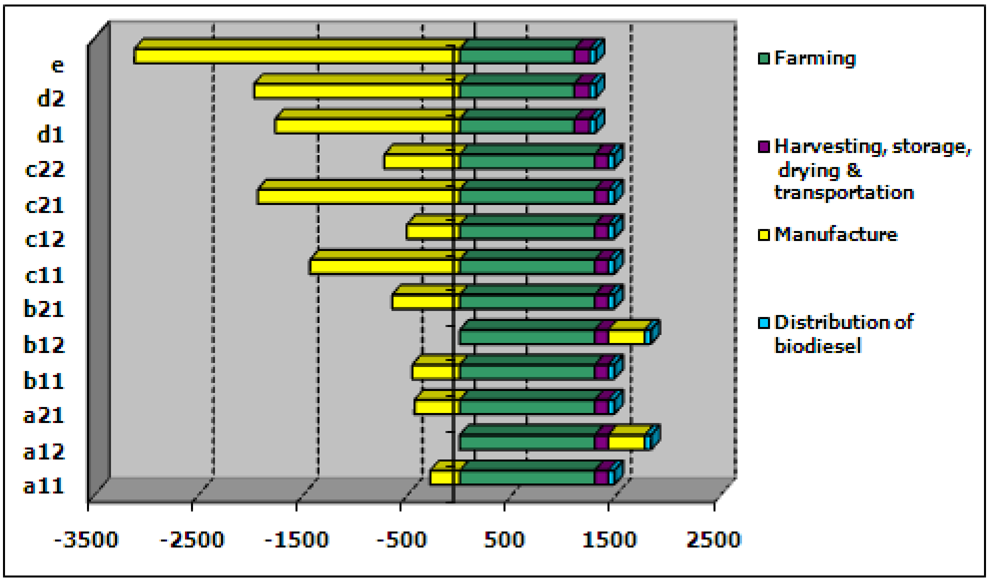


Chart 3.4: Best scenario. GHG balance (kgCO_2eq/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**



For the comparison "biogas generation versus usage as fertilizer" the following conclusion can be drawn. With regards to both energy and GHG balances, results of calculations for biogas generation from *Jatropha* press-cake is clearly to be preferred to its use as fertilizer (green manure). However, certain factors such as fermenting conditions and application technique could be variable and impacted by storage and applications of the residues after fermentation options.

3.8.5 Electricity

In all energy supply scenarios, with exception of basic configuration Models a11, a12 and a21 where electricity is imported from the Indian National Grid, electricity is produced by the transesterification plant. In these cases credits for energy and GHG emissions were calculated based on substitution of the Indian National Grid.

Based on this energy mix the following energy factor was estimated:

Table 3.21: Energy factor estimation for India

	Total production (MW)	%	Efficiency	Energy factor
Coal	67,688	55.4	0.295	16.33
Gas	12,172	10.0	0.3	2.99
Oil	1,202	1.0	0.3	0.29
Hydro	31,745	26.0	0.89	23.11
Nuclear	3,310	2.7	0.35	0.95
Renewable	6,158	5.0	0.1	0.50
Total	122,275	100.0		44.17
Energy factor				2.26

Sources:
1) Bhatt: pers. comm.;
2) GOI. Central Electricity Authority website. Visited 07 February 2006

3.8.6 Potassium phosphate

Biodiesel production with alkali catalyst produces a solution of alkaline glycerin as a waste product (Reaney, *et. al.*: 2006). The solution has sufficient catalyst and solvent capacity to convert oils, fatty acids, soaps and esters rich in linoleate moieties to conjugated linoleic acid by reacting the same in a crude alkaline glycerol solution. The recycled alkalie solution has sufficient reactivity to isomerize linoleate to conjugated linoleate moieties. The oils such as solin oil may be added to the alkaline glycerol solution directly. The conversion of solin oil to conjugated linoleate is achieved by mixing the linoleate containing material with the alkaline glycerol solution and increasing the temperature to above 170^{o}C. The reaction proceeds with the alkali present in the glycerol solution alone and additional alkali might be added to augment the reaction. Conjugated linoleic acid is liberated after the reaction from the solution by cooling the mixture to between 20 and 150^{o}C, and adding acid. The glycerol separated by this method is readily recovered and refined. When phosphoric acid is used the waste solution can be neutralized and used as a surface applied fertilizer (Ibid.). The benefits from sub-production of free chemical fertilizer will be even more significant for the farmers who involved in small-scale biodiesel production in remote Indian villages and to whom transportation cost and cost of chemical fertilizers per se are still insurmountable burden. At present, calculations related to Potassium Phosphate as a by-product of biodiesel production were excluded from these studies due to the absence of reliable data.

3.8.7 Free fatty acids (FFA)

Free fatty acids (FFA) can be burned as a process heat source, sold as ingredient for animal feed, or composted. FFA is produced at 0.004 kg FFA per litre of biodiesel (Dalai, *et. al*.: 2000 cited by Reaney, *et. al*.: 2006). The above cost is comparable to those found in various biodiesel plant models. For example, Richard Dixon (no date) uses a ratio of 5.5-7.0% of unprocessed used cooking oil for the 7.6 million liters per year biodiesel manufacturing plant. Dr. Michael Sills (pers. comm.) uses ratio of 4.0% of raw material used. It should be noted that both models were based on Compact Production Unit (CPU 2000) coupled with Vacuum Oil Purification Unit and Drying Plant with FFA Reduction (VOPUX 2000) (Dixon: no date), and Compact Production Unit (CPU 1000) (Sills: pers. comm.) manufactured by BDT Biodiesel Technologies, Vienna, Austria. At present, calculations related to free fatty acids as a by-product of biodiesel production were excluded from these studies due to the absence of reliable data.

3.9 Attribution of the by-product credits to the biodiesel

Following reasoning and recommendation of the LowCVP Fuels Working Group, WTW Sub-Group (2004) the substitution method has been adopted in this study for calculation of by-products credits as well. For this case it means that the energy and GHG emissions avoided by use of *Jatropha* fruit husk and oilseed shells, and press-cake are calculated by studying the materials they replace. The substitution options for use of the various by-products emerging during *Jatropha* oilseeds cultivation and biodiesel production were discussed in the Chapter 3.7: "By-products" earlier.

While the biodiesel is the major product for the pathway, credits arising from by-products can be simply factored into the overall energy/GHG balances of the biodiesel.

It is recommended by LowCVP (2004) as most commonly used in similar studies, with the figures being expressed per GJ or tonne of biodiesel produced. In fact, the real scenarios in case of oilseeds cultivation and biodeisel production is reality have much larger number and variations for utilization of the by-product components, compare to scenarios of ethanol production from wheat, which might bear additional either environmental lost or benefits. In these cases (Models b, c, d and e in Irrigated scenarios and Models f, g and h in Rainfed scenarios) the effect of by-product credit will have a crucial impact on final decision regarding technical and technological considerations for biodiesel production.

Besides, during field data collection in India in November 2005 - March 2006, the numerous requests made by myself and my assistants to visit more mature (3-4 years old) *Jatropha* plantations or to obtain technical and socio-economic data related to the biodiesel production in India were repeatedly declined. Therefore, no appropriate background results were documented and available for analysis.

3.10 Reference systems

3.10.1 Agriculture

In 2006 an estimated 14 million ha of land was used for the production of biofuels and by-products, approximately 1% of globally available arable land (IEA: 2006 cited by FAO: 2008). At the global level, according to IEA's "World Outlook 2006" projected growth in biofuel production to 2030 will require 35 million ha of land (2.5% of available arable land, approximately equal to the combined area of France and Spain) in the Reference Scenario, and 53 million ha of land (3.8% of available arable land) in the Alternative Policy Scenario (IEA: 2006). For comparison, a recent review of a range of economic estimates of future biofuels demand claims that even modest GHG regulations, combined with successful development of second generation biofuels, could lead to 1,500 million ha, equivalent to the current total global farmland, under biofuel crops by 2050 (Field, *et. al.*: 2007 cited by FAO: 2008).

Production of biodeisel from *Jatropha* oilseeds require also consideration regarding reference system, which are used to agree on credits for alternative activities that are avoided or displaced by the major process under survey and analysis. Mortimer, *et. al.* (2003) considered land as a typical aspect which attracts the use of reference system on Life Cycle Assessment.

The complexity derives from a combination of what crop is being displaced, where it will be grown instead, how it will be grown and what are the resulting GHG emissions, both from the land use and from any land use change (Kindred, *et. al.*: 2008).

A fundamental rule in selecting reference systems (and as it happens, allocation procedures) is that they should reflect the reality of situation which is being assessed (Mortimer: 2004, Kindred, *et. al.*: 2008).

In India, according to an estimate made by National Remote Sensing Agency in 1995, nearly 75.5 million ha is referred to as wasteland (Gundimeda: 2004). Of the total area of around 328.7 million ha, the extent of area under the threat of desertification is about 83.6 million hectares (Pacharuri: no date). Moreover, desertification, a potential and severe consequence of deforestation in arid, semi-arid, and dry sub-humid regions, can have untold ecological and social repercussions. The estimated area of abandoned agricultural land in India is 385-472 million ha, or 66-110% of the areas reported in previous preliminary assessments (Campbell, *et. al.*: 2008). Besides, considerable parts of India's degraded forest land (108,000 km^2), land with shrub vegetation (151,000 km^2) - together amounting to more than 8% of the total geographic area of India could serve for TBOS plantations. Other relevant categories of wastelands with potential for the cultivation of oil-bearing trees include 37,000 km^2 of shallow/moderately gullied or ravenous land and 9,000 km^2 of land with slight or moderate saline or alkaline values (MoRD: 2005 and Shankar: 2006 cited by Altenburg, *et. al.*: 2009). Even though, lately GOI reduced its appraisal of land reserves suitable for energy crops cultivation to 72,000 km^2, this potential is still mammoth (Shankar: 2006 cited by Altenburg, *et. al.*: 2009).

The Report of Committee on Development of Bio-fuels (GOI: 2003) estimates that about 134 lakh ha of land is suitable for *Jatropha* cultivation. Of this, 24 lakh ha land is fallow land and 20 lakh ha land is wasteland, together comprising ~33% of the land estimated to be suitable for *Jatropha* plantation.

Although the total geographic area of India is 328.73 million ha, the reporting area for land utilization estimated as 306.05 million ha. The total break-up is presented in Table 3.21.

Table 3.22: Land use in India

Land use	Area, million ha	Percentage
Total geographic area	328.73	
Reporting area for land utilization	306.05	100.0
Forests	69.02	22.6
Not available for cultivation	42.41	13.9
Permanent pasture and grazing land	11.04	3.6
Land under misc. tree crops and groves	3.62	1.2
Culturable wasteland	13.83	4.5
Fallow land and other than current fallows	10.11	3.3
Current fallows	14.80	4.8
Net area sown	141.23	46.1

Source: Friends of Earth: 2008

Government of India (2003) considers wasteland as a land which does not generate any revenue. As per NOVOD documents, the criteria for waste land is as follow:

- Soil depth: 1.5 to 2 ft (45 to 60 cm);
- Rainfall: 600 mm to 1500 mm;
- Soil type: all types of land including gullied, ravenous, upland with or without scrub, degraded lands under plantation, pastures, grazing lands, mining industrial waste land, hill slopes, fallow land, *etc* (PRAYAS: 2006).

Dr. Vandana Shiva says this approach was adopted with the advent of British rule in India, when traditional norms of community control of the commons began to erode through the implementation of policies of commercialization and privatization of common property resources (CPRs). The colonial concept of wastelands was not an assessment of the biological productivity of land but of its revenue generating capacity; "wasteland" which did not yield any revenue because it was uncultivated. Colonial policy did, however, also create the ecological category of 'wasted lands', which had lost their biological productivity because of societal and governmental action and inaction. These wasted lands lay in areas demarcated as reserved forests, those owned privately by individuals and used for agriculture, and common lands shared by communities for fuel and fodder supplies (Shiva: no date). Gundimeda (2005) cites evidence from several studies on common property resources in arid and semiarid regions of India that show: a) CPRs contribute between 12% and 25% of the poor household income; b) the poorer the households, the more important the contribution of CPRs; thus, a case study of a Gujarat village showed that the poor collect 70% of their fuel and 55% of their fodder requirements from CPRs; c) CPRs contribute to rural equity because they are accessed more by the poor than by the rich (Rajagopal: 2007). It is important that a distinction be made between CPRs and wasteland.

Government wasteland development policy was given a boost in 1985 when the National Wasteland Development Board was set up. Wasteland development generated conflicts because it concentrated on the afforestation of the revenue category of wastelands (i.e. commons) and threatened the customary rights of villagers to use forest produce (Shiva: no date). In India, for instance, the widespread planting of *Jatropha* on "wasteland" has been brought into question because of the heavy reliance of rural people on these lands for collecting fuelwood, food, fodder, timber and thatch (Rajagopal: 2007, FAO: 2008). The tenure status of such lands may also be complex, with governments asserting land ownership but exercising little control at local level, and local groups claiming resource rights based on local "customary" tenure systems that may lack legally enforceable status.

Large amounts of forest and non-forest land in India belong to the government. Only around 58% of India's total land areas for which records are available are private, cultivable land. All other land is considered forest land (22%), uncultivated revenue land (7%) or common land (20%) (Mearns: 1999 cited by Altenburg, *et. al.*: 2009). According to the National Action Programme to Combat Desertification (GOI: 2003), uncultivated land, excluding current fallows, covers areas classified under permanent pastures and grazing lands, the areas under miscellaneous tree crops and groves and culturable wasteland. About 11.8 million ha of land in the country is recorded as permanent pastures and grazing land. These lands are in community use. The states which have considerable proportions of areas under permanent pastures and grazing lands are Himachal Pradesh, Karnataka, Madhya Pradesh, Gujarat, Rajasthan, Tripura and the Union Territory of Dadra and Nagar Haveli.

Madhya Pradesh/Chhattisgarh account for a large percentage of land under pastures and grazing lands. The states with substantial proportions of areas under cultivable wastelands are Rajasthan, Orissa, Goa and the Union Territory of Daman and Diu. The states of Rajasthan, Madhya Pradesh/Chhattisgarh, Uttar Pradesh, Andhra Pradesh, and Orissa together account for more than three fourths of the nation's land resources under this category. In the case of revenue land in Chhattisgarh, land use and ownership are not so clearly defined. Villagers often use government-owned revenue land, simply because there is a need for it, and there is no clear-cut distinction between revenue and communal land.

In Bilaspur District in Chhattisgarh, for example, local tribal farmers were displaced by the Forest Department, which decided to cultivate *Jatropha* on the farmers' paddy land - land that was officially classified as forest land. The leasing of government land in Chhattisgarh will not concern forest land, but still, this case point to the implications such cultivation on government land could have on farmers without land titles (Shiva & Sankar: 2008 cited by Altenburg, *et. al*.: 2009).

There are no official estimates of common property resources in India. Commons provide a wide range of physical products (e.g. food, fuel and fodder), income and employment benefits (e.g. supplementary crops or livestock, drought period sustenance and offseason activities) for the rural poor and socially excluded groups (Friends of Earth: 2008; Shiva: no date; Mearns: 1999 cited by Altenburg, *et. al*.: 2009). *Jatropha* has several drawbacks in this context. First, the leaves of *Jatropha* are not suitable for livestock, i.e. not suitable as fodder. The situation with regard to the severe shortage of fodder for livestock has in fact been deemed the "other food crisis". In this context plantation of *Jatropha* on common lands, which are often grazing lands, is likely to worsen the fodder crisis. Second, *Jatropha* yields insignificant amount of wood per tree (Rajagopal: 2007, Jodha: no date and Negi, *et. al*.: 2006 cited by Nagar: no date).

FAO Climate Change, Bioenergy and Land Tenure Report (2008) noted that in southwest China, much of the "barren" land identified for *Jatropha* production is owned not by the state but by village collectives, with use rights granted to individual households. In Yunnan, for instance, a recent provincial survey found that 76% of forestland is owned by collectives, and the remaining 24% by the state. Most private investment in biofuels has so far been limited to state-owned land - with a few exceptions, including a four-year project begun in 2006 and involving cooperation with individual growers. But the ambitious targets for scaling up *Jatropha* production are likely to encounter problems of land availability, and will have to extend cultivation to collective lands (Weyerhaeuser, *et. al*.: 2007 cited by FAO: 2008).

FAO (2008) Report also exposed facts from Tanzania, where proposed or ongoing land allocations for sugar cane cultivation for ethanol (GRAIN: 2007; ABN: 2007) and *Jatropha* and oil palm cultivation for biodiesel. It was revealed that large-scale *Jatropha* cultivation caused significant negative impacts on land access for local groups. Thus, a multimillion dollar *Jatropha* spared by a British firm in the Kisarawe district of Tanzania has been reported to involve acquiring 9,000 ha of land and the clearing of 11 villages which, according to the 2002 population census, are home to 11,277 people (African Press Agency: 2007).

In South Africa, farmers' organisations and rural communities are opposing plans by the Eastern Cape government to plant 500,000 ha of communal land in the Transkei region with rapeseed for biofuel production. The land is currently used for communal grazing and vegetable gardens, but would be fenced off under the plans (African Centre for Biosafety: 2007 cited by FAO: 2008).

One of the most crucial things for energy crops cultivation is the availability of the land (Pacharuri: no date, Navdanya: 2008). Potential area for *Jatropha* cultivation in various Indian States could be found at Appendix II which presents estimated wasteland capacity in various Indian States. The target break-up which National Biodiesel Mission (GOI: 2003) has suggested achieving 13.4 million ha of *Jatropha* plantations considers only 2 million ha for plantation on wastelands. The remaining target has to be achieved through lands under Joint Forest Management (JFM) committees, agricultural hedges and bunds, agroforestry and other ways.

According to the Department of Land Resources (DoLR, GOI), about 63.9 million ha of land is laying waste in India mainly because they are unsuitable for cultivation in their present state. Besides, the Wasteland Atlas of India NRSA (2000) of the total wasteland of 63.9 million ha, cultivable wasteland amounts to 45 million ha. The 1:50,000 scale wasteland maps prepared from Landsat Thematic Mapper/IPS LISS 11/111 Data indicate various categories of wasteland as per the Table 3.22:

Table 3.23: Categories of wastelands in India

Category of wasteland	Area covered, km	% of total wasteland
Snow covered/glacial	55,788.49	9%
Barren rocky/sheet rock	64,584.77	10%
Sands-inland/coastal	50,021.65	8%
Land affected by salinity/alkalinity	20,477.38	3%
Gullied/or ravinous land	20,563.35	3%
Upland with or without scrub	194,014.29	30%
Waterlogged & marshy land	16,568.45	3%
Steep sloping area	7,656.29	1%
Shifting cultivation land	35,142.20	6%
Mining/ industrial wastelands	1,252.13	0%
Degraded pastures/ grazing land	25,978.91	4%
Under utilised/ degraded notified forest land	140,652.31	22%
Degraded land under plantation crop	5,828.09	1%
Total	**638,578.31**	**100%**

Sources:
1) http://dolr.nic.in/wasteland.htm;
2) Friends of Earth: 2008;
3) Rajagopal: 2007

From the above table, it can be safely said the following land categories: a) Land with or without scrub, b) Shifting cultivation area, c) Under utilized/degraded notified forest land, d) Degraded pasture/grazing land, and e) Degraded land under plantation crop contribute to the assumption of cultivable wasteland, a majority of whom comes under forest land amounting to at least 26 million hectares (Friends of Earth: 2008). Though, the German Development Institute studies reported large tracts of land in Karnataka that had been totally deforested decades ago and are still declared forest lands, although nothing is being done to reverse this situation (Altenburg, *et. al.*: 2009).

Though *Jatropha* plantation is being propagated as a tool of wasteland development, it is really to be seen whether targeted lands are wastelands indeed. Yet growing evidence raises doubts about the concept of "idle" land. In many cases, lands perceived to be "idle", "under-utilised", "marginal" or "abandoned" by government and large private operators provide a vital basis for the livelihoods of poorer and vulnerable groups, including through crop farming, herding and gathering of wild products (Dufey, *et. al.*: 2007 cited by FAO: 2008).

The lands being targeted for *Jatropha* cultivation are usually common land, pasturelands, mela lands, which are an integral part of rural community and their livelihood. Indigenous and local communities have been contesting the criteria of barren and degraded lands. First, many arid and semi-arid ecosystems have been classified as 'barren and degraded'. However, these areas are often inhabited and used by communities, who themselves do not consider them to be barren nor degraded. When these lands are categorized as such, this opens them up for *Jatropha* plantations, or other so-called land improvements that the community may or may not support. Secondly, more than often the driving force behind truly barren and degraded lands is bad land management practices by governments. Large amounts of forest lands in India, including lands cultivated by communities, have been leased out to mining companies for extraction of ores and minerals. Once the extraction is over, these lands have been laid bare without allowing for any kind of natural regeneration to take place. It will be in the best interest of ecosystems and biodiversity to allow these areas to regenerate with native species, not be further colonized by an invasive species known to crowd out other species and spread rapidly (Friends of Earth: 2008, Biofuelwatch and FERN: no date). Also, if that land goes into the hand of private sector, it will rather create a negative impact on rural livelihood as they will have no land to graze by their animals or to collect fuelwood from. "This diversion of commons for bio-fuel production is facilitating corporatisation of the commons in India," says Wilfred D. Costa, General Secretary of Indian Social Action Forum (Ibid.). Bio-diesel feedstock (e.g. *Jatropha curcas*) planting is being promoted through state agencies without seeing all the consequences such as blocking the migration routes of animals and encroaching upon herd-passing pathways (Planning Commission of India: 2006). Also, if agricultural land is targeted, it will be just shifting from one livelihood to another that again contradicts the aim of the *Jatropha* cultivation as a novel income generation tool for villagers. A growing body of evidence documents the negative impacts of large-scale commercial biofuel production for access to land, drawing on contexts as diverse as Africa (e.g. Tanzania, Mozambique, Swaziland), Latin America (e.g. Colombia, Brazil), and Asia (e.g. India, Indonesia, Papua New Guinea) (FAO: 2008, Burley & Griffiths: 2009).

During data collection in rural Andhra Pradesh (Nellore, Kadapa, Kadiri and Anandapur Districts), in January-February 2006 author repeatedly observed and documented the facts of converting food crop fields (e.g. maize) and cash crop fields (e.g. cotton) into *Jatropha* plantations. Burley and Griffiths (2009) reported disastrous impact on local farmers from conversion of irrigated cotton and food crops into *Jatropha* plantations in Swaziland. Also, small-scale *Jatropha* projects implemented in Mali have involved a shift from cotton to *Jatropha*, linked to falling cotton prices and rising perceived (monetary and non-monetary) values of *Jatropha* (FAO: 2008). Evidence of the rural farmers enriched by *Jatropha* production is, however, hard to find (Burley & Griffiths: 2009).

3.10.2 Petrol (Gasoline) and Diesel

The energy and GHG associated with production of conventional fuels including petrodiesel is required to calculate the impact of it's substitution with biodiesel and/or biodiesel blend (LowCVP: 2004). Petroleum refining, the process of converting crude oil into a variety of usable petroleum products, is a highly energy-intensive process (3.0 to 6.0 GJ per tonne of product (IEA: 1995), 2.0 to 7.0 GJ per tonne (Price, *et. al.*: 2000)) with energy consumption in refineries accounting for roughly 8% (12 EJ ($12*10^{18}$ J)) of global industrial energy consumption in 1990 (Price, *et. al.*: 2000).

At present, these data were calculated for Europe (JEC Study: 2003, Fehrenbach, *et. al.*: 2007) and likely for North America ($(S\&T)^2$ Consultants Inc.: 2009), but it was never done for any developing country, including India. As such, further consultations will be required to determine whether results of "the JRC joint WTW study, which was used CONCAWE's refinery model to calculate the marginal impact of reducing petrol or diesel production, for example in response to substitution by biofuels" in Europe (LowCVP: 2004) can be used for similar calculations for Indian case.

Before this conclusion will be reached, the following reference data (Tables 3.24 & 3.25) can be used:

Table 3.24: Reference data for conventional fuels

Petrol		Diesel		Reference
Energy GJ/GJf	GHG $kgCO_2eq/GJf$	Energy GJ/GJf	GHG $kgCO_2eq/GJf$	
-	6.5	-	8.6	Fehrenbach, *et. al.*: 2007
0.16	13.1	0.12	10.2	GM Euro Study: 2002 cited by LowCVP: 2004
0.14	12.5	0.16	14.2	JEC 2003 cited by LowCVP: 2004
0.1510	11.181 (HHV)			Total Energy Balance (1995) $(S\&T)^2$ Consultants Inc.: 2009
0.1716	12.162 (HHV)			Total Energy Balance. (2015 projection). $(S\&T)^2$ Consultants Inc.: 2009
0.1414	11.181 (HHV)			Fossil Energy Balance (1995) $(S\&T)^2$ Consultants Inc.: 2009
0.1612	12.162 (HHV)			Fossil Energy Balance. (2015 projection). $(S\&T)^2$ Consultants Inc.: 2009

Notes:
a) The Net Caloric Values (NCV) was calculated using the formula, NCV= GCV - 53 x H, where GCV is the Gross Caloric Value, and H - is the available hydrogen (MEF. GOI: 2004);
b) CO_2 emitted on fuel combustion is 75.1 $kgCO_2/GJ$ for India-specific diesel, 74.3 $kgCO_2/GJ$ for HSD India-specific diesel, 72.2 $kgCO_2/GJ$ for India-specific gasoline

Table 3.25: Primary energy intensities for petroleum refining

Indicator	China	OECD countries	Best practice
GJ/tonne (refined product)	3.5-5.0	2.9-5.0	1.3-3.8

Notes: Lower Heating Value (LHV):
a) Gasoline:
1) 43.2 GJ/t - GM-LBST: 2002;
2) 42.5 GJ/t - Althause, *et. al.*: 2004.
b) Petroleum diesel:
1) 42.8 GJ/t - Althause, *et. al.*: 2004;
2) 43.8 GJ/t - de Castro, Julio: 2007; Vyas: 2009.
c) Light fuel oil (LSHD):
1) 46.7 GJ/t - FAO: no date. Appendix 4;
2) 44.8184 GJ/t - Woods.: 2003.
3) 44.0-44.8 GJ/t - Iyer, *et. al.*: 2002;
4) 42.462 GJ/t - Dasappa: 2003;
5) 42.6 GJ/t - SimaPro 1.1, Althause, *et. al.*: 2004;
d) Heavy fuel oil: 42.6 GJ/t - Althause, *et. al.*: 2004.
e) C-Heavy fuel oil: 38.8 GJ/t - Mizuho Information & Research Institute, Inc.: 2004.
f) Fuel oil: 41.72 GJ/t - Sharma & Sharma: 1994 cited by Jungbluth: 1995.
g) Biodiesel:
1) 37.27 GJ/t - Mortimer, *et. al.*: 2003;
2) 32.9 MJ/l (~34 MJ/l) - Hill, *et. al.*: 2006, Liska & Cassman: 2008 cited by Connor & Hernanades: 2009.
h) Bioethanol: 21.1 MJ/l - Ibid.

Source: Price, *et. al.*: 2000

3.11 Consensus input data

3.11.1 Basic data

Input data for the *Jatropha curcas* cultivation (both Irrigated and Rainfed scenarios), biodiesel production technological processes, and fuel and energy supply options have been collected, discussed and agreed during field research visit to India in November 2005 - March 2006 conducted in kind cooperation with the Centre for Sustainable Technologies (CST), Indian Institute of Science (IISc), Bangalore, as well as by scrutinizing a considerable number of secondary sources.

Of the country's total 142 million ha cultivated land, 57 million ha, 40% of the total, is irrigated and the remaining 85 million ha is rainfed. Irrigation expansion has been one of the three input-related driving factors (the other two being seeds of modern High Yielding Varieties and fertilizer) in the Green Revolution process. Gross irrigated area went up by over 300%, from 22.6 million ha in 1950-1951 to 57 million ha (gross irrigated area over 75.1 million ha) in 2000-2001, rendering India as the country having the largest irrigated area in the world. Additional 27 million ha intended to be brought under irrigation by the end of the XI Five-years Plan (2007-2012). The GOI's Task Force on Micro-irrigation (2003) had reported that almost 70 million ha can be brought under drip and sprinkler irrigation. The target is to cover 14 million ha by 2012. The ultimate irrigation potential for the country has been estimated at ~140 million ha (59 million ha through major and medium irrigation projects, 17 million ha through minor irrigation schemes and 64 million ha through groundwater development). So far, the irrigation potential of nearly 100 million ha has already been created, but only ~86 million hectares is being utilized, thus leaving a gap of 14 million ha between created and utilized potential. Numerous scientific studies on horticultural crops have shown that irrigation regime has a significant positive impact on both yield and quality of fruits. As if in recognition of this fact, agronomic experiments and field trials on *Jatropha* at institutions like the Tamil Nadu Agricultural University are being conducted under irrigated conditions. The main constraints appeared for irrigation growth include: a) poor quality of the system supplied to the farmers, b) unreliable and spurious spares and non-availability of standard parts, c) ignorance of the users regarding the maintenance and operation of the system, and d) non-availability and uncertainty of power/energy supply (GOI: 2007).

For the Irrigated scenario, the 6 kW electric waterpump powered by the diesel-generator is considered for the *Jatropha* plantation irrigation. It is assumed that this waterpump has 84% efficiency and consumed 0.42 l of diesel per hour for 3 hours per day, 100 days per hectare per annum (Bhatt: pers. comm.). Therefore, the total annual diesel (LHV 42.65 GJ/t) requirement for plantation calculated as 4.51 GJ/ha/yr (Table 3.26).

Table 3.26: Diesel for irrigation. Irrigated scenario

Case		Basic Energy Inputs
B1. Jatropha trees planting		
Diesel for cultivation		
Consumption	GJ ha^{-1} a^{-1}	4.51
Credit for use of set-aside	GJ ha^{-1}	0.0
Total primary energy	GJp ha^{-1}	5.23
Total GHG emissions	$kgCO_2$ ha^{-1}	402.92

In Irrigated scenario the capsulate yield of 7.5 t/ha of *Jatropha* oilseed collected of which 5.2 t/ha of oilseed or 4.13 t/ha of kernel supplied to the oil extraction and trans/esterification plant. Overall, 1.52 t/ha of biodiesel can be produced, which corresponds to the 3.28 tonnes of oilseeds per tonne of biodiesel. In addition, 2.33 tonnes of fruits hulls (husk and coat), 1.1 tonnes seed shells and 4.0 tonnes of dry pruning material produced per hectare (Table 3.27).

Agro-ecologically and socio-economically, rainfed (rain-dependent) areas are very different from irrigated areas. Accounting for 60% of the country's cultivated acreage, their developmental complexities, challenges and potential notwithstanding, rainfed areas have suffered neglect in the past in having not received differentiated technological, institutional, infrastructural and investment support. Based on agro-ecologically and socio-economically differentiated integrated farming system approach, the Working Group on Natural Resources Management (2007) identified three categories of areas, namely, those receiving rainfall of less than 500 mm; those receiving 700-1,100 mm; and those receiving more than 1,100 mm per year. Thus, Kesava Rao, *et. al*. (ICRISAT: 2008. Activity 9.1.2.9) say that in Karnataka State watersheds in Dharwad and Haveri districts are under hot dry sub humid type, while those in the Tumkur taluk in Tumkur district, Chitradurga and Kolar districts fall under hot moist semi-arid type.

Table 3.27: Farming data. Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha)

	Yield t/ha	LHV GJ/t
Harvested Jatropha fruits (whole fresh fruit)		12.8
Whole fruit (dry) (whole nut)	7.5	21.5
Jatropha oilseed	5.2	25.5
Jatropha fruit hulls (husk, coat)	2.33	10.9
Jatropha seed shells	1.1	19.0
Kernel	4.13	29.8
Green prune material	10.0	8.2
Prune material (dry)	4.0	16.0
Leaves (dry)	2.78	14.3
Wood charcoal	2.5	29.02
Shell charcoal	0.84	26.3
Jatropha oil	1.6-2.5	38.5
Biodiesel	1.5238	37.27
	t/t biodiesel	
Jatropha oilseed	3.28	25.5
Jatropha oil	1.05	38.5
Hexane	0.0024	52.05
CH_3OH - Methanol	0.117	19.7
KOH - Potassium Hydroxide (High temperature catalyst)	0.0103	43.3
$NaOCH_3$, 30% in MeOH - Sodium Methylate (Low temperature catalyst)	0.021	12.62
H_2SO_4 - Sulphuric Acid (mineral acid)	0.006	-2.43
H_3PO_4 - Phosphoric Acid	0.0029	6.87
N_2 - Gaseous Nitrogen	0.018	1.2
K_2SO_4 - Potassium Sulphate	0.011	5.0
Water for the process (circulation)	55.0	
Press-cake (seed-cake)	2.23	25.1
Crude glycerine	0.112	18.05
Pharma-grade glycerine	0.095	17.0
Biogas (press-cake used for biogas production)	0.99	23.6
Producer gas (pruning material and hulls gasification)	12.1	5.2

Pavagada in Tumkur district experiences typical hot arid conditions. Wide variation in the agroclimatic potential across the watersheds is observed. Watersheds in Dharwad and Haveri districts receive a seasonal rainfall of ~500-600 mm. Bimodal rainfall distribution is observed; the first peak occurs from mid-July to 1st week of August and the second peak during mid of September to middle of October. Uni-model distribution of rainfall is seen in other watersheds.

Watersheds in Kolar areas of Tumkur and Chitradurga districts have a seasonal rainfall of ~500-670 mm with one peak of rainfall occurring during middle of September to end of October. Parts of Chitradurga district and Pavagada area in Tumkur district have a seasonal rainfall of ~400-500 mm with one peak of rainfall occurring during middle of September to end of October (Ibid.).

Detailed rainfall data for all Karnataka State districts can be found at the Action Plan for Greening of Wastelands Through Biofuel Plantations in Karnataka published by SuTRA, IISc, Bangalore (Sarvesh, *et. al.*: 2004).

Rainfed areas are subjected to high levels of vulnerability, exacerbated by the climatic change. High natural resource fragility and risk, low and highly oscillating productivity, production, and farmers' income, poor investment and capital formation, high vulnerability and volatility of product markets, poor access to credit, insurance and markets, and higher concentration of poverty and hunger are characteristic features of the rainfed areas. Accounting for 60% of the country's cultivated acreage, their developmental complexities, challenges and potential notwithstanding, rainfed areas have suffered neglect in the past in having not received differentiated technological, institutional, infrastructural and investment support (GOI: 2007).

In Rainfed scenario the capsulate yield of 5.3 t/ha of *Jatropha* fruits collected of which 3.45 t/ha of oilseed or 2.9 t/ha of kernel supplied to the oil extraction and trans/esterification plant. Overall, 0.95 t/ha of biodiesel can be produced, which corresponds to the 3.28 tonnes of oilseeds per tonne of biodiesel. In addition, 1.9 tonnes of fruits hulls (husk and coat), 0.5 tonnes seed shells and 0.8 tonnes of dry pruning material produced per hectare (Table 3.28).

Table 3.28: Farming data. Jatropha to biodiesel pathway (Rainfed. 2,500 trees/ha)

	Yield t/ha	**LHV GJ/t**
Harvested Jatropha fruits (whole fresh fruit)		12.8
Whole fruit (dry)	5.3	21.5
Jatropha oilseed	3.45	25.5
Jatropha fruit hulls (husk, coat)	1.9	10.9
Jatropha seed shells	0.5	19.0
Kernel	2.9	29.8
Green prune material	2.0	8.2
Prune material (dry)	0.8	16.0
Leaves (dry)	3.75	14.3
Wood charcoal	0.5	29.02
Shell charcoal	0.6	26.3
Jatropha oil	1.00	38.5
Biodiesel	0.95	37.27
	t/t biodiesel	
Jatropha oilseed	3.28	25.5
Jatropha oil	1.05	38.5
CH_3OH - Methanol	0.117	19.7
KOH - Potassium Hydroxide (High temperature catalyst)	0.0103	43.3
$NaOCH_3$, 30% in MeOH - Sodium Methylate (Low temperature catalyst)	0.021	12.62
H_2SO_4 - Sulphuric Acid (mineral acid)	0.006	-2.43
H_3PO_4 - Phosphoric Acid	0.0029	6.87
N_2 - Gaseous Nitrogen	0.018	1.2
K_2SO_4 - Potassium Sulphate	0.011	5.0
Water for the process (circulation)	55.0	
Press-cake (seed-cake)	2.23	25.1
Crude glycerine	0.125	18.05
Pharma-grade glycerine	0.095	17.0
Biogas (press-cake used for biogas production)	0.99	23.6
Producer gas (pruning material and hulls gasification)	8.37	5.2

Note:
Connor & Hernandez (2009) reported the following energy content values (per unit dry mass):
a) sugars, cellulose, and hemicelluloses - 14-16 GJ/t;
b) vegetative biomass - 17 GJ/t;
c) proteins and lignin - 25 GJ/t, and
d) fats and oils - 38-41 GJ/t

The energy used in the production for diesel (used as a reference fuel), High Speed Diesel (used as a transport fuel), gasoline (used in real Indian conditions very rarely for agricultural machinery), Natural Gas, Oil, Fuel oil, Non-cocking coal and Lignite (used as a fuel in transesterification plant) is reflected in the Primary Energy Factors of 1.16, 1.16, 1.14, 1.03, 1.01, 1.01, 1.01, and 1.01 respectively (Bhatt: pers. comm.) and are based on Indian average (Table 3.31). Similar numbers are shown for electricity at the same Table. These figures reveal an All-India average, or average for Karnataka State (Bhatt: pers. comm.).

At present for energy production in India the following fuels are commonly used: a) Non-coking, Sub-bituminous Coal (Grade E and Grade F) (Tables 3.29 & 3.30) and Lignite, b) C-Heavy Fuel Oil (Table 3.31), and c) Natural Gas. LNG (liquefied natural gas) or CNG (compressed natural gas) (Table 3.32) (Bhatt: pers. comm.).

The gradation of non-coking coal is based on Useful Heat Value (UHV) (Table 3.28).

$$UHV = 8900 - 138\,(A+M) \qquad (3.1)$$

where (A+M) is ash (%) + moisture (%) at 60% RH & 40^{o}C (Table 3.28).

Table 3.29: Grades of non-coking coal

Grade	Useful Heat Value (UHV), kcal/kg	Corresponding Ash (%) + Moisture (%) at (60% RH & 40^{o}C)	Gross Caloric Value (GCV), kcal/kg
A	>6,200	≤19.5	>6,454
B	>5,600 - <6,200	19.6 to 23.8	>6,049 - <6,454
C	>4,940 - <5,600	23.9 to 28.6	>5,597 - <6,049
D	>4,200 - <4,940	28.7 to 34.0	>5,089 - <5,597
E	>3,360 - <4,200	34.1 to 40.0	>4,324 - <5,089
F	>2,400 - <3,360	40.1 to 47.0	>3,865 - <4,324
G	>1,300 - <2,400	47.1 to 55.0	>3,113 - <3,865

Source: Indian Ministry of Coal website. Visited 25 May 2009

Coal, a fuel that typically produces higher emissions appears as a major source (55.4%) for energy production. Hardcoal extracted in India has a lower heating value (LHV) of 19.98-20.93 GJ/t. Other data as vary as 11.85 GJ/t (GEMIS 4.2), 24.18 GJ/t (India Initial National Communication to UNFCCC: 2004), 16.454 GJ/t (OECD/IEA: 1997-1998), 18.0 GJ/t (SimaPro 1.1).

The ash content of this coal is 23 wt% and the moisture content is estimated to be 10 wt% (IPNGS: 1992; TEDDY: 1994 cited by Jungbluth: 1995). Hardcoal is used for power plants and has a relatively high ash content of 40 wt% and a moisture content of 10 wt%.

The LHV estimated at 11.8 GJ/t (Harant, *et. al.*: 1993; TEDDY: 1994 cited by Jungbluth: 1995). Imported coal has reported LHV values of 29.4 GJ/t and 25.5 GJ/t; with default value 19.841 GJ/t (OECD/IEA: 1997-1998).

Indian coals contain significant amounts of ash (40-50%) both as inherent and extraneous matter. Ash affects combustion, heat transfer, fluid flow and size reduction processes in the system. The effect of ash has been quantified.

The higher caloric value of coal (GJ/t) has been fitted to a curve as follows (Seethramu, *et. al.*: 1992):

$$HCV = 34.83375 - 37.8037\, f\, ash - 46.4646\, f\, moisture \qquad (3.2)$$

where f is a fraction (0.1-0.9) (Bhatt, *et. al.*: 1999).

Coal has a carbon dioxide emission coefficient of 26 kg, while oil and gas have 21 kg and 16 kg respectively (Ghosh: no date).

Table 3.30: Non-coking, sub-bituminous coal data

Average Caloric Value	Emission Factor	Reference
kcal/kg	$kgCO_2/GJ$	
4,807		Grade E. CEA, New Delhi, 2001
4,195		Grade F. CEA, New Delhi, 2001
	96.00	Based on LHV. WRI/WBCSD
	91.45	Based on HHV. WRI/WBCSD
	96.10	2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2: Energy. Table 2.2
	95.80	Bhawan and Puram: 2008

Table 3.31: Fuel and energy data

Diesel (India-specific)			
Primary energy factor	1.16	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
IPCC emission factor for diesel	73.5	kg CO_2/GJ	IPCC 2001
Energy for 1 kWh	0.00747	GJ/kWh	1785 kcal/kWh, MNES study taking CEA 98-99 figures
Direct CO_2 emissions from diesel burning	75.1	kg CO_2/GJ	Calculated based on LHV 42.65 GJ/t, 87.4% C. GEMIS 4.2
Diesel emission factor	0.54	kg CO_2/kWh	Calculated
GHG emissions factor	89.3	kg CO_2eq/GJ	LowCVP Report. 2004
Diesel (HSD) (India-specific)			
Primary energy factor	1.16	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
IPCC emission factor for diesel	73.5	kg CO_2/GJ	IPCC 2001
Energy for 1 kWh	0.00747	GJ/kWh	1785 kcal/kWh, MNES study taking CEA 98-99 figures
Direct CO_2 emissions from diesel burning	74.3	kg CO_2/GJ	Calculated based on LHV 42.46175 GJ/t, 86.1% C. GEMIS 4.2
Diesel emission factor	0.54	kg CO_2/kWh	Calculated
GHG emissions factor	88.5	kg CO_2eq/GJ	LowCVP Report. 2004
Gasoline (India)			
Primary energy factor	1.14	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Direct CO_2 emissions from gasoline burning	72.2	kg CO_2/GJ	Calculated based on LHV 38.8 GJ/t, 78.0% C. Toyota Motor. Corp.
GHG emissions factor	84.7	kg CO_2eq/GJ	LowCVP Report. 2004
Oil crude (India/Imported)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Direct CO_2 emissions from oil burning	79.4	kg CO_2/GJ	Calculated based on LHV 38.745 GJ/t, 83.9% C. GEMIS 4.2
Oil crude (India)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Direct CO_2 emissions from oil burning	79.2	kg CO_2/GJ	Calculated based on LHV 39.685 GJ/t, 85.7% C. GEMIS 4.2
Oil crude (India-mix)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Direct CO_2 emissions from oil burning	74.1	kg CO_2/GJ	Calculated based on LHV 42.79 GJ/t, 86.5% C. OECD/IEA 1993b
Fuel oil (India specific)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Energy for 1 kWh	0.03739	GJ/kWh	Calculated from Karnataka Electricity Regulatory Commission
Energy for 1 t of fuel oil	0.00519	GJ/t oil	Calculated from Karnataka Electricity Regulatory Commission
Specific oil consumption (Avg.)	0.96358	g/kWh	Calculated from Karnataka Electricity Regulatory Commission
Direct CO_2 emissions from oil burning	73.7	kg CO_2/GJ	Calculated based on LHV 38.8 GJ/t, 78.0% C. Toyota Motor. Corp.
Lubricants and greases			
Energy factor	1.01	GJp/GJe	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Emission factor	40.71	kg CO_2/GJe	Calculated based on LHV 44.62 GJ/t, 78.0% C. IPCC 1996
Coal (General/Imported)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Energy for 1 kWh	0.01336	GJ/kWh	Karnataka State average 1999-2004. Karnataka Electricity Regulatory Commission
IPCC emission factor for coal	94.0	kg CO_2/GJ	IPCC 2001
Direct CO_2 emissions from coal burning	96.28	kg CO_2/GJ	Calculated based on LHV 29.4 GJ/t, 77.2% C. EU WTT studies
Coal emission factor	1.08	kg CO_2/kWh	CDM-SSC-PDD (version 02), APRANSCO. India
Coking coal (India-specific)			
Primary energy factor	1.02	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Energy for 1 kWh	0.01336	GJ/kWh	Karnataka State average 1999-2004. Karnataka Electricity Regulatory Commission
Specific coal consumption (Avg.)	0.6806	kg/kWh	Calculated from Karnataka Electricity Regulatory Commission
IPCC emission factor for coal	94.0	kg CO_2/GJ	IPCC 2001
Direct CO_2 emissions from coking coal burning	67.73	kg CO_2/GJ	Calculated based on LHV 19.98 GJ/t, 77.2% C. EU WTT studies
Coal emission factor	1.08	kg CO_2/kWh	CDM-SSC-PDD (version 02), APRANSCO. India
Non-coking coal (India-specific)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
Energy for 1 kWh	0.01336	GJ/kWh	Karnataka State average 1999-2004. Karnataka Electricity Regulatory Commission
Energy for 1 t of non-coking coal	0.00529	GJ/t oil	Calculated from Karnataka Electricity Regulatory Commission
IPCC emission factor for coal	94.0	kg CO_2/GJ	IPCC 2001
Direct CO_2 emissions from non-coking coal burning	144.20	kg CO_2/GJ	Calculated based on LHV 39.685 GJ/t, 85.7% C. GEMIS 4.2
Lignite (India-specific)			
Primary energy factor	1.01	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
IPCC emission factor for lignite	90.0	kg CO_2/GJ	IPCC 2001
Energy for 1 kWh	0.01488	GJ/kWh	3555 kcal/kWh - All India heat Rate. Review of Thermal Power Stations 2003-2004
Direct CO_2 emissions from lignite burning	340.41	kg CO_2/GJ	NCV: 9.69 +/- 0.4 GJ/t. India's initial National Communication to the UNFCCC.2004
Lignite emission factor	1.35	kg CO2/kWh	Calculated
Lignite emission factor	92.61	kg CO_2/GJ	CEF: 28.95 kg CO2/GJ. India's initial National Communication to the UNFCCC.2004
NG (GT)			
Primary energy factor	1.03	GJp/GJ	Dr. M. Siddhartha Bhatt, CPRI. Bangalore
IPCC emission factor for NG	60.0	kg CO_2/GJ	IPCC 2001
Heat rate	0.00828	GJ/kWh	1978 kcal/kWh - ALSTOM GT 11N2 gas turbines with max steam extraction
GT emission factor	0.448	kg CO2/kWh	CDM-SSC-PDD (version 02), APRANSCO. India
Direct CO2 emissions from NG burning	56.96	kg CO_2/GJ	83.534876 tCO2/GWh. Emissions Factor IPCC for Southern Region. 2005
Electricity			
Energy factor	2.26	GJp/GJe	Calculated
Emission factor	1.052	kg CO_2/kWh	Karnataka State specific. MNES, GOI/ Southern Online Biotechnologies Ltd.
Emission factor	155.9	kg CO_2/GJe	Calculated
Electricity from wood (SRC)			
Energy factor	3.34	GJp/GJe	Dr. Dasappa, S. IISc. Bangalore
Emission factor	36.0	kg CO_2/GJe	Dr. Mortimer. 2002
Emission factor	100.44	kg CO_2/GJ wood	100.44 kg CO2/GJ - based on LHV, WRI/WBCSD

Notes:

a) The Net Caloric Values (NCV) was calculated using the formula, NCV = GCV - 53 x H, where GCV is the Gross Caloric Value, and H - is the available hydrogen (MEF. GOI: 2004);

b) The internationally accepted norm of estimating HCV at 96% moisture level of coal called capacity moisture was used in present estimates (MEF. GOI: 2004);

c) In case of diesel substitution the IPCC default emission factor 20 tC/TJ. The default value for the emission coefficient for diesel fuel 3.2 kg CO_2 per kg of diesel fuel) (IPCC: 2001).

Phil Humphres, IFDC Senior Specialist-Engineering points that the natural gas is increasingly being liquefied and shipped in huge tankers as liquid natural gas - which now accounts for ~22% of global energy use. One hundred eighty-seven vessels are currently shipping LNG worldwide, Humphres says. Another 130 tankers are on order.

Construction capacity is 40 vessels per year, so there is now a 3-year backlog (Hargrove: 2008). As Indian plans to augment the supply of gas with imports brought in by trans-border pipelines and a planned fifteen LNG terminals, as well as to broaden its nuclear power program, these factors could undergo drastic changes in the near future.

The sulphur content of fuel oil ranges between 0.5 wt% and the maximum of 4.5 wt% prescribed by the standard. Refineries normally use fuel oil with a sulfur content of 1 wt% to reduce the emissions of sulfur dioxide. The specified ash content is less than 0.1 wt% and the water content is less than 1 wt%. The carbon content of fuel oil is 88 wt% and of HSD is 86.1%. Fuel oil has a lower heating value of 41.72 GJ/t (CFHT: 1995; ISI: 1988; IOC: 1995; OCC: 1995; Sharma & Sharma: 1994 cited by Jungbluth: 1995).

The crude oil extracted in India contains small amounts of sulphur in the range of 0.2 to 0.4 wt%. The crude oil imported from the OPEC contains between 2 and 2.5 wt% of sulphur. The sulphur content of the feed stock for refineries on average lies between 1.2 to 1.5 wt% (IOC: 1995; OCC: 1995). The content of water in the crude oil for the processing in the refinery should not exceed 1 wt% (CBWP: 1985 cited by Jungbluth: 1995). In most cases, the content of nitrogen compounds does not exceed 0.3 wt% (Sharma & Agnihorti: 1992 cited by Jungbluth: 1995).

Table 3.32: C-Heavy fuel oil and LNG data

	Density	**HHV**	**LHV**		**Emission Factor**	
	kg/l	GJ/t	MJ/L	GJ/t	$kgCO_2/l$	$kgCO_2/kg$
C-Heavy Fuel Oil[1)]	0.9130		42.5	38.8	2.99	3.27
LNG[1)2)]	0.7173	43.89/54.5		39.77/49.1		2.77

Sources:
1) Mizuho Information & Research Institute, Inc.: 2004;
2) Bhatt: pers. comm.

The content of sulfur in Indian diesel ranges between 0.3 and 0.7 wt% with an average of 0.5 wt%. This is less than the legal specification of 1 wt%. For metropolitan cities this maximum was reduced in 2000, to 0.25 wt% (IIP: 1994; IOC: 1995).

Regarding heating value, for general LCA purposes, lower heating value is used as the basis for calculations in this study. The difference between Higher Heating Value (HHV) and Lower Heating Value (LHV) is the energy in vapour-generated during fuel combustion, which HHV includes and LHV does not. In heat and power generation plants where fuel is combusted in stationary facilities some of the energy in vapour can be recovered for use. Otherwise, in ethanol fueled motor vehicles energy in combustion vapour cannot be recovered (Shapouri, *et. al.*: 2006). According to the Institute of Energy Economics, Japan (IEEJ: 1999) the following conversion factors (Table 3.33) should be applied if LHV should be calculated using data on fuels higher heating value (value which includes the condensation heat of moisture in fuel, HHV).

Table 3.33: HHV/LHV conversion factors

❐ Coal: HHV*0.96 = LHV	❐ LNG: HHV*0.9 = LHV
❐ Oil: HHV*0.93 = LHV	❐ LPG: HHV*0.92 = LHV

Source: IEEJ: 1999

3.11.2 Greenhouse gas factors

The Intergovernmental Panel on Climate Change (IPCC) has developed a characterization factor system that can weigh the various substances according to their efficiencies as greenhouse gases (Houghton, *et. al.*: 1995 cited by Sonneman, *et. al.*: 2003). Many of the substances emitted to the atmosphere as a result of human activities contribute to this manmade greenhouse effect and must be classified in this impact category. In order of importance they listed by Hauschild and Wenzel (1998) as: a) CO_2 (carbon dioxide), b) CH_4 (methane), c) N_2O (nitrous oxide or "laughing gas"), d) Halocarbons (hydrocarbons containing chlorine, fluorine or bromine). The system classifies these substances according to their global warming potential (GWP), which is calculated as the anticipated contribution to warming over a chosen time period from a given emission of the substance, divided by the contribution to warming from emission of a corresponding quantity of carbon dioxide (CO_2) (Sonneman, *et. al.*: 2003).

Global Warming caused by Greenhouse Gas (GHG) emissions represents the global environmental effects and is expressed in terms of "CO_2-equivalents" for 100 years time horizon.

GWP indicator result [kg CO_2 eq] =

*GHG emission [kg] * GWP 100-year factor [kg CO_2 eq /kg]* (3.3)

Regarding emissions other than CO_2 (CH_4, N_2O), evaluation was conducted through conversion to equivalent CO_2 in accordance with the Global Warming Potential (GWP). Global Warming Potential or GWP is a time dependent index used to compare the radiative forcing, on a mass basis, of an impulse of a specific greenhouse gas relative to that of CO_2. Gases included in the Kyoto Protocol are weighted in the first commitment period according to their GWP over a 100-year time horizon as published in the 1995 Second Assessment Report of the IPCC. In that report, methane, for example has a radiative forcing that was estimated to be ~23 times greater than that of CO_2, thus it has a GWP of 23 (IPIECA: 2007).

The GWP 100-year factor used in this study is shown in Table 3.34. CO_2 was chosen as a reference substance by the IPCC because it makes the most significant contribution to the manmade greenhouse effect.

The expected contribution in terms of warming from a greenhouse gas is calculated based on knowledge of its specific infrared wave radiation absorption capacity and its expected lifetime in the atmosphere. Table 3.34 presents GWP values for direct contribution of three substances mentioned previously: CO_2, CH_4 and N_2O used in calculations for this study.

Table 3.34: Greenhouse gas factors

	$kgCO_2eq/kg$
N_2O	296
CH_4	23
CO_2	1

Source: The GWP 100-years factor. IPCC: 2006

3.12 Oilseed production and delivery to the transesterification plant

3.12.1 Fertilizers and agrochemicals applications

3.12.1.1 Fertilizers

In literature the values stated for the amount of fertilizers required for the *Jatropha curcas* plantations are vary in a wide range.

Thus, in Euler and Gorriz (2004) the input of synthetic fertilizers assumed as 2 annual fertilizer applications with 150 kg per ha Super Phosphate being in the first dose, to be increased by 10% every year and 180 kg NPK in the second application. NPK in India usually referred to NPK 17:17:17, if not indicated differently (Chanakya: pers. comm.). Professor Neelakantan, Dean for the Forest College and Research Institute, indicates that each *Jatropha* plant will need of 5 kg of organic fertilizer, ~150 g of inorganic and 50 g of bio fertilizer (Friends of Earth: 2008). Heller (1996), Patil & Singh (1991) assumed a fertilizer use of 20 g urea plus 120 g Single Super Phosphate and 16 g Muriate of Potash per plant applied near the planting hole and covered by soil. The remaining dose of urea should be applied in this case in two splits at 10 g per plant. NPK ration should be 46:48:24 kg per ha. Out of NPK, nitrogen is required in larger quantity. Labland Biotech Pvt. Ltd. of Mysore (pers. comm.) advised usage of 20 g urea plus 120 g Single Super Phosphate and 16 g Muriate of Potash per tree on biannual basis, combined with small quantities of calcium, magnesium and sulphur to enhance the growth and yield. Lele (2004), as well as Planning Commission of India (2003) cited annual per ha fertilizer applications as 50 kg of urea plus 300 kg of Single Super Phosphate, plus 40 kg of Potassium Nitrate per hectare. Farooqui and Shrinivasapa (2004) assumed a fertilizer use of 150 kg per ha of Super Phosphate and alternated with one dose of 40:100:40 kg per ha NPK on bi-annual basis. From forth year onwards, 10% extra Super Phosphate should be added to the above dose. Finally, Paramathma, *et. al*. (2004) indicates that during planting of *Jatropha curcas* each pit should be filled with 5 kg of Farm Yard Manure (FYM), 100 g of Neem cake and 100 g of Single Super Phosphate). Organic fertilizers should be applied form second year onwards. For one acre 20:120:60 kg of NPK respectively during September-October. From fourth year onwards, 150 g Super Phosphate per acre is recommended over and above the regular dose. Prueksakorn and Gheewala (2008) of the King Mongkut's University of Technology Thonburi, Thailand reported that the required amount of chemical fertilizer for years 1, 2, 3, 4, 5, 6, and onward is 160, 25.5, 63, 126, 252, 378, and 378 kg of N:P:K (40:20:10), respectively. From second year to 20th year of plantation, *Jatropha* press-cake substitute partially or in full required chemical fertilizers applications.

The ICRISAT Archival Report 2007 (ICRISAT: 2008. Activity 7.2.1.2) recommends "of the graded levels of nutrient applied to *Jatropha*, application of 100 g urea plus 38 g SSP per plant showed good performance followed by the application of 50 g urea plus 76 g SSP per plant. It revealed that there is significant improvement in terms of the number of inflorescences with the application of 100 g of urea per plant per year compared to plants that received 50 g of urea. However, there was no other marked difference in growth parameters among the nitrogen treatments".

It is not possible to select one single guideline which might be recommended as a universal and most advisable as territories in India where *Jatropha curcas* currently planted and tried are numerous, areas where *Jatropha* planted are very large, with various climatic, geological, watershed and soil conditions. As a result, *Jatropha* plantations situated in different areas will be definitely require individual applications for both organic and chemical fertilizers as well as for agrochemicals and, if applicable, irrigation. Based on data collected during field work in India and secondary sources (GOI: 2003; Vinayak & Kanwarjit: 1991, Heller: 1996; Lele: no date; Lele: 2004; Openshaw: 2000; Rao & Korwar: 2003; Euler & Gorriz: 2004; Farooqui and Srinivasappa: 2004; Paramathma: 2004; Labland Biotechs Pvt. Ltd.: pers. comm., Murphy: pers. comm.) three scenarios for fertilizers applications were considered for each irrigated and rainfed scenarios for *Jatropha curcas* oilseed cultivation and the following blocks of organic and chemical fertilizers application were developed:

Scenario I:

a) Organic fertilizers (Paramathma: pers. comm.):

Basal dressing: Farm Yard Manure (FYM): 5 kg per plant.

Top dressing: 3,430 kg/ha/yr of *Jatropha* fruit hulls and shells started from 5th year of plantation - for Irrigated plantation. Spacing 3x3 m. 1,111 trees/ha, and 2,400 kg/ha/yr of *Jatropha* fruit hulls and shells started from 5th year of plantation - for Rainfed plantation. Spacing 2x2 m. 2,500 trees/ha.

b) Chemical fertilizers (Labland Biotech Pvt. Ltd.: pers. comm.):

Top dressing: Muriate of Potash (MoP, 60%) - 35.5 kg/ha; P - 266.64 kg/ha; and N - 44.44 kg/ha.

Scenario II:

a) Organic fertilizers:

Top dressing: 3,430 kg/ha/yr of *Jatropha* fruits hulls and shells started from 5th year of plantation - for Irrigated plantation. Spacing 3x3 m. 1,111 trees/ha, and 2,400 kg/ha/yr of *Jatropha* fruit hulls and shells started from 5th year of plantation - for Rainfed plantation. Spacing 2x2 m. 2,500 trees/ha.

b) Chemical fertilizers:

Basal and Top dressing (Lele (2004), Heller (1996), Patil & Singh (1991)): assumed a fertilizer use of 20 g urea plus 120 g Single Super Phosphate and 16 g Muriate of Potash (60%) per plant. The remaining dose of urea applied in this case in two splits at 10 g per plant. NPK ratio 46:48:24 kg/ha.

Scenario III:

a) Organic fertilizers:

Top dressing: 3,430 kg/ha/yr of *Jatropha* fruits hulls and shells started from 5^{th} year of plantation - for Irrigated plantation. Spacing 3x3 m. 1,111 trees/ha, and 2,400 kg/ha/yr of *Jatropha* fruits hulls and shells started from 5^{th} year of plantation - for Rainfed plantation. Spacing 2x2 m. 2,500 trees/ha.

b) Chemical fertilizers:

Basal dressing (Chativerdi: pers. comm.): Di-ammonium phosphate (DAP) - 15 g per plant; and NPK 17:17:17 - 15 g per plant.

Top dressing (Faroqui & Srinivasappa: 2004): Single Super Phosphate - 150 kg/ha, applied on biannual basis with 10% increase from year 4 onwards; and NPK 40:100:40 on biannual basis. As a result, phosphorous application applied as much as 254 kg/ha/yr in years 1-3, and 259.4 kg/ha/yr from year 4 onwards.

There are two cases assumed: a) the fruit hulls and seed shells used as fertilizer or b) the fruit hulls and seed shells used as combustibles. In earlier case the crop residues are ploughed in and as a result reduce the demand of synthetic fertilizer, and in latest case it is assumed that all by products produced after extraction of oil is used as combustibles for energy production.

In Models a, b and c, fruit husks and oilseed shells is considered to be left in the field and ploughed back in, which leads to reduction in the amount of chemical fertilizers needed (LowCVP: 2004).

Table 3.35: *Jatropha curcas* fertilizers and agrochemicals requirements

		Irrigated scenario	Rainfed scenario
		1,111 trees/ha	**2,500 trees/ha**
K fertilizer (as K_2O equivalent)			
Low	kg/ha	21	24
Best	kg/ha	100	60
High	kg/ha	180	95
P fertilizer (as P_2O_5 equivalent)			
Low	kg/ha	28	48
Best	kg/ha	144	80
High	kg/ha	260	122
N fertilizer (as N equivalent)			
Low	kg/ha	20	23
Best	kg/ha	100	75
High	kg/ha	175	120
Pesticides & Fungicides	kg/ha	27.2	61.2

Note[1]):
Phosphorous (P) and potassium (K) fertilizers are always listed in oxide form (P_2O_5 and K_2O) for esoteric reasons. Granular fertilizer recommendations from University of Arkansas use the oxide form. Recommendations from other sources are sometimes given in terms of elemental form, for fertigation. Conversions:

$P = P_2O_5 \times 0.44$	$P = P_2O_5/2.27$	$P_2O_5 = P \times 2.27$
$K = K_2O \times 0.83$	$K = K_2O/1.20$	$K_2O = K \times 1.20$
Mg = MgO x 0.60	Mg = MgO/1.67	MgO = Mg x 1.67

Sources:
1) Das: 2004;
2) Paramathma: pers. comm.;
3) Raina: pers. comm.;
4) Farookqi: 2004;
5) Labland Biotechs Pvt. Ltd.: 2005;
6) Murphy: pers. comm.

Table 3.36: Specific energy consumption by feedstock type (GJ/tNH_3)

Feedstocks based plants		India average	India best (improvement potential)
Gas based plants	Ammmonia	36.5	30.3 TCL Babrala (17%)
	Urea	26.5	22.5 TCL Babrala (15%)
Naphta based plants	Ammonia	39.9	34 CFCL Kota (15%)
	Urea	29.1	24.3 CFCL Kota (16%)
Fuel-oil based plants	Ammmonia	58.4	47.9 GNFC Bharuch (18%)
	Urea	40.5	31.3 GNFC Bharuch (23%)

Note: The urea figures include the embedded energy in the production of ammonia

Sources:
1) Ashraf, *et. al.*: 2003;
2) Kongshaug: 1998;
3) GOI: 2003;
4) EFMA: 2000;
5) Worrell, *et. al.*: 1997

Table 3.37: Primary energy intensities for ammonia production

Indicator	China	OECD countries	Best practice
GJ/tonne (ammonia)	39-65	33-44	19.1

Source: Price, *et. al.*: 2000

Table 3.38: Energy factors for fertilisers, seeds and pesticides

Agricultural Input	Energy factor (GJ/t)	Comments
Nitrogen fertilizer (as N)	60.0	Rehman: 2003
Phosphate fertilizer (as P)	11.1	Rehman: 2003
Potash fertilizer (as K)	6.7	Rehman: 2003
Pesticides (as active ingredient)	315.0	Calculated based on LHV 45 GJ/t
Seed material	25.5	Openshaw: 2000

Notes:
a) 65.3 GJ/t for nitrogen fertilizers; 7.2 GJ/t - for phosphorous fertilizers; 6.4 GJ/t - for potassium fertilizers (Pretty, *et. al.*: 2002 cited by FAO: 2004);
b) 87.9 GJ/t for nitrogen fertilizers production, 26.4 GJ/t - for phosphorous fertilizers production, 10.5 GJ/t - for potassium fertilizers production - Pimintel: 1992 cited by Prueksakorn & Gheewala (2008).

Sources:
1) Woods, *et. al.*: 2005;
2) Woods, *et al.*: 2008

Table 3.39: GHG emission factors for fertilisers, seeds and pesticides

Agricultural Input	**GHG emissions (kg CO_2eq/kg applied)**
Nitrogen fertilizer (as N)	6.69
Phosphate fertilizer (as P)	0.71
Potash fertilizer (as K)	0.46
Pesticides (as active ingredient)	5.41
Seed material	0.87

Sources:
1) Woods, *et. al.*: 2005;
2) Woods, *et al.*: 2008

In rainforests of Karnataka, annual variations in the concentration of litter-fall nitrogen (N) were in the range 3.9-20.3 mg/g. Generally, the woody litter has lower nitrogen (N) concentration than leaf litter (Raghubanshi: 2008). Seasonal variations in litter N content are also reported for many ecosystems. For example, in northeast forests, nitrogen (N) concentration was generally greater during autumn (0.6-1.3%) and lowest during the rainy season (0.4-0.9%) in all forest stands. Conservative estimates indicate that total nitrogen (N) return (aboveground and belowground litter) in forests of India is in the range 63-101 kgN/ha/yr (Ibid.).

Nitrogen returned to the soil by *Jatropha* leaf fall calculated based on the leaf fall volume of 2,431 kg/ha/yr, nitrogen percentage of 0.81, nitrogen returned - 19 kg/ha/yr (Rao & Korwar: 2003), and LHV: 14.3 GJ/t (Nivitchanyong: 2007) as 1,230.2 kgN/ha per Life Cycle for Irrigated I and Irrigated II Scenarios 1,659.4 kgN/ha per Life Cycle for Rainfed I and Rainfed II Scenarios.

Table 3.40: Macronutrients in *Jatropha* plant compared with average agricultural crops straw and green manure composition

	N (%)	P (%)	K (%)
Green manure. Belarus[a)]:			
Leguminous crops	0.50	0.11c[)]	0.30[d)]
Cruciferous crops	0.40	0.13[c)]	0.38[d)]
Graminaceous crops/grain varieties	0.35	0.12[c)]	0.28[d)]
Mixture	0.42	0.12[c)]	0.32[d)]
Straw. Belarus[b)]:			
Graminaceous crops	0.40	0.15[c)]	1.00[d)]
Leguminous crops/grain legumes	1.00	0.20[c)]	1.10[d)]
Cruciferous crops	0.50	0.15[c)]	0.90[d)]
Oats crops	0.70	0.30[c)]	1.25[d)]
Maize	0.45	0.20[c)]	1.20[d)]
***Jatropha* plant parts.**			
Stem and branch	0.50	0.25	1.74
Leaves	1.77	0.53	2.43
Shell	0.86	0.14	7.10
Press-cake (oil cake)[e)]	3.94	0.77	1.93
Press-cake (oil cake)[f)]	5.70-6.48	2.60-3.10	0.90-1.00
Crop residues. India			
Paddy husk	0.30-0.50	0.20-0.30	0.30-0.50
Straw	0.36	0.08	0.71
Groundnut shell and stem	1.60-1.80	0.30-0.50	1.10-1.70
Oil cakes. India			
Edible oil cakes			
Mustard cake	5.10-5.20	1.80-1.90	1.10-1.20
Linsed cake	5.50-5.60	1.40-1.50	1.20-1.30
Til or sesame cake	6.20-6.30	2.00-2.10	1.20-1.30
Coconut cake	3.00-3.20	1.90-2.00	1.70-1.80
Safflower cake (Deccorticated)	7.90	2.20	1.90
Cotton seed cake (Decorticated)	6.40	2.90	2.20
Groundnut cake	7.00-7.30	1.50-1.60	1.30-1.40
Non-edibe oil cakes			
Castor cake	4.30	1.80	1.30
Cottom seed cake (Undecorticated)	3.90-4.00	1.80-1.90	1.60-1.70
Karanja or Honge cake	3.90	0.90	1.20
Mahua cake	2.50-2.90	0.80-0.90	1.80
Neem cake	5.20-5.30	1.00-1.10	1.40-1.50
Safflower cake (Undecorticated)	4.90	1.40	1.20

Notes:
a) Humidity: 80%;
b) Humidity: 16%;
c) as P_2O_5;
d) as K_2O;
e) Nivitchanyong: 2007;
f) GTZ Jatropha Energy Project: 1995

Sources:
1) Nivitchanyong: 2007;
2) Лапа: 2007;
3) Das: 2004;
4) GTZ Jatropha Energy Project: 1995

3.12.1.2 Lime application

A lower soil pH caused unfavorable growth and development conditions for agricultural crops. Acidic soils tend to decrease plant growth for a variety of reasons, major of which are: deficit of Ca^{2+}; increased concentration of toxic Al^{3+}; Mn^{4+}, H^{+}; lower availability of nutritious elements for plants; unfavorable physical properties of soils (Лапа: 2007, Maheshwari: no date, FAO: 1994). Sharma, *et. al.* (2008) reports that number of fine roots and lateral roots are very much restricted in *Jatropha* plants growing at higher pH than in lower pH soils. Crop production on acid soils can be improved greatly by adjusting pH to near neutrality. As such, one of the most important and practically feasible management practices is the use of lime and liming materials to ameliorate the soil acidity. The addition of lime raises the soils pH, thereby eliminating most major problems of soil acidity. It is currently unclear whether or not liming is required at the areas where *Jatropha* is growing. There is only one reference related to the pH effect on *Jatropha* growth, which is not really clear statement.

However, if it is necessary to apply lime to the *Jatropha* field, the following recommendations will be appropriate. When the measured soil pH is 6.4 and above, there is no need to apply limestone. Ground limestone is recommended in the case of soils whose pH is 6.3 and below. For such soils the lime ($CaCO_3$, Calcium Carbonate) can be recommended as furnished in Tables 3.41, 3.42 and 3.43 (Santhi & Mani at Paramathma, *et. al.*: 2004).

Table 3.41: Lime ($CaCO_3$, calcium carbonate) required to raise pH to 6.5 for an acidic soil (kg/ha)

	Soil Type				
Textural Category	**Very Light**	**Light**	**Medium**		**Heavy**
pH range	**Sandy**	**Sandy loam**	**Loam**	**Silty loam**	**Clay & loamy clay**
4.5 to 5.0 (pure $CaCO_3$)	4,250	7,250	10,750	15,000	20,000
5.1 to 5.5 (pure $CaCO_3$)	2,500	4,250	6,250	8,500	11,300
5.6 to 6.0 (pure $CaCO_3$)	1,000	1,750	2,500	3,500	5,000

Sources:
1) Maheshwari: no date;
2) Santhi & Mani at Paramathma, *et. al.*: 2004

Table 3.42: Lime ($CaCO_3$, calcium carbonate) required to neutralize soil acidity

	Ground Limestone Required to Bring the Soil (kg/ha)		
pH of soil buffer suspension	pH 6.0	pH 6.4	pH 6.8
6.3	2,700	3,200	3,700
6.2	3,100	3,700	4,200
6.1	3,500	4,200	4,800
6.0	3,900	4,700	5,400
5.9	4,400	5,200	6,000

Source: Santhi & Mani at Paramathma, *et. al.*: 2004

Table 3.43: Gypsum ($CaSO_4 \cdot 2H_2O$, calcium sulfate) requirement for an alkali soil

Soil pH	Gypsym Requirement (kg/ha)
9.0	2,500
9.1	3,500
9.2	4,500
9.3	5,500
9.4	6,500
9.5	7,500
9.6	8,500
9.7	9,500
9.8	10,500
9.9	11,500
10.0 and above	12,500

Source: Paramathma, *et. al.*: 2004

Application of fertilizers, especially nitrous fertilizers (e.g. urea) is the most important factor for achieving *Jatropha curcas* high yields and high oil content in *Jatropha* seeds in Southern India. However, the natural rate of acidification is accelerated by regular agricultural practices like use of nitrogen fertilizers. According to Maheshwari (no date), the impact of nitrogen fertilizers on acidification depends on the type of fertilizer. Therefore, nitrous fertilizers applications caused increase of soil acidity and generally should be accompanied with simultaneous limestone application for acidity neutralization.

3.12.1.3 Agrochemicals

Promising experiences are emerging across India on managing insect pests with minimum use of chemical pesticides. The agriculture research system should recognize these emerging low-cost, low external input pest management options and strengthen them irrespective of the source of innovation (GOI: 2007).

According to ReneLakshmi Agro the Bio-foliar spray should be applied to treat larval feeding on *Jatropha curcas* leaves and a special insecticide, Karate at 250 ml/acre plus SAAF (commercial name) at 250 g/acre should be applied to control the flower Webber and the Plant Bug (ReneLakshmi: 2005).

Input data and the results of energy and GHG emissions balances for "Jatropha oilseed cultivation: Irrigated Scenario and Rainfed Scenario" presented at the Tables 3.27, 3.28, 4.6, 4.7, and 4.8. The inputs of N, P and K fertilizers are considerably larger when the fruits hulls and seed shells are used as a fertilizers (green manure) rather than used as combustibles as co-fuel for power plant, eventually resulting in 2.50 to 7.25 times increase in GHG emissions from agriculture.

The following recommendations for the fungicides and insecticides applications (Table 3.44) advised by Dr. Ashok K. Raina of the Phytotron Research, Yehalanka, Bangalore were used for energy inputs and GHG emissions calculations:

Table 3.44: Extent of agrochemicals applications

Chemical (commercial name) and application requirements	Frequency of application	Cost (Rs. per unit)
Fungicides:		
1) Cabendazim 50% w/w (0.5 g/l) plus Kiran (2 ml/l)	Two times a year	
Cabendazim		60.0 per 100 g
Kiran		188.0 per 500 ml
2) Tridemorph 80% E.C. (0.5 ml/l) plus Kiran (2 ml/l)	Two times a year	
Tridemorph		91.0 per 100 g
Kiran		188.0 per 500 ml
Incecticides:		
1) Dimethoate 30% E.C. (1ml/l)	Two times a year	150.0 per liter
2) Triazophos 40% E.C. (1ml/l)	Two times a year	130.0 per 250 ml

Source: Raina: pers. comm.

Energy requirements and carbon emissions for organic and mineral fertilizers and agrochemicals are based on data presented in Tables 3.38, 3.39 and Appendix III, which reflect average production for EU, USA and specifically for India.

3.12.1.4 Nitrous oxide (N_2O) emissions

Besides from being a greenhouse gas with greenhouse gas factor of 298 $kgCO_2eq/kgN_2O$, nitrous oxide is also takes part in reactions, which lead to the distraction of stratospheric ozone, which may expose humanity to the harmful effect of solar ultra-violet radiation (Smith, *et. al.*: 2007, IPCC: 2007, Cruitzen: 1981 cited by Majumdar, *et. al.*: 2002). The alarm due to the presence of N_2O in atmosphere becomes greater due to the fact that N_2O has a lifetime of 166±16 years in atmosphere (Prinn, *et. al.*, 1990 cited by Majumdar, *et. al.*: 2002).

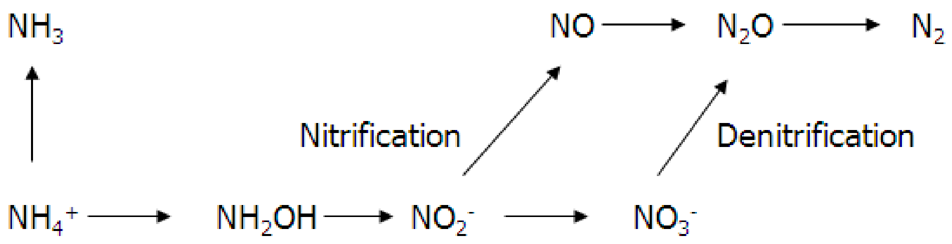
According to Crutzen, *et. al.* (2008), the increasing use of biofuels to reduce dependence on imported fossil fuels and to achieve "carbon neutrality" will further cause athmospheric N_2O concentration to increase, because of N_2O emissions associated with N-fertilization. Thus, for biodiesel from rape, nitrogen inputs responsible for over 90% of the on-farm greenhouse gas emissions. For ethanol from wheat, nitrogen use accounts for 80% of the on-farm emissions, nitrous oxide (N_2O) alone responsible for over 60% of those farm-based greenhouse gas emissions (Woods, *et. al.*: 2008). There are large uncertainties in the current annual emission figures for nitrous oxide (N_2O) and methane (CH_4) from soils. It has been estimated, for example, that the uncertainty in the current global emission of N_2O from agricultural sources may be larger than 100% (Olivier & Berdowski: 2001 cited by ICRISAT: 2006. Project 8).

Agriculture is by far the largest source of N_2O, contributing 85% to the global anthropogenic total in 1995; with synthetic fertilizers and animal waste contributing approximately equal amounts to direct N_2O emissions (Smith, *et. al.*: 2007). There are very few data on emissions of these gases from dryland agroecosystems (Ibid.). The field N_2O emission also remains a blind spot area. Appropriate correction for N_2O emissions associated with fallow land required further research. At the last point, reliable calculation method and reliable data sources for Indian agriculture, soils and croplands in relation to N_2O emissions remains a big area for further investigations.

From agricultural perspective, N_2O emission from soil represents a loss of soil nitrogen in terms of its availability to plants. Soil is considered a major source of N_2O emissions. Soils receiving industrially and biologically fixed nitrogen contribute to this emission during denitrification and nitrification (Flowchart 3.8) (Ghosh, *et. al.*: 2002).

Soil denitrification is determined predominantly by weather conditions (temperature and moisture), soil aeration status, organic carbon supply, nitrogen availability (N uptake and N sources), soil pH, spatial variability, and texture (Aulakh, *et. al.*: 2000, Grace & Chen: no date, Kindred, *et. al.*: 2008).

Flowchart 3.8: Nitrogen cycle



Source: Grace & Chen: no date

Soil organic matter (SOM) is the largest N pool within terrestrial ecosystems accounting for more than 90% of total ecosystem N. Soil N in Indian dry tropical forests may vary from 0.84 to 1.58 t/ha in its 0-10 cm profile (Raghubanshi: 2008). The conversion of dry tropical forest to alternate and simpler land uses (e.g. conversion to savannah, cropland or mines) significantly reduces soil nitrogen. Raghubanshi (2008) reports 38% decrease in total N content after conversion of a forest to cropland. Conversion of natural forest in eastern India has led to a reduction of total N (26-35%) and total microbial biomass N (25-60%) over a period of 30-50 years. Indian soils in tropical zones on average contain only 0.05% N and 0.6% of SOC (1.03% of SOM) (Ayala & Rao: 2002). However, cultivated over a period of seven years continuously with grain crops, but with legume crop rotation, as much as 1.8% organic matter could be obtained.

According to Davidson (1991) and Davidson and Verchot (2000) cited by Holtgrieve, *et. al.* (2006), theoretical models of trace gas flux predict that with soil water content sufficient to stimulate microbe activity but less than field capacity (~10-60% water filled pore space (WFPS - Appendix X)), nitrification dominates as a source of N trace gases. For soils above field capacity, however, denitrification dominates as the source of N gases with N_2O being the dominant flux from 60% to 80% WFPS and N_2 most important under more saturated conditions.

Pretty, *et. al.* (2002 cited by FAO: 2004) consider tillage to be one of the major factors responsible for decreasing carbon stocks in agricultural soils. Although no-tillage systems are a potential tool for combating the carbon losses associated with conventional cultivation, they do have drawbacks, and Baker, *et. al.* (2007) question the carbon savings associated with no-tillage. Application of N fertilizer can also be problematic when used on undisturbed, no-tillage soils. Where the soil is poorly drained, denitrification can occur and the reduced rate of evaporation increases the risk of nitrate leaching. In addition the native soil N has a lower rate of mineralization in undisturbed soil. Considering the overall carbon budget, no-tillage systems have a lower energy requirement because tillage is very energy intensive.

Irrigation can cause inorganic carbon to become unstable if acidification takes place through inputs of nitrogen and sulphur. The release of CO_2 through carbonate precipitation is seen as a major problem if irrigation waters are used in any system that is trying to store carbon. Schlesinger of Duke University, USA (2000) has pointed out that the groundwater of arid lands often contains up to 1% calcium and CO_2. This concentration is much higher than that which occurs in the atmosphere. Consequently, when these waters are applied to arid lands, CO_2 is released to the atmosphere and calcium carbonate precipitates. His calculations conclude that irrigation of some cropping systems would yield a net transfer of CO_2 from the soil to the atmosphere (FAO: 2004). Moreover, climate change is likely to amplify the problem as increased temperature is predicted to promote N_2O emissions (Li, *et. al.*: 1996 cited by FAO: 2004).

Jatropha curcas requires a lot of nitrogen and water to yield well. During visits to *Jatropha* plantations in Chhattisgharh, author's attention was driven to the fact that irrigation and planting in areas with a high water table is crucial for growing it under the climatic conditions of this region. However, in Tamil Nadu, application of fertilizers, especially nitrogen-fertilizers (i.e. urea) was found a most important factor, as average ambient temperatures in Tamil Nadu are not as high as in Chhattisgharh. The press-cake and shed leaves are nitrogen-rich, and these can be used as green manure. The N_2O emissions from the crop residue depend on the overall nitrogen content and C:N ratio of the residue (Kindred, *et. al.*: 2008). Dr. Arvin Mosier, one of co-authors of the ACP paper (Crutzen, *et. al.*: 2007), expects that there would be significant loss of nitrogen through ammonia volatilization from *Jatropha* press cake and leaves. A study in India in the mid-1980s showed that the nitrogen from Sesbania green manure crop was quickly mineralized and losses were similar to those from the same amount of nitrogen applied as urea (Smith: pers. comm.). Considering the high soil NO_3^- at the end of the *rabi* (October-March) season, the loss of soil nitrogen (in form of NO_3^-) through leaching at the very start of *kharif* (June-September) season may be also very significant (Majumdar, *et. al.*: 2002).

In upland (arable) farming, most soils remain aerobic (Aulakh, *et. al.*: 2000). Increasing water content from typical upland soil conditions (60% WFPS) to near-saturation

(90% WFPS) and flooded conditions (120% WFPS) creates anaerobic conditions leading to four to six fold higher rates of denitrification than the upland system (Smith & Tiedje: 1997, Hobbie, *et. al.*: 2000 cited by Padney & Srivastava: 2009). The intensive rainfall (i.e. monsoons) in the humid tropical climate increases WFPS in sandy-clay-loamy soils which makes the soils anaerobic and the products of anaerobic soil nitrogen transformation (N_2O, NO) accumulate in the soils due to lack of gaseous exchange from the atmosphere, which also temporarily contributes to the anaerobic conditions. Medium to fine soils had optimum activity above 60% WFP, while coarse textured soils had their maximum below 60% WFP. A third group consisting of two highly weathered (Hawaiian) soils had their maximum above 70% (Ilstedt, *et. al.*: 2000).

The wet and warm climatic conditions that prevail in subtropical regions might contribute to substantial N_2O emissions from soils high in nitrates as these climatic conditions favor denitrifying organisms (Majumdar, *et. al.*: 2002, Dobbie & Smith: 2003 cited by Kindred, *et. al.*: 2008). When soils are wet and warm (WFPS>70-80%), emissions can be very high, if nitrate is readily available in the soil (Kindred, *et. al.*: 2008). High rainfall events reduce nitrification rate and cause the reduction of nitrate nitrogen into ammonium in soils via dissimilatory (anaerobic) pathways in the field shortly after exposure to these conditions (Padney & Srivastava: 2009). The percentage content of (NO_3^- + NO_2^-)–N in total soil inorganic N content (i.e. (NH_4^++NO_3^-+NO_2^-)–N) increases considerably during this period, indicating denitrification (Majumdar, *et. al.*: 2002). This is supported by the findings of Aulakh, *et. al.* (2000). They found that: a) when aeration was restricted and nitrate present, soils could support high rates of denitrification (~6 mgN/kg/day) for short period; b) application of fertilizer N as nitrate enhances N losses via denitrification (from ~6 mgN/kg/day to 10 mgN/kg/day) depending on the availability of C; c) when N is applied in an ammoniacal form, nitrification proceeds slowly and nitrate availability limits denitrification in flooded soil; d) soil near saturation, being partially aerobic, supported greater nitrification of the applied ammoniacal fertilizer N than flooded soil which resulted in higher relative rates of denitrification; and e) under aerobic soil conditions, 26 $mg_{mineral}$N/kg accumulated in control soil over a 16-day period, demonstrating a modest capacity of such semiarid subtropical soils, low in organic matter, to supply N to growing plants.

Jatropha hull, due to low nitrogen content, had a wide C:N ratio of ~66.93, which is higher than that recommended (35-45) for composting. Although the initial C:N ratio of hulls was high (66:1), degradation completed at a faster rate, and lower C:N ratio was achieved in the degraded hulls after composting for one month. The C:N ratio of 16.96 is reported in uninoculated compost and 12.30 in inoculated with mixture of four lignocellulolytic fungi compost. A C:N range of 12-15 is also reported in mature *Jatropha* hulls compost (Golueke: 1992 cited by Sharma, *et. al*.: 2008). *Jatropha* press-cake C:N ratio reported as 13.3 (Henning: 2004, www.bagani.de), and 7-17 (Van Beers: 2007). Residues with low C:N ratios (such as sugar beet with C:N ratio 9:1-11:1 for sugar beet leaves) tend to give higher N_2O emissions than those with higher C:N ratios (such as cereal straw which usually has a high C:N ratio (>70) or typical of wheat straw C:N ratio 40:1 to 90:1) (DEFRA: 2001 cited by Kindred, *et. al*.: 2008). Hence, in case of immediate return of *Jatropha* hulls and shells to the soil as organic fertilizer, N_2O emissions are likely to be much less than in case of Jatropha hulls and shells compost, or *Jatropha* press-cake applications. However, taking into account *Jatropha curcas* annual timetable (e.g. recommended time for fertilizers applications and harvesting), as well as massive production of *Jatropha* hulls (2.33 t/ha for Irrigated scenarios and 1.9 t/ha for Rainfed scenarios), shells (1.1 t/ha for Irrigated scenarios and 0.9 t/ha for Rainfed scenarios), and press-cake (2.23 $t/t_{biodiesel}$) around the year, it is reasonable to predict that *Jatropha* hulls and shells compost and *Jatropha* press-cake with low C:N ratio will be rather utilized as a green manure.

Finally, it is reasonable to assume that choice of fertilizers, including nitrogen fertilizers, applied will be considered by local farmers in developing countries based on availability and local market price of fertilizers rather than concerns over nitrogen oxide (N_2O) or greenhouse gases (CO_2eq) emissions from these applications.

3.12.1.5 Nitrification inhibitors

Several nitrification inhibitors have proved to be efficient in mitigating N_2O emissions from arable soils. Thus, the crop could be treated with fertilizer in combination with nitrification inhibitors, for example: 1) neem (crushed neem seed powder) coated N-fertilizer; 2) nimin (commercial derivative of neem); 3) dicyandiamide (DCD); and 4) thiosulphate. Thus, nimin is a concentrated neem extract, prepared by processing industrial grade neem oil which contains 5% neem bitters responsible for nitrification inhibitors in soils. N-fertilizer (i.e. urea) could be mixed with nimin in 100:1 ratio (w/w) to prepare nimin coated N-fertilizer (Majumdar, *et. al*.: 2002).

Percent nitrification inhibition by nitrification inhibitors might be calculated by the formula given by Sahrawat (1996) cited in Majumdar, *et. al*. (2002):

$$\%\ inhibition\ of\ nitrification = (N_U - N_I)/N_U \times 100, \qquad (3.4)$$

where

N_U - the % (NO_3^-+NO_2^-)–N in soil inorganic N (i.e. (NH_4^+ +NO_3^- +NO_2^-)–N) in soil fertilised with urea, and

N_I - the % (NO_3^- + NO_2^-)–N in soil inorganic N (i.e. (NH_4^+ +NO_3^- +NO_2^-)–N) in soil fertilised with urea + inhibitor.

Nevertheless, under continuously submerged conditions, nitrification inhibitors may not have a significant role to play in controlling nitrification and N_2O emission during nitrification, as in these environment N_2O emissions will be mainly controlled by soil NO_3^-, organic matter content and O_2 concentration. But, in upland fields, water is drained out frequently and the soil becomes aerobic intermittently and inhibitors may come into play during these periods (Majumdar, *et. al.*: 2002).

After cessation of high rainfall, WFPS declined quickly within 2 hours in the upper layer (0-5 cm) of the soils. These indicate that the high rainfall together with labile carbon increases the extractable phosphorous (P) through anaerobiosis, whereas quick decline in the WFPS (0-5 cm) following cessation of the high rainfall helps its uptake by plants and microflora (Padney & Srivastava: 2009).

IPCC 2006 Guidelines evaluated the relationship between the amount of nitrogen fixed by chemical, biological or atmospheric processes and the total emissions of nitrous oxide. They also outline the calculation methodology for 'indirect' emissions to account subsequent N_2O-N emissions from ammonia volatilized and deposited elsewhere or nitrate leached from the original N inputs of N fertilizers, organic N, crop residues and changes in soil organic matter. Recommended emission factors can be found in Table 3.45 as well. Converting from kg N_2O-N to kg N_2O simply requires multiplying by 44/28 (the molecular weight of N_2O as a proportion of the weight of N in N_2O-N) (IPCC: 2006, Kindred, *et. al.*: 2008).

Cruitzen, *et. al.* (2007) challenge the IPCC approaches for N_2O emissions calculations from arable soils as they find that ratio y=N_2O output/fresh fixed nitrogen input is 3-5% and assumes that the same global ratio is true for agro/biofuel production systems. This conclusion has been made based on the "top-down" estimates of nitrous oxide (N_2O) emissions from inputs of newly fixed nitrogen (N) and also considered the large-scale changes in synthetic nitrogen fertilizer production. According to authors, this parametric relationship is not dependent on detailed knowledge of the terrestrial nitrogen cycle but based on the global budgets of nitrous oxide and fixed nitrogen input, well known nitrous oxide lifetime and its concentration in atmosphere.

Table 3.45 : IPCC 2006 Guidelines for N_2O emissions calculations.

	Values	Range		
		Lower	Upper	Units
EF1. Emission factor for N additions (fertilizers, manures, crop residues and changes in SOM)	0.01	0.003	0.03	kg N_2O-N/kg N
EF2. Emission factor for organic soils (temperate)	8	2	24	kg N_2O/ha
EF4. Emission factor from N volatilized and re-deposited	0.01	0.002	0.05	kg N_2O-N/kg N
EF5. Emission factor from N leached	0.0075	0.0005	0.025	kg N_2O-N/kg N
FracGASF. Volatilization from synthetic fertilizer	0.1	0.03	0.3	Proportion
FracGASM. Volatilization from organic addition	0.2	0.05	0.5	Proportion
FracLEACH. Fraction of N leached	0.3	0.1	0.8	Proportion

Sources:
1) IPCC: 2006;
2) Kindred, *et. al.*: 2008

Jatropha curcas requires an initial application of 50 kgN/ha in the first year and then the annual application of nitrogen would be provided by the crop residue and an additional 10 kgN/ha of mineral nitrogen fertilizer top up. Thus in the first 6 years the average annual application would be 17 kgN/ha. The emissions from the artificial fertilizer and crop residues are therefore approximately one third of that than if artificial fertilizers alone were used (Smith: pers. comm.).

Cruitzen, *et. al.* (2007) and lately author's personal communication with Professor Keith Smith of the Edinburgh University reveal that in prior life cycle studies release rates typically are based on the default values estimated by IPCC (2006) for direct emissions which were derived from plot-scale measurements (1% or 1.25% of the nitrogen fertilizer applied). Only very few assessments also include the associated default values for indirect emissions, which combined with direct emissions make overall 1.5% of applied nitrogen fertilizer.

Agreed with conclusion that underestimation of the N_2O release the atmosphere might have an immense impact on climate warming, the value of 3-5% was used for the nitrous oxide emissions estimations: 3% for Low scenarios, 4% for Best scenarios and 5% for High scenarios.

Chapter 4: Low, Best and High scenarios. WTT results before credits

What all the wise man promised has not happened and what all the damned fools said would happen has come to pass.

Lord Melbourne

This chapter presenting WTT results before credits aiming to demonstrate progress in Life Cycle Assessment calculations. It started with Energy inputs and GHG emissions estimations for *Jatropha* oilseed cultivation. Later, it followed by detailed evaluation of input data, and Energy inputs and GHG emissions calculations for logistics and transportation, biodiesel production, biodiesel distribution and glycerine transportation. Finally, by-products credits for surplus electricity, glycerine usage and press-cake utilization as fertilizer (green manure) or as co-fuel for power plant will be expored and discussed.

4.1 Jatropha oilseed cultivation

4.1.1 Irrigated Scenario I: Industrial scale production. One-stage Transesterification Process (90 bar, 240°C)

In terms of Primary total energy input for farming the Models a11, a12, a21, b11, b12, b21, c11, c12, c21, and c22, which utilize fruit hulls and seed shells as fertilizer (green manure), have a value of 5.65-12.83 GJp/$t_{biodiesel}$. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 3.77-10.95 GJp/$t_{biodiesel}$ which is significantly lower than in other scenarios (Appendix IV: Table IV.3, Table IV.15 & Table IV.27).

The farming share of the Primary total energy input has a range of 31.3-51.3% for Models a11, a12 and a21, 28.5-47.9% for Models b11, b12 and b21 and 15.4-39.6% for Models c11, c12, c21 and c21. In this case, the farming share is getting 3.0-3.5% lower for the more efficient Models b11, b12 and b21 which elaborate Combined Heat and Power (CHP) option and 12.0-16.0% lower in Models c11, c12, c21 and c21 equipped with unfired or co-fires Heat Recovery Steam Generator (HRSG) compare to the Models a11, a12 and a21, where the basic fuel input provided by fuel oil, coal and natural gas.

The farming share of the Primary total energy input has a notably lower range of 8.7-21.7% in Models d1, d2 and e, which utilize biomass as co-fuel for power plant.

The farming share of the Primary total energy input and of the GHG emissions before credits (%) for Irrigated scenario I available in Table 4.2.

Charts 4.1, 4.2 and 4.3 represent Energy balance (%) for the following biodiesel production scenario: "Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. Net balance: Press-cake as fertilizer (green manure)" - Low, Best and High scenarios correspondingly. For all three charts the energy balance results for: a) harvesting, storage, drying and transportation; b) manufacture; and c) distribution of biodiesel have the same values between Low, Best and High scenarios. However, the energy balance results for farming (agricultural models) have noticeable difference between Low, Best and High scenarios.

Low fertilizers and agrochemicals requirements for *Jatropha* cultivation presented in Table 3.34 has been used for Low agricultural scenario calculations; Best fertilizers and agrochemicals requirements for *Jatropha* cultivation presented in Table 3.34 has been used for Best agricultural scenario calculations; and High fertilizers and agrochemicals requirements for *Jatropha* cultivation presented in Table 3.34 has been used for High agricultural scenario calculations.

Table 4.1: Cumulative emissions of nitrogen (N_2O_N) and total farming emissions from perennial *Jatropha curcas* under three different irrigation and fertilization regimes

		Scenario Irrigated 1111 trees/ha		Scenario Rainfed I 2500 trees/ha		Scenario Rainfed II 2500 trees/ha	
		Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as cobustibles	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as cobustibles	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as cobustibles
N_2O emissions (sum up per Life Cycle) GHG emissions (kg N2O/ha)							
Low scenario:	Low	40.2	40.2	53.6	53.6	49.8	49.8
kg N2O_N/ kg N= 0.03	Best	91.0	91.0	63.3	63.3	49.8	49.8
	High	159.2	159.2	111.8	111.8	81.6	49.8
Best scenario:	Low	53.6	53.6	71.5	71.5	66.4	66.4
kg N2O_N/ kg N = 0.04	Best	121.3	121.3	84.4	84.4	66.4	66.4
	High	212.2	212.2	149.0	149.0	108.9	66.4
High scenario:	Low	67.1	67.1	89.4	89.4	83.0	83.0
kg N2O_N/ kg N = 0.05	Best	151.7	151.7	105.5	105.5	83.0	83.0
	High	265.3	265.3	186.3	186.3	136.1	83.0
Total for farming (sum up per Life Cycle) GHG emissions (kg CO2eq/ha)							
Low scenario:	Low	34557.6	25289.5	30312.0	17810.0	27242.4	27242.4
kg N2O_N/ kg N= 0.03	Best	63934.3	54671.0	36128.8	23626.8	27242.4	27242.4
	High	102929.4	93661.3	62773.3	49788.4	44674.2	27242.4
Best scenario:	Low	38527.4	29259.3	35602.6	23100.7	32154.2	32154.2
kg N2O_N/ kg N = 0.04	Best	72912.0	63648.7	42372.5	29870.6	32154.2	32154.2
	High	118635.1	109367.0	73799.3	60814.4	52729.5	32154.2
High scenario:	Low	42497.2	33229.1	40893.2	28391.3	37065.9	37065.9
kg N2O_N/ kg N = 0.05	Best	81889.7	72626.4	48616.3	36114.3	37065.9	37065.9
	High	134340.9	125072.8	84825.3	71840.4	60784.7	37065.9

Table 4.2: The farming share before credits (%). Irrigated scenario I

Scenarios	a11	a12	a21	b11	b12	b21	c11	c12	c21	c22	d1	d2	e
Total for farming (sum up per Life Cycle)													
Primary Total Energy Input (%)													
Low scenario:	31.7	31.7	31.3	28.8	28.8	28.5	18.8	22.4	15.4	18.5	8.7	8.7	8.7
Best scenario:	41.9	41.9	41.5	38.6	38.6	38.2	26.5	31.0	22.0	26..1	14.9	14.9	14.9
High scenario:	51.3	51.3	50.9	47.9	47.9	47.5	34.5	39.6	29.2	34.0	21.7	21.7	21.7
Total for farming (sum up per Life Cycle)													
GHG emissions (%)													
Low scenario:	35.0	24.0	39.3	31.9	20.8	36.6	25.7	29.9	21.4	25.3	58.5	58.5	58.2
Best scenario:	59.1	45.8	63.4	55.7	41.3	60.7	48.1	53.3	42.2	47.6	84.3	84.3	84.3
High scenario:	74.3	62.8	77.7	71.6	58.5	75.6	65.0	69.5	59.4	64.5	92.2	92.2	92.2

Chart 4.1: Energy balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Low scenario**

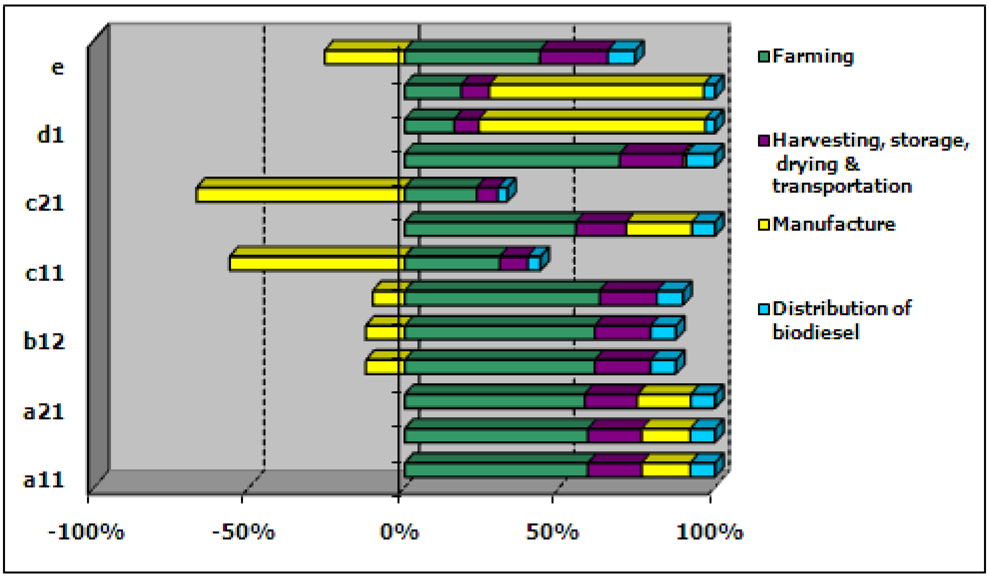


Chart 4.2: Energy balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

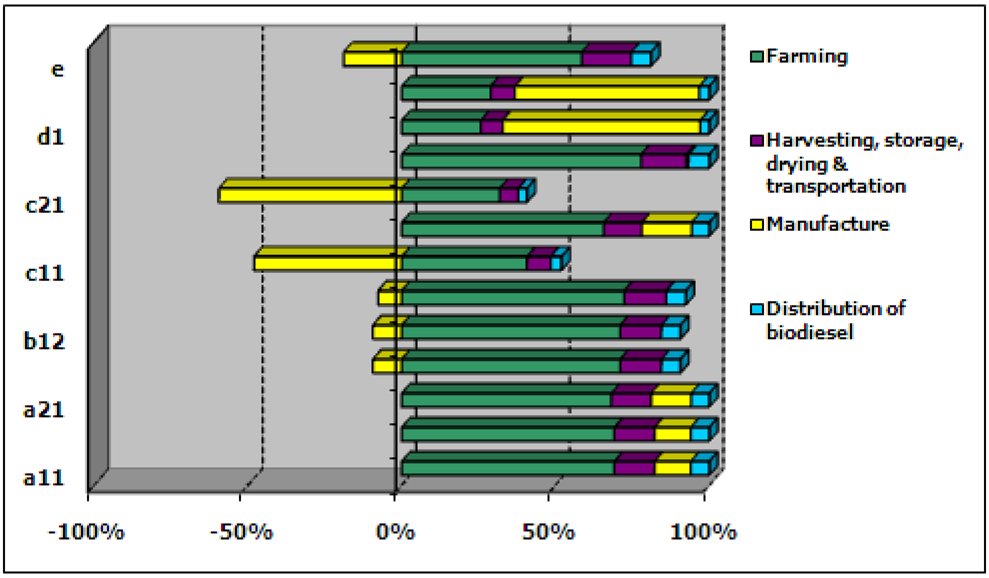
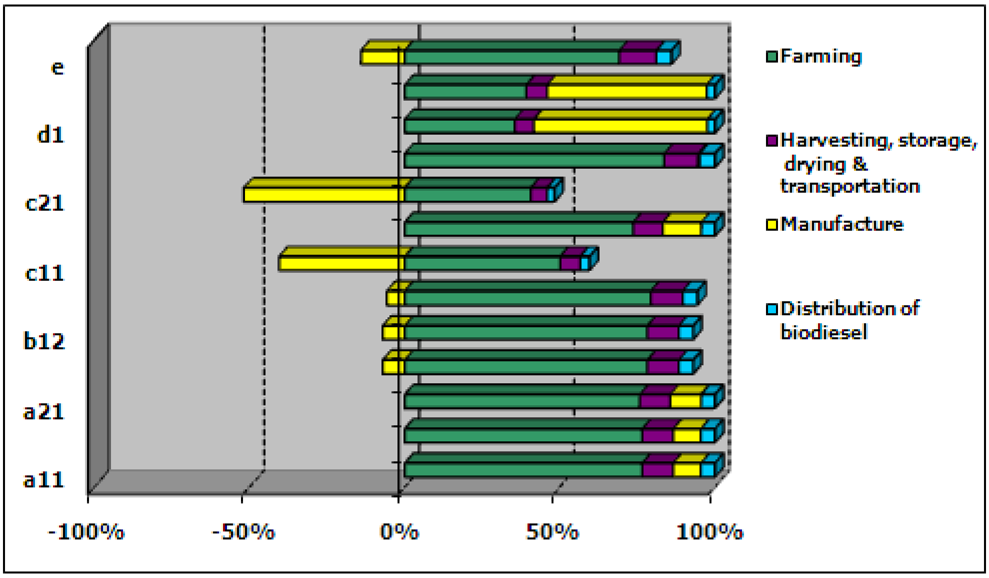


Chart 4.3: Energy balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). High scenario**



In terms of the Total GHG emissions the Models a11, a12, a21, b11, b12, b21, c11, c12, c21, and c22, which utilize biomass as fertilizer (green manure), have a range of 483.2-2,591.4 $kgCO_2eq/t_{biodiesel}$. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 287.4-2,395.6 $kgCO_2eq/t_{biodiesel}$ (Appendix IV: Table IV.3, Table IV.15 & Table IV.27).

The farming share of the GHG emissions has a range of 20.8-77.7% for all Models with no apparent trend between Models. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 58.5-92.2% which is 14.5-38.0% higher compare to other Models (Table 4.2).

4.1.2 Irrigated Scenario II: Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C)

In terms of Primary total energy input for farming the Models a11, a12, a21, b11, b12, b21, c11, c12, c21, and c22, which utilize fruit hulls and seed shells as fertilizer (green manure), have a value of 5.65-12.83 $GJp/t_{biodiesel}$. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 3.77-10.95 $GJp/t_{biodiesel}$ which is significantly lower than in other scenarios (Appendix IV: Table IV.6, Table IV.18 & Table IV.30).

The farming share of the Primary total energy input has a range of 48.4-68.2% for Models a11, a12 and a21, 52.5-71.7% for Models b11, b12 and b21 and 38.6-63.5% for Models c11, c12, c21 and c21. In this case, the farming share is getting 3.5-4.0% higher for the more efficient Models b11, b12 and b21 which elaborate Combined Heat and Power (CHP) option and 4.5-10.0% lower in Models c11, c12, c21 and c21 equipped with unfired or co-fires Heat Recovery Steam Generator (HRSG) compare to the Models a11, a12 and a21, where the basic fuel input provided by fuel oil, coal and natural gas.

The farming share of the Primary total energy input has a notably lower range of 8.7-21.7% in Models d1, d2 and e, which utilize biomass as co-fuel for power plant.

The farming share of the Primary total energy input and of the GHG emissions before credits (%) for Irrigated scenario II available in Table 4.3.

Charts 4.4, 4.5 and 4.6 represent GHG balance (%) for the following biodiesel production scenario: "Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. Net balance: Press-cake use as co-fuel for power plant" - Low, Best and High scenarios correspondingly. For all three charts the GHG balance results for: a) harvesting, storage, drying and transportation; b) manufacture; and c) distribution of biodiesel have the same values between Low, Best and High scenarios. However, the GHG balance results for farming (agricultural models) have noticeable difference between Low, Best and High scenarios.

Cruitzen, *et. al.* (2007) publication and author's personal communication with Professor Keith Smith of the Edinburgh University led to understanding that underestimation of the N_2O release to the atmosphere might have an immense impact on climate warming, and, therefore, value of 3-5% for the kg N_2O_N/kg N factor has to be used for the nitrous oxide emissions estimations.

For Low agricultural scenario kg N_2O_N/kg N = 0.03 factor has been used for the nitrous oxide emissions calculation combined with Low fertilizers and agrochemicals requirements for the *Jatropha* cultivation presented in Table 3.34. For Best agricultural scenario kg N_2O_N/kg N = 0.04 factor has been used for the nitrous oxide emissions calculation combined with Best fertilizers and agrochemicals requirements for the *Jatropha* cultivation presented in Table 3.34. For High agricultural scenario kg N_2O_N/kg N = 0.05 factor has been used for the nitrous oxide emissions calculation combined with High fertilizers and agrochemicals requirements for the *Jatropha* cultivation presented in Table 3.34.

Cumulative emissions of nitrogen and Total farming emissions from perennial *Jatropha curcas* cultivation under three different irrigation and fertilization regimes presented in Table 4.1.

Table 4.3: The farming share before credits (%). Irrigated scenario II

Scenarios	a11	a12	a21	b11	b12	b21	c11	c12	c21	c22	d1	d2	e
Total for farming (sum up per Life Cycle)													
Primary Total Energy Input (%)													
Low scenario:	48.6	48.6	48.4	52.8	52.8	52.5	39.3	43.4	38.6	42.8	8.7	8.7	8.7
Best scenario:	59.5	59.5	59.3	63.5	63.5	63.2	50.1	54.4	49.5	53.8	14.9	14.9	14.9
High scenario:	68.2	68.2	68.0	71.7	71.7	71.5	59.5	63.5	58.8	63.0	21.7	21.7	21.7
Total for farming (sum up per Life Cycle)													
GHG emissions (%)													
Low scenario:	52.2	43.6	54.8	56.0	46.2	59.0	47.4	51.2	46.8	50.7	58.5	58.5	58.5
Best scenario:	74.5	67.4	76.4	77.3	69.7	79.4	70.7	73.8	70.2	73.4	84.3	84.3	84.3
High scenario:	85.4	80.6	86.7	87.2	82.1	88.5	82.9	84.9	82.5	84.6	92.2	92.2	92.2

Chart 4.4: GHG balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake use as co-fuel for power plant. Low scenario**

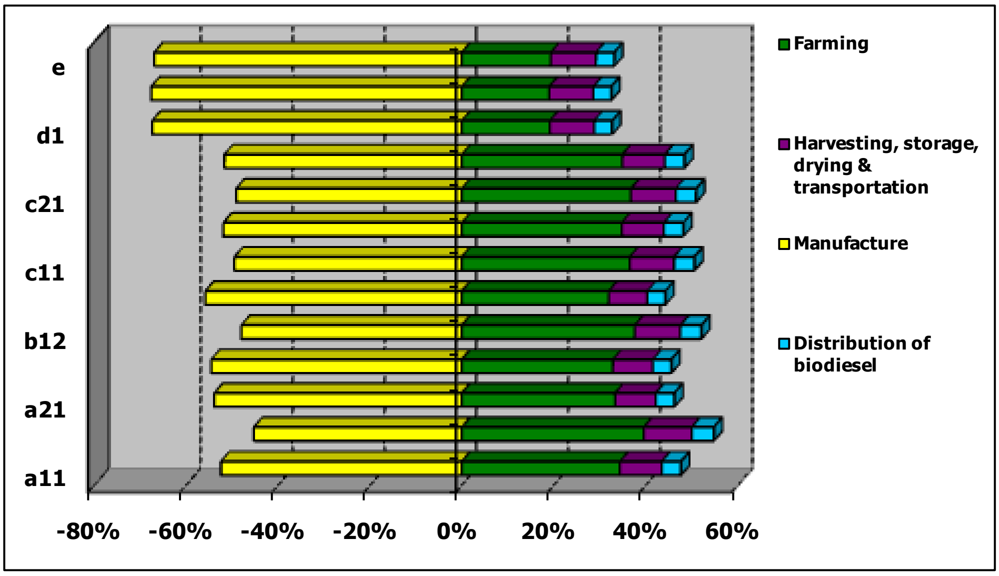


Chart 4.5: GHG balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake use as co-fuel for power plant. Best scenario**

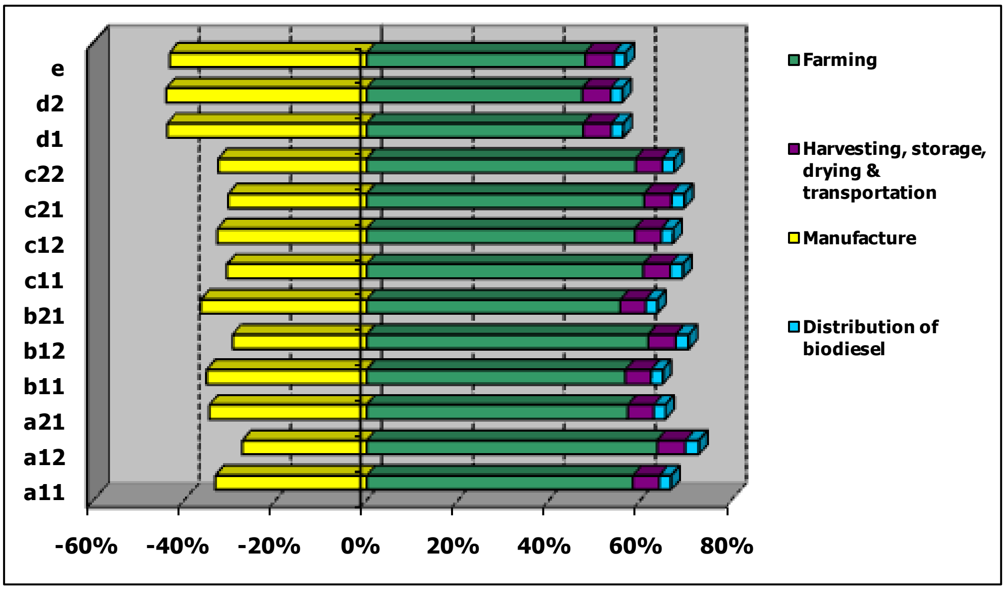
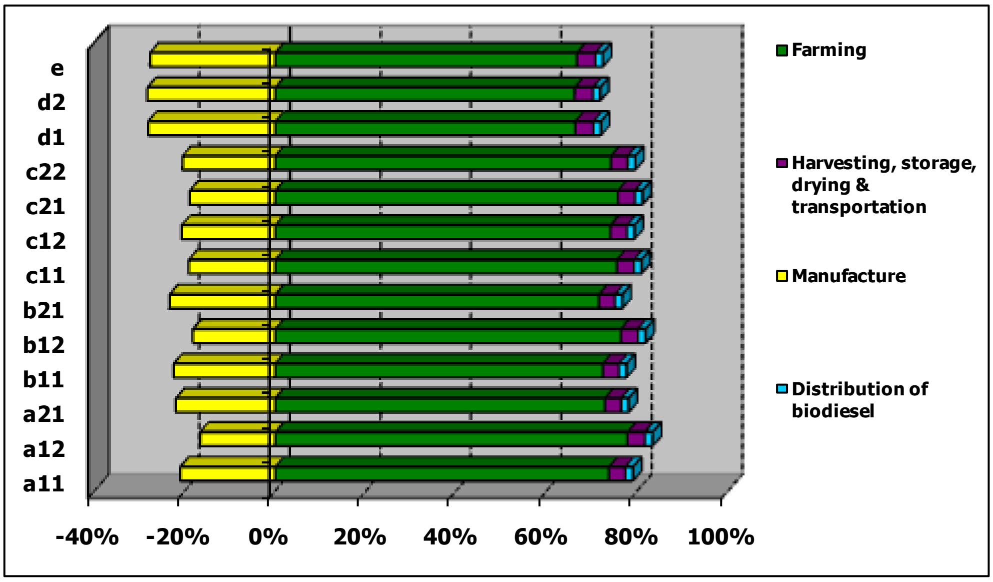


Chart 4.6: GHG balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake use as co-fuel for power plant. High scenario**



In terms of the Total GHG emissions the Models a11, a12, a21, b11, b12, b21, c11, c12, c21, and c22, which utilize biomass as fertilizer (green manure), have a range of 483.2-2,591.4 $kgCO_2eq/t_{biodiesel}$. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 287.4-2,395.6 $kgCO_2eq/t_{biodiesel}$ (Appendix IV: Table IV.6, Table IV.18 & Table IV.30).

The farming share of the GHG emissions has a range of 43.6-88.5% for all Models with no apparent trend between Models. Models d1, d2 and e, which utilize biomass as co-fuel for power plant, have a range of 58.5-92.2% which is 3.5-15.0% higher compare to other Models (Table 4.3).

4.1.3 Rainfed Scenario I: Small-scale production. Organic, chemical fertilizers and agro-chemicals applied. Transesterification Process (1.4 bar, 60°C)

In terms of Primary total energy input for farming the Models a11, a12, a21, f11, f12 and g, which utilize fruit hulls and seed shells as fertilizer (green manure), have a range of 5.04-9.83 $GJp/t_{biodiesel}$. Models h11 and h12, which utilize fruit hulls and seed shells as co-fuel for power plant, have a range of 1.23-5.8 $GJp/t_{biodiesel}$ which is significantly lower than in other scenarios (Appendix IV: Table IV.9, Table IV.21 & Table IV.33).

The farming share of the Primary total energy input has a range of 64.9-78.4% in Models a11, a12, a21, and 67.9-73.0% in Models f11, f12 and g. In this case, the farming share is getting 3.0-5.5% higher for the more efficient Models f11, f12 which elaborate Combined Heat and Power (CHP) option by means of diesel or natural gas fired gensets equipped with Heat Utilization Block (HUB) and Model g equipped with natural gas fired CHP Microturbine compare to the Models a11, a12 and a21, where the basic fuel input provided by fuel oil, coal and natural gas.

The farming share of the Primary total energy input has a has a notably lower range of 2.1-9.1% in Models h11 and h12, which utilize biomass as co-fuel for power plant.

The farming share of the Primary total energy input and of the GHG emissions before credits (%) for Rainfed scenario I available in Table 4.4.

Table 4.4: The farming share before credits (%). Rainfed scenario I

Scenarios	a11	a12	a21	f11	f12	g	h11	h12
Total for farming (sum up per Life Cycle)								
Primary Total Energy Input (%)								
Low scenario:	65.0	65.0	64.9	67.9	69.3	68.5	2.1	2.1
Best scenario:	69.0	69.0	68.9	71.7	73.0	72.2	3.7	3.7
High scenario:	78.4	78.4	78.3	80.5	81.5	80.9	9.1	9.1
Total for farming (sum up per Life Cycle)								
GHG emissions (%)								
Low scenario:	82.8	77.7	84.2	84.0	86.8	86.4	84.0	84.0
Best scenario:	87.0	82.7	88.1	88.0	90.2	89.9	89.8	89.8
High scenario:	93.1	90.6	93.7	93.6	94.8	94.7	95.5	95.5

In terms of the Total GHG emissions the Models a11, a12, a21, f11, f12 and g, which utilize fruit hulls and seed shells as fertilizer (green manure), have a range of 960.6-2,688.2 $kgCO_2eq/t_{biodiesel}$. Models h11 and h12, which utilize fruit hulls and seed shells as co-fuel for power plant, have a range of 564.4-2,276.7 $kgCO_2eq/t_{biodiesel}$ (Appendix IV: Table IV.9, Table IV.21 & Table IV.33).

The farming share of the GHG emissions has a range of 77.4-94.8% for all Models with no apparent trend between Models. Models h11 and h12, which utilize biomass as co-fuel for power plant, have a range of 84.0-95.5% which is 0.5-7.0% higher compare to other Models (Table 4.4).

4.1.4 Rainfed Scenario II: Small-scale production. No fertilizers and agro-chemicals used. Transesterification Process (1.4 bar, 60°C)

In terms of Primary total energy input for farming the Models a11, a12, a21, f11, f12 and g, which utilize fruit hulls and seed shells as fertilizer (green manure), have a range of 3.82-6.26 GJp/$t_{biodiesel.}$ Models h11 and h12, which utilize fruit hulls and seed shells as co-fuel for power plant, have a have the same value of 3.82 GJp/$t_{biodiesel}$ for all scenarios which stays the same or 1.6 times lower than in other scenarios (Appendix IV: Table IV.12, Table IV.24 & Table IV.36).

The farming share of the Primary total energy input has a range of 58.3-69.8% in Models a11, a12, a21, and 61.6-73.8% in Models f11, f12 and g. In this case, the farming share is getting 3.0-4.0% higher for the more efficient Models f11, f12 which elaborate Combined Heat and Power (CHP) option by means of diesel or natural gas fired gensets equipped with Heat Utilization Block (HUB) and Model g equipped with natural gas fired CHP Microturbine compare to the Models a11, a12 and a21, where the basic fuel input provided by fuel oil, coal and natural gas.

The farming share of the Primary total energy input has a has a notably lower value of 6.2% for all scenarios in Models h11 and h12, which utilize biomass as co-fuel for power plant.

The farming share of the Primary total energy input and of the GHG emissions before credits (%) for Rainfed scenario II available in Table 4.5.

Table 4.5: The farming share before credits (%). Rainfed scenario II

Scenarios	a11	a12	a21	f11	f12	g	h11	h12
Total for farming (sum up per Life Cycle) Primary Total Energy Input (%)								
Low scenario:	58.5	58.5	58.3	61.6	63.2	62.2	6.2	6.2
Best scenario:	58.5	58.5	58.3	61.6	63.2	62.2	6.2	6.2
High scenario:	69.8	69.8	69.7	72.5	73.8	73.0	6.2	6.2
Total for farming (sum up per Life Cycle) GHG emissions (%)								
Low scenario:	81.2	75.5	82.4	82.5	85.5	85.1	88.9	88.9
Best scenario:	83.6	78.4	84.9	84.7	87.5	87.1	90.5	90.5
High scenario:	90.6	87.3	91.4	91.3	93.0	92.7	91.6	91.6

In terms of the Total GHG emissions the Models a11, a12, a21, f11, f12 and g, which utilize fruit hulls and seed shells as fertilizer (green manure), have a range of 863.3-1,926.3 $kgCO_2eq/t_{biodiesel}$. Models h11 and h12, which utilize fruit hulls and seed shells as co-fuel for power plant, have a range of 863.3-1,174.65 $kgCO_2eq/t_{biodiesel}$ (Appendix IV: Table IV.12, Table IV.24 & Table IV.36).

The farming share of the GHG emissions has a range of 75.5-93.0% for all Models with no apparent trend between Models. Models h11 and h12, which utilize biomass as co-fuel for power plant, have a range of 88.9-91.6% which is 1.5% lower or up to 13.5% higher compare to other Models (Table 4.5).

Table 4.6: *Jatropha* oilseed production and supply (Irrigated scenarios I & II. Best)

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as combustibles
B1. Jatropha trees planting				
Diesel for irrigation				
Consumption	GJ/ha/a	4.51		
Credit for use of set-aside	GJ/ha	0.0		
Total primary energy	GJp/ha	5.23		
Total GHG emissions	kg CO_2/ha	402.92		
Agrochemicals and fertilizers				
Usage				
Manuring (Organic fertilizers)				
Top dressing (years 6-30)	kg/ha/a			
Total organic fertilizers applied				
Low			2780	2780
Best			5830	2780
High			6210	2780
K fertilizer (as K2O equivalent)				
Low			68	68
Best			100	68
High			128	68
P fertilizer (as P2O5 eqivalent)				
Low			15	15
Best			47	15
High			68	15
N fertilizer (as N equivalent)				
Low			49	49
Best			71	49
High			85	49
Fertilizer management				
Basal dressing	kg/ha			
K fertilizer (as K2O equivalent)				
Low			11	11
Best			24	24
High			44	44
P fertilizer (as P2O5 equivalent)				
Low			17	17
Best			28	28
High			50	50
N fertilizer (as N equivalent)				
Low			11	11
Best			33	33
High			56	56
Top dressing (years 1-5)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			21	21
Best			100	100
High			180	180
P fertilizer (as P2O5 equivalent)				
Low			28	28
Best			144	144
High			260	260
N fertilizer (as N equivalent)				
Low			20	20
Best			100	100
High			175	175
Top dressing (years 6-30)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			0	0
Best			0	32
High			52	112
P fertilizer (as P2O5 equivalent)				
Low			13	13
Best			97	129
High			192	245
N fertilizer (as N equivalent)				
Low			0	0
Best			29	51
High			90	126
Pesticides & Fungicides	kg/ha		27.2	27.2
Seed material			2.7	2.7
Production primary energy	GJ/t			
K fertilizer		6.7		
P fertilizer		11.1		
N fertilizer		60.0		
Pesticides & Fungicides		315.0		
Seed material		25.5		
Production GHG emissions	kg CO_2eq/kg			
K fertilizer		0.46		
P fertilizer		0.71		
N fertilizer		6.69		
Pesticides & Fungicides		5.41		
Seed material		0.87		

Table 4.6 (cont):

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as combustibles
Organic fertilizers (sum up per Life Cycle)	GJ/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			11.3	11.3
Best			16.7	11.3
High			21.4	11.3
P fertilizer (as P2O5 equivalent)				
Low			4.1	4.1
Best			13.0	4.1
High			18.7	4.1
N fertilizer (as N equivalent)				
Low			73.8	73.8
Best			105.8	73.8
High			127.7	73.8
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			0.78	0.78
Best			3.5	8.9
High			15.1	25.2
P fertilizer (as P2O5 equivalent)				
Low			5.4	5.4
Best			35.3	44.2
High			68.4	83.0
N fertilizer (as N equivalent)				
Low			6.7	6.7
Best			76.1	108.1
High			190.4	244.4
Pesticides & Fungicides			8.6	8.6
Seed material			0.07	0.07
Organic fertilizers (sum up per Life Cycle)	kg CO_2eq/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			776.9	776.9
Best			1145.2	776.9
High			1467.2	776.9
P fertilizer (as P2O5 equivalent)				
Low			261.5	261.5
Best			830.0	261.5
High			1199.1	261.5
N fertilizer (as N equivalent)				
Low			8229.7	8229.7
Best			11800.5	8229.7
High			14253.2	8229.7
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			53.4	53.4
Best			241.0	614.2
High			1037.1	1727.4
P fertilizer (as P2O5 equivalent)				
Low			346.9	346.9
Best			2257.1	2825.6
High			4374.4	5312.0
N fertilizer (as N equivalent)				
Low			742.6	742.6
Best			8490.3	12061.1
High			21243.9	27267.4
Pesticides & Fungicides			147.34	147.34
Seed material			2.35	2.35
Nitrogen returned by Jatropha leaf fall (sum up per Life Cycle)	kg N/ha	1230.2		
N_2O emissions (sum up per Life Cycle)	kg N_2O/ha			
Low			53.6	53.6
Best			121.3	121.3
High			212.2	212.2
Total primary energy required	GJp/ha			
Low			110.7	21.5
Best			259.0	169.9
High			450.4	361.2
Total GHG emissions	kg CO_2eq/ha			
Low			10560.7	1292.6
Best			24913.7	15650.5
High			43724.6	34456.5
Total for farming (sum up per Life Cycle)				
Primary energy	GJp/ha			
Low			267.6	178.5
Best			415.9	326.8
High			607.4	518.2
GHG emissions	kg CO2eq/ha			
Low			38527.4	29259.3
Best			72912.0	63648.7
High			118635.1	109367.0

Table 4.7: *Jatropha* oilseed production and supply (Rainfed scenario I. Best)

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as combustibles
B1. Jatropha trees planting				
Diesel for irrigation				
Consumption	GJ/ha/a	0.0		
Credit for use of set-aside	GJ/ha	0.0		
Total primary energy	GJp/ha	0.0		
Total GHG emissions	kg CO_2/ha	0.0		
Agrochemicals and fertilizers				
Usage				
Manuring (Organic fertilizers)				
Top dressing (years 6-30)	kg/ha/a			
Total organic fertilizers applied				
Low			3750	3750
Best			3750	3750
High			6150	3750
K fertilizer (as K2O equivalent)				
Low			91	91
Best			91	91
High			133	91
P fertilizer (as P2O5 eqivalent)				
Low			20	20
Best			20	20
High			57	20
N fertilizer (as N equivalent)				
Low			66	66
Best			66	66
High			92	66
Fertilizer management				
Basal dressing	kg/ha			
K fertilizer (as K2O equivalent)				
Low			11	11
Best			60	60
High			100	100
P fertilizer (as P2O5 equivalent)				
Low			22	22
Best			45	45
High			63	63
N fertilizer (as N equivalent)				
Low			13	13
Best			75	75
High			125	125
Top dressing (years 1-5)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			24	24
Best			60	60
High			95	95
P fertilizer (as P2O5 equivalent)				
Low			48	48
Best			80	80
High			122	122
N fertilizer (as N equivalent)				
Low			23	23
Best			75	75
High			120	120
Top dressing (years 6-30)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			0	0
Best			0	0
High			0	0
P fertilizer (as P2O5 equivalent)				
Low			28	28
Best			60	60
High			65	102
N fertilizer (as N equivalent)				
Low			0	0
Best			0	0
High			28	54
Pesticides & Fungicides	kg/ha		61.2	61.2
Seed material			6.0	6.0
Production primary energy	GJ/t			
K fertilizer		6.7		
P fertilizer		11.1		
N fertilizer		60.0		
Pesticides & Fungicides		315.0		
Seed material		25.5		
Production GHG emissions	kg CO_2eq/kg			
K fertilizer		0.46		
P fertilizer		0.71		
N fertilizer		6.69		
Pesticides & Fungicides		5.41		
Seed material		0.87		

Table 4.7 (cont):

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as combustibles
Organic fertilizers (sum up per Life Cycle)	GJ/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			15.3	15.3
Best			15.3	15.3
High			22.3	15.3
P fertilizer (as P2O5 equivalent)				
Low			5.5	5.5
Best			5.5	5.5
High			15.8	5.5
N fertilizer (as N equivalent)				
Low			99.5	99.5
Best			99.5	99.5
High			137.3	99.5
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			0.88	0.88
Best			2.41	2.41
High			3.9	3.9
P fertilizer (as P2O5 equivalent)				
Low			10.7	10.7
Best			21.6	21.6
High			25.6	35.8
N fertilizer (as N equivalent)				
Low			7.7	7.7
Best			27.0	27.0
High			86.1	123.9
Pesticides & Fungicides			19.3	19.3
Seed material			0.15	0.15
Organic fertilizers (sum up per Life Cycle)	kg CO_2eq/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			1047.9	1047.9
Best			1047.9	1047.9
High			1530.9	1047.9
P fertilizer (as P2O5 equivalent)				
Low			352.8	352.8
Best			352.8	352.8
High			1008.8	352.8
N fertilizer (as N equivalent)				
Low			11101.2	11101.2
Best			11101.2	11101.2
High			15315.9	11101.2
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			60.3	60.3
Best			165.6	165.6
High			264.5	264.5
P fertilizer (as P2O5 equivalent)				
Low			685.2	685.2
Best			1383.2	1383.2
High			1634.5	2290.5
N fertilizer (as N equivalent)				
Low			856.3	856.3
Best			3010.5	3010.5
High			9604.3	13819.0
Pesticides & Fungicides			331.1	331.1
Seed material			5.22	5.22
Nitrogen returned by Jatropha leaf fall (sum up per Life Cycle)	kg N/ha	1659.4		
N_2O emissions (sum up per Life Cycle)	kg N_2O/ha			
Low			71.5	71.5
Best			84.4	84.4
High			149.0	149.0
Total primary energy required	GJp/ha			
Low			159.0	38.7
Best			190.7	70.4
High			310.3	182.9
Total GHG emissions	kg CO_2eq/ha			
Low			14440.1	1938.1
Best			17397.5	4895.6
High			29695.3	16710.4
Total for farming (sum up per Life Cycle)				
Primary energy	GJp/ha			
Low			159.0	38.7
Best			190.7	70.4
High			310.3	182.9
GHG emissions	kg CO2eq/ha			
Low			35602.6	23100.7
Best			42372.5	29870.6
High			73799.3	60814.4

Table 4.8: ***Jatropha*** **oilseed production and supply (Rainfed scenario II. Best)**

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as cobustibles
B1. Jatropha trees planting				
Diesel for irrigation				
Consumption	GJ/ha/a	0.0		
Credit for use of set-aside	GJ/ha	0.0		
Total primary energy	GJp/ha	0.0		
Total GHG emissions	kg CO_2/ha	0.0		
Agrochemicals and fertilizers				
Usage				
Manuring (Organic fertilizers)				
Top dressing (years 6-30)	kg/ha/a			
Total organic fertilizers applied				
Low			3750	3750
Best			3750	3750
High			6150	3750
K fertilizer (as K2O equivalent)				
Low			91	91
Best			91	91
High			149	91
P fertilizer (as P2O5 eqivalent)				
Low			20	20
Best			20	20
High			33	20
N fertilizer (as N equivalent)				
Low			66	66
Best			66	66
High			109	66
Fertilizer management				
Basal dressing	kg/ha			
K fertilizer (as K2O equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
P fertilizer (as P2O5 equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
N fertilizer (as N equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
Top dressing (years 1-5)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
P fertilizer (as P2O5 equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
N fertilizer (as N equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
Top dressing (years 6-30)	kg/ha/a			
K fertilizer (as K2O equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
P fertilizer (as P2O5 equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
N fertilizer (as N equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
Pesticides & Fungicides	kg/ha		0.0	0.0
Seed material			6.0	6.0
Production primary energy	GJ/t			
K fertilizer		6.7		
P fertilizer		11.1		
N fertilizer		60.0		
Pesticides & Fungicides		315.0		
Seed material		25.5		
Production GHG emissions	kg CO_2eq/kg			
K fertilizer		0.46		
P fertilizer		0.71		
N fertilizer		6.69		
Pesticides & Fungicides		5.41		
Seed material		0.87		

Table 4.8 (cont):

Case		Basic Energy Inputs	Fruit hulls and seed shells used as compost	Fruit hulls and seed shells used as cobustibles
Organic fertilizers (sum up per Life Cycle)	GJ/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			15.3	15.3
Best			15.3	15.3
High			25.0	15.3
P fertilizer (as P2O5 equivalent)				
Low			5.5	5.5
Best			5.5	5.5
High			9.0	5.5
N fertilizer (as N equivalent)				
Low			99.5	99.5
Best			99.5	99.5
High			163.2	99.5
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
P fertilizer (as P2O5 equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
N fertilizer (as N equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
Pesticides & Fungicides			0.0	0.0
Seed material			0.15	0.15
Organic fertilizers (sum up per Life Cycle)	kg CO_2eq/ha			
Top dressing				
K fertilizer (as K2O equivalent)				
Low			1047.9	1047.9
Best			1047.9	1047.9
High			1718.6	1047.9
P fertilizer (as P2O5 equivalent)				
Low			352.8	352.8
Best			352.8	352.8
High			578.6	352.8
N fertilizer (as N equivalent)				
Low			11101.2	11101.2
Best			11101.2	11101.2
High			18206.0	11101.2
Chemical fertilizers (sum up per Life Cycle)				
K fertilizer (as K2O equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
P fertilizer (as P2O5 equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
N fertilizer (as N equivalent)				
Low			0.0	0.0
Best			0.0	0.0
High			0.0	0.0
Pesticides & Fungicides			0.0	0.0
Seed material			5.22	5.22
Nitrogen returned by Jatropha leaf fall (sum up per Life Cy	kg N/ha	1659.4		
N_2O emissions (sum up per Life Cycle)	kg N_2O/ha			
Low			66.4	66.4
Best			66.4	66.4
High			108.9	66.4
Total primary energy required	GJp/ha			
Low			120.4	120.4
Best			120.4	120.4
High			197.4	120.4
Total GHG emissions	kg CO_2eq/ha			
Low			12507.2	12507.2
Best			12507.2	12507.2
High			20508.4	12507.2
Total for farming (sum up per Life Cycle)				
Primary energy	GJp/ha			
Low			120.4	120.4
Best			120.4	120.4
High			197.4	120.4
GHG emissions	kg CO2eq/ha			
Low			32154.2	32154.2
Best			32154.2	32154.2
High			52729.5	32154.2

After juxtaposition of the Total primary energy requirements for the *Jatropha* oilseed cultivation and Total GHG emissions from the fertilizers and agrochemical use for all three scenarios, for Irrigated and Rainfed scenarios separately, Scenario III for fertilizers applications described in subchapter 3.11.1: "Fertilizers and agrochemicals applications", were selected for the further LCA calculations as a most energy intensive and least favorable in terms of GHG emissions (Tables 4.6 & 4.7).

In both Irrigated and Rainfed cases the *Jatropha* oilseeds are assumed to be sundried with no additional energy inputs. Harvesting, handling and storage of oilseeds in conditions of Indian cheap and abundant labour force will not required additional hydrocarbon energy carriers or electricity inputs.

4.2 Logistics and transportation

Regarding the collection of oilseed, biomass, fruits hulls and seed shells, calculations were based on the assumption that for oilseed, *Jatropha* oil, biomass, fruits hulls and seed shells transportation a medium sized truck will travel an average 35-100 km one way and heavy duty truck will travel an average 200-300 km one way for methanol delivery to the large-scale transesterification plant. For small-scale biodiesel production scenarios, calculations were based on the assumptions that a light truck travelling up to 55 km for oilseed, biomass, fruits hulls and seed shells transportation and 30-55 km for methanol transportation (Balachandra: pers. comm.).

Table 4.9: Data for modern India vehicle fleet and its energy performance

Medium-duty truck (diesel)								
GVW[a)]	**Life time**	**Mileages**	**Load factor**	**Payload**	**Land use**	**Specific fuel consumption[b)]**		
t	years	km/year	%	t	m^2	g/km	l/100km	MJ/km
9.0	30	25,000	50	5.8		153.8	18.5	7.03
Heavy-duty truck (diesel)								
18.0	30	40,000	50	11.2		207.8	25.0	9.50
Light truck (India)								
0.8	10				180.0			9.9964956
Truck (India)								
10.0	10				10×10^3			19.619290

Notes:
a) GVW - permitted gross vehicle weight;
b) Specific fuel consumption of vehicles used for freight traffic (Rural traffic mode. Moderate and/or Advanced emission control system).
c) Fuel efficiency is vary from 2.94 (Arunachal Pradesh) to 5.30 (Gujarat) km per liter.
In Karnataka it corresponds to 4.46/4.87/5.01 km per liter (2001-2002).

Sources:
1) Schmied. Öko-Institute. EM Database: Transport;
2) GEMIS 4.2

Table 4.10: Data for modern India vehicle fleet and its emissions performance

GVW[a)]	Emission factors (g/km)[b)]					
t	CO	NOx	NMVOC	CH_4	N_2O	Particulates
Medium-duty truck (diesel)						
9.0	1.737/1.544	3.283/2.818	0.974/0.866	0.024/0.021	0.03/0.03	0.355/0.133
Heavy-duty truck (diesel)						
18.0	1.984/1.764	5.224/4.478	0.994/0.884	0.024/0.022	0.03/0.03	0.383/0.144

Notes:
a) GVW - permitted gross vehicle weight;
b) Specific emission factors of vehicles used for freight traffic (Rural traffic mode. Moderate and/or Advanced emission control system).

Source: Schmied. Öko-Institute. EM Database: Transport

Data for typical for contemporary India vehicle fleet and its energy and emissions performance were accepted as summarized in Tables 4.9 and 4.10.

The different types of roads in India are: National Highways, State Highways, major district roads, minor district roads, and village roads (Dattatri & Bhatt: 1985). The road transport mode option is based on fossil diesel use. The GHG emission factor is based on diesel consumption for road freight of 0.53 MJ/t*km for Heavy-duty truck and 0.781 MJ/t*km for Medium-duty truck (Table 4.9) (Öko-Institute. EM Database: Transport) and the GHG emissions factor for diesel burning of 89.3 kgCO_2eq/GJ (GEMIS 4.2). For oilseed, *Jatropha* oil, biomass, fruits hulls and seed shells transportation delivery range was considered as 55 km for both Irrigates and Rainfed scenarios; and 250 km and 55 km respectively for Irrigated and Rainfed scenarios for methanol transportation (Balachandra: pers. comm.). The diesel consumption for transport to end use includes an allowance for an empty return trip after delivery of biodiesel over the specific one-way distance.

The total energy and GHG emissions associated with the production and transportation of the oilseeds to the trans/esterification plant are shown at the Table 4.11 for Irrigated scenario and in Table 4.12 for Rainfed scenario. The higher digits for the 'fruits hulls and seed shells used as fertilizer' case reflect the higher fertilizer input.

Table 4.11: Energy inputs and GHG emissions for transportation and total for oilseed at biodiesel plant gate. Irrigated scenario

B3. Oilseed, Jatropha oil, biomass, fruits hulls and seed shells transportation				
Mode		Road/diesel fuel		
Distance (one-way)	km	55		
Diesel consumption for road transport	MJ/t.km	0.781		
Requirement per tonne transported (round trip)				
Primary energy	GJp/t	0.10		
GHG emissions	kg CO_2eq/t	7.7		
Total for oilseed at biodiesel plant gate				
Primary energy	GJp/t oilseed			
Low			52.01	34.68
Best			80.67	63.35
High			117.66	100.33
GHG emissions	kg CO_2/t oilseed			
Low			7467.94	5669.33
Best			14112.30	12314.62
High			22947.69	21149.08
B4. Methanol transportation				
Mode		Road/diesel fuel		
Distance (one-way)	km	250		
Diesel consumption for road transport	MJ/t.km	0.528		
Requirement per tonne transported (round trip)				
Primary energy	GJp/t	0.306		
GHG emissions	kg CO_2eq/t	23.6		

Table 4.12: Energy inputs and GHG emissions for transportation and total for oilseed at biodiesel plant gate. Rainfed scenario

B3. Oilseed, Jatropha oil, biomass, fruits hulls and seed shells transportation				
Mode		Road/diesel fuel		
Distance (one-way)	km	55		
Diesel consumption for road transport	MJ/t.km	0.781		
Requirement per tonne transported (round trip)				
Primary energy	GJp/t	0.100		
GHG emissions	kg CO_2eq/t	7.7		
Total for oilseed at biodiesel plant gate				
Primary energy	GJp/ t oilseed			
Low			46.38	11.42
Best			55.58	20.62
High			90.23	53.23
GHG emissions	kg CO2/ t oilseed			
Low			10342.62	6711.19
Best			12304.91	8673.49
High			21414.14	17642.71
B4. Methanol/Ethanol transportation				
Mode		Road/diesel fuel		
Distance (one-way)	km	55		
Diesel consumption for road transport	MJ/t.km	0.53		
Requirement per tonne transported (round trip)				
Primary energy	GJp/t	0.07		
GHG emissions	kg CO_2eq/t	5.19		

4.3 Biodiesel production and distribution

4.3.1 Process chains

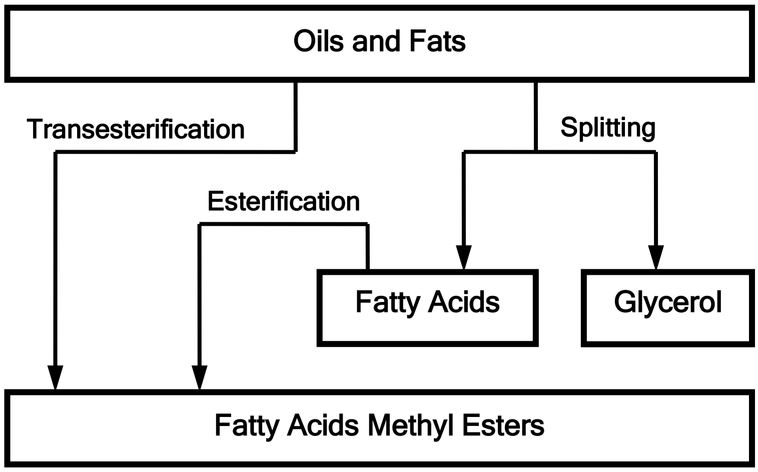
Regarding the biodiesel production stage of this LCA, energy and greenhouse gas balances calculated for a hypothetical plant on a production scale of 1,000.0 tonnes of oilseeds per day (101,524.4 tonnes of biodiesel per year) for a large industrial transesterification plant and 10.0 tonnes of oilseeds per day (1,015.2 tonnes of biodiesel per year) for small-scale local production, using the three following technologies currently in operation in the EU for reference: a) One-stage Henkel Transesterification Process (90 bar, 240^{o}C); b) Two-stages Lurgi process. Fat-splitting (60 bar, 260^{o}C) and Esterification (10 bar, 240^{o}C); c) Small-scale Transesterification Process (1.4 bar, 60^{o}C).

4.3.1.1 Processes for industrial and small-scale biodiesel production

The detailed descriptions of chemical processes and technologies selected for the Life Cycle Assessment calculations described by Gervajio (2005).

Methyl esters of fatty acids can be made either by esterification of the fatty acids or transesterification of the triglycerides using methanol (Figure 4.1).

Figure 4.1: Fatty Acids Methyl Esters derived from natural fats and oils



Sources:
1) Gervajio: no date;
2) Brackman, *et. al.*: 1984

4.3.1.2 Fat-splitting processes

There are at least four known methods of fat splitting. These are (1) Twitchell process, (2) batch autoclave process, (3) continuous process, and (4) enzymatic process. At the first stage of the Fatty Acid Methyl Esthers production scenario is a Lurgi single-stage countercurrent splitting plant employed using the continuous countercurrent, high-pressure fat-splitting process, more popularly known as the Colgate-Emery process, is the most efficient of the current methods of fat hydrolysis.

In this process, the deaerated fat is introduced by means of a sparge ring, around 1 m from the bottom with a high-pressure pump. Degrees of splitting up to 99% can be reached (Gervajio: 2005). Water is introduced near the top at a ratio of 40-50% of the weight of the fat. The high splitting temperature (250-260^{o}C) ensures adequate dissolution of the water phase into the fat so that mechanical means for bringing the two phases into contact are not required. The high temperature and pressure used permit short reaction time. Full countercurrent flow of oil and water produces a high degree of splitting without the need of a catalyst. However, a catalyst may be used to increase reaction rate further (Lurgi: 1991 cited by Gervajio: 2005).

The continuous countercurrent high-pressure process splits fats and oils more efficiently than other processes in a reaction time of only 2-3 hrs. Some insignificant discoloration of the fatty acids occurs. As a result of the efficient internal heat exchange, this process affords high steam economy.

4.3.1.3 Esterification processes

There are two general methods used for esterification: the batch process and the continuous process. Henkel has developed a continuous countercurrent esterification using a doubleplate reaction column. The technology is based on the principle of an esterification reaction with the simultaneous absorption of the superheated methanol vapor and desorption of the methanol–water mixture.

The Henkel continuous process of fatty acid esterification reaction is carried out at a pressure close to 1,000 kPa and a temperature of 240^{o}C. One advantage of this process is the excess methanol can be kept significantly lower at 1.5:1 molar ratio of methanol: fatty acid versus the batch process at 3-4:1 molar ratio. The methyl ester, having undergone distillation, does not require further refining. The excess methanol is rectified and reused (Kreutzer: 1984 cited by Gervajio: 2005).

The continuous esterification process is superior to the batch process, in that the same high yield can be obtained in a much shorter dwell time and with substantially less excess methanol. The esterification process is a preferred method for the production of esters from specific fatty acids (Ibid.).

The basic energy requirements for the Two-stage biodiesel production process: Fat-splitting (60 bar, 260°C) and Esterification (10 bar, 240°C), excluding by-product credits are shown in Table 4.13:

Table 4.13: Energy requirements for biodiesel production. Industrial scale production. Two-stage process. Fat-splitting and Esterification

Energy requirement		
Oil extraction		
Electrical energy for oil extraction		
Oil extraction	kWh/t oilseed	7.0
Other processes	kWh/t oilseed	5.0
Total energy for oil extraction	kWh/t oilseed	12.0
Oil extraction	GJe/t oilseed	0.02926
Other processes	GJe/t oilseed	0.02090
Total energy for oil extraction	GJe/t oilseed	0.05016
Primary energy for oil extraction		
Oil extraction	GJp/t oilseed	0.084
Other processes	GJp/t oilseed	0.060
Total primary energy for oil extraction	GJp/t oilseed	0.144
Fat-Splitting and auxiliaries		
As heat	t steam/t oilseed	0.19
	GJ heat /t oilseed	0.441
As electricity	kWh/t oilseed	10.0
	GJe /t oilseed	0.036
Esterification and auxiliaries		
As heat	t steam/t biodiesel	0.25
	t steam/t oilseed	0.0762
	GJ heat /t oilseed	0.128
As electricity	kWh/t oilseed	13.0
	GJe /t oilseed	0.0468
Press-cake drying (heat)	GJ heat /t oilseed	0.0
Total energy requirements		
As heat	GJ heat/t oilseed	0.57
	GJ heat/t biodiesel	1.87
As electricity	kWh/t oilseed	35.0
	GJe/t oiseed	0.13
	GJe/t biodiesel	0.4133
Biodiesel yield	t oiseed/t biodiesel	3.28

In case of the Two-stage industrial scale biodiesel production process electricity is required for the oil extraction from the oilseeds as well as for fat splitting, esterification and auxiliaries' processes, including running of pump drives, lighting and control devices. At the same time, much more energy as a steam heat is required for the oil extraction, fat splitting and esterification. The amount of primary energy needed to supply basic listed above requirements depends on the different scenarios represented by the various models (LowCVP: 2004).

The energy (electricity and heat) supply scenarios for trans/esterification plant were studied in depth in the Energy Conservation & Development Division (EC & DD) at the Central Power Research Institute, Bangalore in November 2005 - March 2006, supervised by Dr. Bhatt, Joint Director of CPRI, Head of the EC & DD. The EC & D Division is a team of qualified engineers for providing energy services like conducting energy audits and energy managers training. This Division has been accredited by Bureau of Energy Efficiency (BEE), New Delhi for conducting energy audit and energy conservation service for a variety of customers for more than one and a half decade in several energy intensive industries, thermal power stations, hydroelectric power stations, oil refineries, refrigeration and air conditioning plants and buildings, *etc*. The generating, distribution and utilization segments of the power sector and the fuel sector are covered by EC & DD as well. Division also takes up a number of R&D projects for the energy sector. Some of the areas of R&D are energy conservation, modeling, simulation and development of energy instrumentation (CPRI website, Bhatt: pers. comm.).

The results for the energy consumption and GHG emissions in the biodiesel plant for the Industrial scale production, two-stage biodiesel production process is given in Table 4.9.

4.3.1.4 Transesterification processes

Transesterification of fats and oils is the most commonly used process for the manufacture of methyl esters, except in cases where methyl esters of specific fatty acids are needed.

Triglycerides can be transesterified batchwise at atmospheric pressure and at a slightly elevated temperature of approximately 60-70^{o}C with an excess of methanol and in the presence of an alkaline catalyst.

This batchwise transesterification technology was chosen for the Life Cycle Assessment small-scale biodiesel production at 0.14 MPa (1.4 bar) and 60^{o}C.

The basic energy requirements for the Small-scale Transesterification Process (1.4 bar, 60^{o}C), excluding by-product credits are shown in the Table 4.14:

Table 4.14: Energy requirements for biodiesel production. Small-scale production. Transesterification Process

Energy requirement		
Oil extraction		
Oil extraction with electricity-driven press		
As heat	GJ heat /t oilseed	0.139
As electricity	GJe /t oilseed	0.0225
Oil extraction with hand-press		
As human power	GJ/t oilseed	0.008387
Transesterification		
As heat	t steam/t biodiesel	0.25
	t steam/t oilseed	0.0762
	GJ heat/t oilseed	0.128
As electricity	GJe/t oilseed	0.0468
Press-cake drying (heat)	GJ heat/t oilseed	0.0
Total energy requirements		
As heat	GJ heat/t oilseed	0.2670
	GJ heat/t biodiesel	0.876
As electricity	GJe/t oiseed	0.0693
	GJe/t biodiesel	0.2273
Biodiesel yield	t oiseed/t biodiesel	3.28

The mild reaction conditions, however, requires the removal of free fatty acids from the oil by refining or pre-esterification before transesterification. This pretreatment is not required if the reaction is carried out under high pressure (9,000 kPa) and high temperature (240^{o}C). Under these conditions, simultaneous esterification and transesterification take place (Kreutzer: 1984 cited by Gervajio: 2005). The mixture at the end of the reaction is allowed to settle. The lower glycerine layer is drawn off whereas the upper methyl ester layer is washed to remove entrained glycerin and is then processed further. The excess methanol is recovered in the condenser, sent to a rectifying column for purification, and recycled.

Continuous transesterification is well suited for large capacity requirements and was chosen as a second industrial scale technology for the Life Cycle Analysis. Depending on the quality of the feedstock, the unit can be designed to operate at high pressure and high temperature or at atmospheric pressure and slightly elevated temperature. Henkel transesterification process operated at 9,000 kPa pressure and 240^{o}C using unrefined oil as feedstock. Unrefined oil, methanol in excess, and catalyst are metered and heated to 240^{o}C before feeding into the reactor. The bulk of the excess methanol is flashed off as it leaves the reactor and is fed to a bubble tray column for purification. The recovered methanol is recycled into the system. The mixture from the reactor enters a separator where the glycerin in excess of 90% concentration is removed. The methyl ester is subsequently fed to a distillation column for purification. Further fractionation into special cuts may follow if desired (Kreutzer: 1984 cited by Gervajio: 2005).

The basic energy requirements for the One-stage Transesterification Process (90 bar, 240^{o}C), excluding by-product credits are shown in Table 4.15:

Table 4.15: Energy requirements for biodiesel production. Industrial scale production. One-stage Transesterification Process

Energy requirement		
Oil extraction		
Electrical energy for oil extraction		
Oil extraction	kWh/t oilseed	7.0
Other processes	kWh/t oilseed	5.0
Total energy for oil extraction	kWh/t oilseed	12.0
Oil extraction	GJe/t oilseed	0.02926
Other processes	GJe/t oilseed	0.02090
Total energy for oil extraction	GJe/t oilseed	0.05016
Primary energy for oil extraction		
Oil extraction	GJp/t oilseed	0.084
Other processes	GJp/t oilseed	0.060
Total primary energy for oil extraction	GJp/t oilseed	0.144
Transesterification and auxiliaries		
As heat	t steam/t biodiesel	0.25
	t steam/t oilseed	0.0762
	GJ heat /t oilseed	0.128
As electricity	kWh/t oilseed	13.0
	GJe /t oilseed	0.0468
Press-cake drying (heat)	GJ heat /t oilseed	0.0
Primary thermal energy in boiler (steam generator)		
Heating	t steam/t oilseed	0.08
Boiling	t steam/t oilseed	0.08
Water removal	t steam/t oilseed	0.20
Drying	t steam/t oilseed	0.08
Total primary energy for generation of steam	t steam/t oilseed	0.44
Total energy requirements		
As heat	GJ heat/t oilseed	1.4
	GJ heat/t biodiesel	4.59
As electricity	kWh/t oilseed	25.0
	GJe/t oiseed	0.09
	GJe/t biodiesel	0.2952
Biodiesel yield	t oiseed/t biodiesel	3.28

4.4 Biodiesel distribution

Calculations of GHG emissions resulting from transport to end use of biodiesel are shown in Table 4.16 for irrigated scenario and in Table 4.17 for Rainfed scenario. The road transport mode option is based on fossil diesel use.

The GHG emission factor is based on diesel consumption for road freight of 0.53 MJ/t*km for Heavy-duty truck and 0.781 MJ/t*km for Medium-duty truck (Table 4.9) (Öko-Institute. EM Database: Transport) and the GHG emissions factor for diesel burning of 89.3 kgCO_2eq/GJ (GEMIS 4.2).

Table 4.16: Energy inputs and GHG emissions for biodiesel distribution. Irrigated scenario

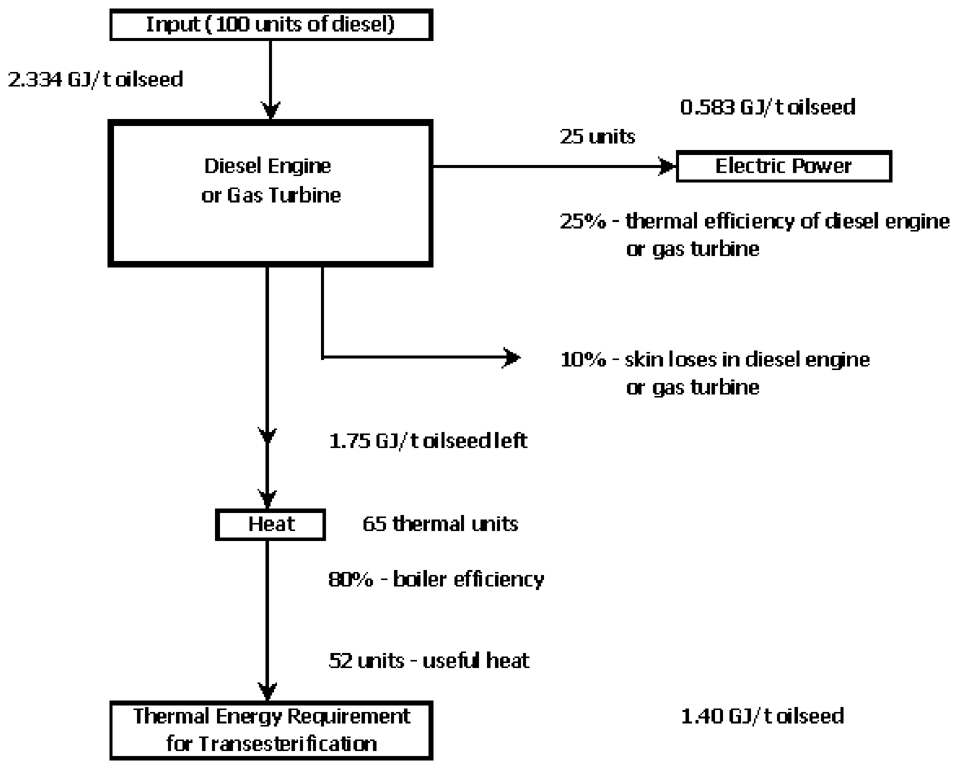
C2. Biodiesel distribution		
Mode	Road/diesel fuel	
Distance (one-way)	km	250
Diesel consumption for road transport	MJ/t.km	0.5278
Requirement per tonne transported (round trip)		
Primary energy	GJp/t biodiesel	0.306
GHG emissions	kg CO_2/t biodiesel	23.6
C3. Glycerine transportation		
Mode	Road/diesel fuel	
Distance (one-way)	km	250
Diesel consumption for road transport	MJ/t.km	0.781
Requirement per tonne transported (round trip)		
Primary energy	GJp/t	0.45
GHG emissions	kg CO_2eq/t	34.9

Table 4.17: Energy inputs and GHG emissions for biodiesel distribution. Rainfed scenario

C2. Biodiesel distribution		
Mode	Road/diesel fuel	
Distance (one-way)	km	55
Diesel consumption for road transport	MJ/t.km	0.528
Requirement per tonne transported (round trip)		
Primary energy	GJp/t biodiesel	0.07
GHG emissions	kg CO_2/t biodiesel	5.19
C3. Glycerine transportation		
Mode	Road/diesel fuel	
Distance (one-way)	km	55
Diesel consumption for road transport	MJ/t.km	0.781
Requirement per tonne transported (round trip)		
Primary energy	GJp/t	0.10
GHG emissions	kg CO_2eq/t	7.7

For biodiesel distribution transportation delivery (one-way) was considered as 250 km for Irrigated scenario and 55 km for Rainfed scenario (Balachandra: pers. comm.). The diesel consumption for transport to end use includes an allowance for an empty return trip after delivery of biodiesel over the specific one-way distance.

Flowchart 4.2: Diesel engine or gas turbine in Combined Heat and Power (CHP) regime (energy balance)



The contemplation and analysis of the produced results demonstrates that the final efficiency of the Models very much depends on assumptions set up for each model. Also, as LowCVP (2004) WTW evaluation report noticed, in practice, schemes are likely to be selected more on the basis of economic profitability than maximum energy or GHG savings.

4.5 By-products credits

Oilseeds-to-biodiesel production pathways also produce various by-products and co-products, most of which has their value per se. As such, it is crucial to consider and incorporate into total GHG emissions calculations all multiply products derived from the particular production chain. For these estimations, allocation by substitution is used following recommendations of LowCVP (2004) and Woods, *et. al.* (2005). In this method, the primary product is assigned the total GHG emissions minus credits equal to the GHG emissions avoided as a result of co-product displacement of alternative products elsewhere (Ibid.).

4.5.1 Surplus electricity

Any surplus electricity produced but not used by a biodiesel plant is assumed to displace generation of an equal amount of the electricity from grid with GHG emissions equal to the Southern Indian/Karnataka electricity generation average of 155.9 kgCO_2/GJe (based on 1,052 gCO_2/kWh for Karnataka. Baselines for renewable energy projects by MNES (Southern Online Biotechnologies Ltd.: 2004). There are five regional grids within the country viz. Northern, Western, Southern, Eastern and North-Eastern and different states are connected to one of the five regional grids (MNES: 2003). With respect to the CO_2 emission factor for electricity in gCO_2/kWh, the range of regional grid average emissions factors in India ranges from 450 gCO_2/kWh in the North Eastern grid to 1,040 gCO_2/kWh in the Eastern grid (CEA: 2006), or even 1,270 gCO_2/kWh for India's coal-dominated grid (Defra/DECC: 2009) -*ef* to 87 gCO_2/kWh for France's mainly nuclear-generated electricity (Defra/DECC: 2009); 527 gCO_2/kWh (Defra: 2007), 538 gCO_2/kWh (The Carbon Trust: 2008), 543 gCO_2/kWh (Energy Savings Trust: 2009) for grid-supplied electricity in the UK, 520 gCO_2/kWh - for 3-year rolling average emission factor for the UK electricity (2008/2009) (Defra/DECC: 2009); 712 gCO_2/kWh - for average U.S. electricity, including a penalty of 9% for transmission loses, 655 gCO_2/kWh - for U.S. electricity mix, not including the penalty for transmission loses (Jaramillo, *et. al.*: 2009); 835 gCO_2/kWh for the China's coal-dominated grid (Defra/DECC: 2009); and 1,060 gCO_2/kWh for NSW, Australia (COSPP: May-June 2008)), and this value is used to calculate credits for those biodiesel production chains which include generation of surplus electricity.

4.5.2 Press-cake

If *Jatropha* press-cake is used as fertilizer (green manure) it could substitute either soybean meal or rapeseed press-cake. As no credits associated to these products were ever calculated for Indian conditions, from the secondary sources available the following figures from Australian studies for a soybean meal were adopted: 0.311 GJp/GJ (Calais & Sims: no date cited by LovCVP: 2004) and 32.6 kgCO_2eq/GJ (Beer, *et. al.*: no date) to keep estimations going.

In calculations for substituting rapeseed press-cake the figures of 0.238 GJp/GJ and 29.7 kgCO_2eq/GJ were used in the calculations based on data at the Table 4.18:

Table 4.18: Energy requirements and greenhouse gas (GHG) emissions factors for substitutes

	GJp/GJ	$kgCO_2eq/GJ$	Reference
Soybean meal	0.311		Calais & Sims: no date
		32.6	Beer, *et. al.*: no date
Rapeseed press-cake	0.437		Mortimer, *et. al.*: 2003
	0.238-0.567		Woods and Bauen: 2003
		54 (32-73)	animal feed as a byproduct (CONCAWE: 2004)
		49 (29-69)	chemical feedstock as a byproduct (CONCAWE: 2004)

Following methodology adopted by LovCVP 'Well-to-Wheel sub-group' (LowCVP 2004), it was assumed that if *Jatropha* press-cake use as co-fuel for power plant, it will substitute Southern Indian/Karnataka-mix electricity.

In our case the option of biogas generation from *Jatropha* press-cake substituting fuel oil were adopted for further estimations. Data applied for these estimations were discussed and approved by Dr. Chanakya, Principal Research Scientist for the Centre for Sustainable Technologies (CST), Indian Institute of Science, Bangalore; Dr. Bhatt, Joint Director, Energy Conservation and Development Division, Central Power Research Institute, Bangalore; and Mr. Siddheshwas, Scientist for the Appropriate Rural Technology Institute (ARTI), Pune, Maharashtra.

4.5.3 Glycerine

Currently, the glycerine from esterification plants is displaces conventionally produced glycerine which is the co-product from the production of oleochemicals. Biodiesel producers are purifying the glycerol so that it is acceptable as either food-grade or pharmaceutical grade. It can be also utilized as an additive to the animal forage, combustible fuel for energy generation, especially for small-scale local production. Also, as it was described earlier, novel technologies allow converting glycerine into syn gas and/or hydrogen. For each of the listed above glycerine use, the replacement credits will be different. For the short-term planning it would be relevant to assume that rough glycerine produced in industrial scale biodiesel plants will be purified and used as pharma-grade glycerine, and glycerine produced locally, at the small-scale biodiesel plants, just combusted as a co-fuel or used as animal forage. Even though, rough glycerine purification and marketing at the few existed biodiesel plants does not incorporated into Indian pharmaceutical industry and glycerol market yet, author believes that as biofuels industry will undertake rapid development all around India, all glycerol in the medium- and long-terms will be purified and utilized at the pharmaceutical or food industry as it will bring much more financial and economic advantages for the biodiesel industry.

Table 4.19: Material and energy requirement for conventional production of 1 kg of glycerine

Chliorine	kg	2.0
NaOH	kg	1.4
Propylene	kg	0.8
Steam	MJ	60
Electric power	kWh	0.9

Note: 30 kg steam at 11 bar with 2.0 GJ/t

Source: UBA: 1999 cited by GM-LBST: 2002

The conventional production of glycerine in the chemical industry leads to relatively high emissions of CO_2. This fact results in lower GHG-emissions for *Jatropha* biodiesel production and supply when the by-product glycerine replaces conventionally produced glycerine (LBST: 2002).

Calculations for the replacement credit for glycerine assume that the glycerine produced displaces synthetic glycerine (Delucchi & Lipman: 2003). The production of one pound of synthetic glycerine requires 0.281 kg of propylene, 0.907 kg of chlorine, 0.204 kg of sodium chloride, and 0.204 kg of sodium hydroxide. The energy contents of these raw materials are 5.539, 3.435, 0.382, and 7.281 kWh/kg respectively. Based on these figures, the energy required to produce a kilogram of glycerine is 13.75 kWh/kg, ignoring the small amount of energy used in the final synthesis of the glycerine (the reaction is exothermic, requiring no heat or pressure, and only a small amount of electricity is used to stir the reactors), and any potential recovery of the (very inexpensive) reactants (Ibid.). The same energy requirement 49.5 GJ/t for the synthetic glycerol production is reported by Hill, *et. al.* (2006). However, it is noticed that as synthetic glycerol is of a higher purity than raw glycerol, this co-product credit overestimates the displacement energy. Emission of climatic gases from glycerine production calculated by Scharmer and Gosse (1995) as ~9.0 kgCO_2eq/kg glycerine. The UBA study (1999) finds similar values of 177.0 GJ/t glycerine and 10.41 kgCO_2eq/kg glycerine respectively.

Chapter 5: WTT results with applicable by-products credits

5.1 Overall gross energy and GHG balances before credits

At the very beginning, the 'overall gross energy' and 'GHG balances', before credits, for all four scenarios are shown in Tables from 5.1 to 5.12. Even thought, these results without applicable credits are incomplete; it will show the progress of calculations and preliminary results analysis. Tables represent a juxtaposition of the overall gross energy and GHG emissions balances (Low, Best and High scenarios) for the different biodiesel production technologies at both industrial and small-scale level, considering at the same time 13 various energy (heat and electricity) supply for trans/esterification plant scenarios for Irrigated (industrial scale production) and 8 energy supply scenarios for Rainfed (small-scale), and excluding any possible by-products credits.

5.1.1 Irrigated Scenario I: Industrial scale production. One-stage Transesterification Process (90 bar, 240°C)

For Models a11, a12 and a21, the basic fuel input provided by fuel oil, coal and natural gas respectively. The total primary energy input in each of these cases is around 48.0% of the energy contained in the produced biodiesel in Low scenario, 56.0% - in Best scenario and 67.0% - in High scenario. This numbers stay almost unchanged in the more efficient Models b11, b12 and b21 which elaborate Combined Heat and Power (CHP) option: around 53% of the biodiesel energy in Low scenario, 61% - in Best scenario and 72% - in High scenario (Tables 5.1, 5.2 & 5.3).

Models c11, c12, c21 and c22 equipped with unfired or co-fired Heat Recovery Steam Generator (HRSG), have the total primary energy input by a good 20.0-51.0% higher than in previous models, and about the same energy as contained in the produced biodiesel: 68.0-99.0% - for Low scenario, 76.0-107.0% - for Best scenario, and 87.0-118.0% - for High scenario correspondingly. The total primary energy input in Model c22 (118.0%) - High scenario is even slightly higher than the same for petrodiesel (116.0%). Both cases c21 and c22 with back-pressure steam turbine (BPSTG) are slightly less efficient than cases c12 and c21 without back-pressure steam turbine (BPSTG). It caused by much larger surplus of electricity exported to the National Grid in these cases (LowCVP: 2004).

Table 5.1: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (before by-products credits). Low scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.479**	**0.479**	**0.484**	**0.527**	**0.527**	**0.533**	**0.804**	**0.677**	**0.986**	**0.819**	**0.172**	**0.172**	**0.172**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.479**	**0.479**	**0.484**	**0.527**	**0.527**	**0.533**	**0.804**	**0.677**	**0.986**	**0.819**	**1.160**	**1.160**	**1.160**	**1.16**
	GJp/t biodiesel		17.85	17.85	18.03	19.63	19.63	19.85	29.98	25.22	36.73	30.51	43.24	43.24	43.2	
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**37.03**	**54.08**	**32.98**	**40.59**	**62.23**	**35.45**	**50.47**	**43.41**	**60.49**	**51.25**	**13.18**	**13.18**	**13.18**	**89.3**
	kg CO_2eq/t biodiesel		1380.01	2015.57	1228.98	1512.70	2319.16	1321.05	1881.02	1617.86	2254.37	1910.13	491.24	491.24	491.24	
Farming (CO_2)			231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	35.82	35.82	35.82	
Farming (N_2O)			251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table 5.2: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (before by-products credits). Best scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Intetgated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.563**	**0.563**	**0.568**	**0.611**	**0.611**	**0.617**	**0.888**	**0.761**	**1.070**	**0.903**	**0.256**	**0.256**	**0.256**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.563**	**0.563**	**0.568**	**0.611**	**0.611**	**0.617**	**0.888**	**0.761**	**1.070**	**0.903**	**1.24**	**1.24**	**1.24**	**1.16**
	GJp/t biodiesel		20.98	20.98	21.16	22.76	22.76	22.99	33.11	28.36	39.86	33.64	46.38	46.38	46.4	
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**58.77**	**75.82**	**54.72**	**62.33**	**83.97**	**57.19**	**72.21**	**65.15**	**82.23**	**72.99**	**34.93**	**34.93**	**34.93**	**89.3**
	kg CO_2eq/t biodiesel		2190.34	2825.89	2039.30	2323.02	3129.48	2131.38	2691.34	2428.18	3064.69	2720.45	1301.66	1301.66	1301.66	
Farming (CO_2)			534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	339.16	339.16	339.16	
Farming (N_2O)			758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table 5.3: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (before by-products credits). High scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.671**	**0.671**	**0.676**	**0.719**	**0.719**	**0.725**	**0.997**	**0.869**	**1.178**	**1.011**	**0.365**	**0.365**	**0.365**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.671**	**0.671**	**0.676**	**0.719**	**0.719**	**0.725**	**0.997**	**0.869**	**1.178**	**1.011**	**1.4**	**1.4**	**1.4**	**1.16**
	GJp/t biodiesel		25.02	25.02	25.20	26.80	26.80	27.03	37.16	32.40	43.91	37.68	50.42	50.42	50.4	
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95	
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**93.59**	**110.64**	**89.54**	**97.15**	**118.79**	**92.01**	**107.03**	**99.97**	**117.05**	**107.82**	**69.74**	**69.74**	**69.74**	**89.3**
	kg CO_2eq/t biodiesel		3488.16	4123.72	3337.12	3620.85	4427.31	3429.20	3989.16	3726.00	4362.51	4018.27	2599.38	2599.38	2599.38	
Farming (CO_2)			932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	736.48	736.48	736.48	
Farming (N_2O)			1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Models d1, d2 and e demonstrate the reduction in fossil energy inputs of 21.0-36.5% due to the utilization of biomass such as fruits husks, seed shells and pruning material in the transesterification plant. However, total primary energy input 116.0-140.0% is higher than in Models a11, a12 and a21 as exported electricity is again much higher, especially in the Model d2 when electricity generated with backpressure turbine to match heat requirement augmented by the condensing turbine for surplus steam. The total primary energy input in Models d1, d2 and e is equal or even higher than the same for petrodiesel (116.0%). The technical and technological aspects of this model were discussed earlier in the "Biodiesel plant utility generation models" subchapter 3.4 and the "Combined Heat and Power (CHP) plant fuelled by biomass" subchapter 3.5.3.

Total greenhouse emissions are vary from 32.98 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model a21 where natural gas boiler and electricity from grid are used to 118.79 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model b12 with conventional coal boiler and back-pressure steam turbine (BPSTG) (Tables 5.1, 5.2 & 5.3). Emissions are raised by 5.5-24.0% in Models c11, c21 and c22, equipped with unfired or co-fires Heat Recovery Steam Generator (HRSG) compare to the Models a11, a12 and a21, where the basic fuel input provided by fuel oil, coal and natural gas. Models d1, d2 and e demonstrate significant reduction in GHG emissions which become as low as 13.18-69.74 $kgCO_2eq/GJ_{biodiesel}$ due to the utilization of biomass in the energy supply scenario for a biodiesel plant.

5.1.2 Irrigated Scenario II: Industrial scale production. Two-stage process. Fat-splitting (60 bar, 260°C) and Esterification (10 bar, 240°C)

For Models a11, a12 and a21, the basic fuel input provided by fuel oil, coal and natural gas respectively. The total energy input in each of these cases is around 31.0-50.5% of the energy contained in the produced biodiesel. This numbers stay almost unchanged, around 29.0-48.0% of the biodiesel energy in the more efficient Models b11, b12 and b21 which elaborate Combined Heat and Power (CHP) option. Models c11, c12, c21 and c22 equipped with unfired or co-fired Heat Recovery Steam Generator (HRSG), have the total energy input higher by 4.0-8.0%, and ~35.0-39.0% (Low), 44.0-48.0% (Best) and 55.0-58.0% (High) of the energy contained in the produced biodiesel.

Models d1 and d2 demonstrate the reduction in fossil energy inputs by 44.9-64.2% due to the utilization of biomass such as fruits husks, seed shells and pruning material in the transesterification plant. However, Model e, which employed integrated biomass gasifier and the natural gas turbine, show the drastic increase in fossil energy inputs by 85.4-104.7%. The total primary energy input of 116.0-140.0% in Models d1, d2 and e is higher than in Models a11, a12 and a21 as exported electricity is again much higher, especially in the Models d2 and e. The total primary energy input in Models d1, d2 and e is equal or even higher than the same for petrodiesel (116.0%) (Tables 5.4, 5.5 & 5.6).

Total greenhouse emissions are vary from 21.96 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model b21 where natural gas boiler and backpressure turbogenerator are used to 84.25 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model c21 using natural gas with unfired HRSG and BPSTG. In both maximum and minimum cases, the total emissions are lower by 14.6-28.0% (Low), 23.6-39.9% (Best), and 38.8-54.2% (High) respectively compare to the One-stage transesterification process. Models a12 and b12 utilizing conventional coal boiler demonstrate slight increase of GHG emissions in this scenario by 2.4-15.0% and 0.5-10.0% respectively compare to the Models c11, c12, c21 and c22, equipped with unfired or co-fires Heat Recovery Steam Generator (HRSG) (Tables 5.4, 5.5 & 5.6).

Table 5.4: Overall Gross balance. Industrial scale production. Two-stage process. Fat-splitting and Esterification (before by-products credits). Low scenario

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.312**	**0.312**	**0.314**	**0.287**	**0.287**	**0.289**	**0.386**	**0.35**	**0.392**	**0.354**	**0.449**	**0.449**	**0.854**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.312**	**0.312**	**0.314**	**0.287**	**0.287**	**0.289**	**0.386**	**0.35**	**0.392**	**0.354**	**1.16**	**1.16**	**1.16**	**1.16**
	GJp/t biodiesel		11.63	11.63	11.69	10.71	10.71	10.77	14.39	13.02	14.63	13.20	43.24	43.24	43.2	
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**24.83**	**29.75**	**23.66**	**23.14**	**28.09**	**21.96**	**27.34**	**25.30**	**27.69**	**25.58**	**13.18**	**13.18**	**13.18**	**89.3**
	kg CO_2eq/t biodiesel		925.52	1108.84	881.95	862.29	1046.77	818.45	1018.87	942.97	1031.95	953.20	491.24	491.24	491.24	
Farming (CO_2)			231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	35.82	35.82	35.82	
Farming (N_2O)			251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.00	0.00	0.00	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table 5.5: Overall Gross balance. Industrial scale production. Two-stage process. Fat-splitting and Esterification (before by-products credits). Best scenario

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.396**	**0.396**	**0.398**	**0.372**	**0.372**	**0.373**	**0.470**	**0.43**	**0.477**	**0.438**	**0.533**	**0.533**	**0.938**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.396**	**0.396**	**0.398**	**0.372**	**0.372**	**0.373**	**0.470**	**0.43**	**0.477**	**0.438**	**1.2**	**1.2**	**1.2**	**1.16**
	GJp/t biodiesel		14.77	14.77	14.82	13.85	13.85	13.90	17.52	16.15	17.76	16.34	46.38	46.38	46.4	
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.9	6.9	6.90	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**46.57**	**51.49**	**45.41**	**44.88**	**49.83**	**43.70**	**49.08**	**47.04**	**49.43**	**47.32**	**34.93**	**34.93**	**34.93**	**89.3**
	kg CO_2eq/t biodiesel		1735.84	1919.16	1692.27	1672.62	1857.09	1628.78	1829.19	1753.29	1842.27	1763.53	1301.66	1301.66	1301.66	
Farming (CO_2)			534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	339.16	339.16	339.16	
Farming (N_2O)			758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table 5.6: Overall Gross balance. Industrial scale production. Two-stage process. Fat-splitting and Esterification (before by-products credits). High scenario

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.505**	**0.505**	**0.506**	**0.480**	**0.480**	**0.481**	**0.579**	**0.54**	**0.585**	**0.547**	**0.642**	**0.642**	**1.047**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.505**	**0.505**	**0.506**	**0.480**	**0.480**	**0.481**	**0.579**	**0.54**	**0.585**	**0.547**	**1.4**	**1.4**	**1.4**	**1.16**
	GJp/t biodiesel		18.81	18.81	18.86	17.89	17.89	17.94	21.57	20.20	21.80	20.38	50.42	50.42	50.4	
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**81.40**	**86.32**	**80.23**	**79.70**	**84.65**	**78.52**	**83.90**	**81.87**	**84.25**	**82.14**	**69.74**	**69.74**	**69.74**	**89.3**
	kg CO_2eq/t biodiesel		3033.66	3216.98	2990.10	2970.44	3154.91	2926.60	3127.02	3051.11	3140.09	3061.35	2599.38	2599.38	2599.38	
Farming (CO_2)			932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	736.48	736.48	736.48	
Farming (N_2O)			1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Emissions are also slightly raised to 27.34-84.25 $kgCO_2eq/GJ_{biodiesel}$ in Models c11 and c21 when unfired HRSG is a part of the energy supply scheme. However, it is much less (by ~22.0-46.0%) than in case of the One-stage transesterification process.

Models d1, d2 and e demonstrate significant reduction in GHG emissions which become as low as 13.18-69.74 $kgCO_2eq/GJ_{biodiesel}$ due to the utilization of biomass in the energy supply scenario for a biodiesel plant (Tables 5.3, 5.4 & 5.5).

5.1.3 Rainfed Scenario I: Small-scale production. Organic, chemical fertilizers and agro-chemicals applied. Transesterification Process (1.4 bar, 60°C)

For Models a11, a12 and a21, the basic fuel input provided by fuel oil, coal and natural gas respectively. The total energy input in each of these cases is ~21.0-33.7% of the energy contained in the produced biodiesel. This numbers stay unchanged, approximately 19.5% (Low), 22.6% (Best) and 32.8% (High) of the biodiesel energy in the more efficient Models f11, and f12 which elaborate Combined Heat and Power (CHP) option by means of diesel or natural gas fired gensets equipped with Heat Utilization Block (HUB) (Tables 5.7, 5.8 & 5.9).

Model g equipped with natural gas fired CHP Microturbine have the total energy input of the energy contained in the produced biodiesel roughly the same as all previous models: 19.8% (Low), 22.5% (Best) and 32.6% (High).

Models h11 and h12 demonstrate the drastic boost in fossil energy inputs (154.3% (Low), 150.0% (Best) and 166.0% (High)) due to the utilization of biomass such as fruits husks, seed shells and pruning material in the transesterification plant.

Table 5.7: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (before by-products credits). Low scenario

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**	**Diesel**
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.208**	**0.208**	**0.209**	**0.199**	**0.195**	**0.198**	**1.543**	**1.543**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.208**	**0.208**	**0.209**	**0.199**	**0.195**	**0.198**	**1.594**	**1.594**	**1.16**
	GJp/t biodiesel		7.75	7.75	7.77	7.42	7.27	7.36	59.41	59.41	
Farming			5.04	5.04	5.04	5.04	5.04	5.04	1.23	1.23	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**31.14**	**33.30**	**30.62**	**30.70**	**29.69**	**29.83**	**18.03**	**18.03**	**89.3**
	kg CO_2eq/t biodiesel		1160.52	1241.09	1141.37	1144.10	1106.67	1111.78	671.88	671.88	
Farming (CO_2)			457.62	457.62	457.62	457.62	457.62	457.62	61.42	61.42	
Farming (N_2O)			503.0	503.0	503.0	503.0	503.0	503.0	503.0	503.0	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table 5.8: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (before by-products credits). Best scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.235**	**0.235**	**0.236**	**0.226**	**0.222**	**0.225**	**1.570**	**1.570**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.235**	**0.235**	**0.236**	**0.226**	**0.222**	**0.225**	**1.62**	**1.62**	**1.16**
	GJp/t biodiesel		8.75	8.75	8.78	8.43	8.28	8.37	60.41	60.41	
Farming			6.04	6.04	6.04	6.04	6.04	6.04	2.23	2.23	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**41.39**	**43.56**	**40.88**	**40.95**	**39.95**	**40.09**	**28.28**	**28.28**	**89.3**
	kg CO_2eq/t biodiesel		1542.73	1623.30	1523.58	1526.31	1488.88	1493.99	1054.09	1054.09	
Farming (CO_2)			551.34	551.34	551.34	551.34	551.34	551.34	155.14	155.14	
Farming (N_2O)			791.5	791.5	791.5	791.5	791.5	791.5	791.5	791.5	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table 5.9: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (before by-products credits). High scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.337**	**0.337**	**0.337**	**0.328**	**0.324**	**0.326**	**1.666**	**1.666**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.337**	**0.337**	**0.337**	**0.328**	**0.324**	**0.326**	**1.72**	**1.72**	**1.16**
	GJp/t biodiesel		12.54	12.54	12.57	12.21	12.06	12.16	64.0	64.0	
Farming			9.83	9.83	9.83	9.83	9.83	9.83	5.80	5.80	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**77.49**	**79.65**	**76.98**	**77.05**	**76.05**	**76.18**	**63.97**	**63.97**	**89.3**
	kg CO_2eq/t biodiesel		2888.09	2968.66	2868.95	2871.67	2834.25	2839.35	2384.14	2384.14	
Farming (CO_2)			941.07	941.07	941.07	941.07	941.07	941.07	529.57	529.57	
Farming (N_2O)			1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

The total primary energy input (159.4% (Low), 162.0% (Best) and 172.0% (High)) is also higher than in Models a11, a12 and a21 as exported to the grid electricity is again much higher in the Models h12 and h22. This total primary energy input for the Models h11 and h12 in case of the Rainfed I scenario even by 23.0-35.0% higher than for the same Models in case of the Irrigated I and Irrigated II scenarios. The total primary energy input in Models h11 and h12 is higher than the same for petrodiesel (116.0%) by 24.8-30.0%. The fossil energy input in Models h11 and h12 is higher than the same for petrodiesel (116.0%) by 27.2-32.6%.

Total greenhouse emissions are not transparent variations per model, and fluctuate as little as from 29.69 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model f12 to 79.65 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12. Models h11 and h12 demonstrate significant reduction in GHG emissions which become as low as 18.03-63.97 $kgCO_2eq/GJ_{biodiesel}$ (High) due to the utilization of biomass in the energy supply scenario for a biodiesel plant. However, this is a minor increase compare to 13.18-69.74 $kgCO_2eq/GJ_{biodiesel}$ with biomass utilized energy supply options (Models d1, d2 and e) in Irrigated I and Irrigated II scenarios (Tables 5.7, 5.8 & 5.9).

5.1.4 Rainfed Scenario II: Small-scale production. No fertilizers and agro-chemicals used. Transesterification Process (1.4 bar, 60°C)

The last scenario looks just slightly different from the previous one by removing organic and mineral fertilizers, as well as agro-chemicals during feedstock cultivation stage. Even though observations made and data collected during field work in India make very clear that following this scenario it is not realistic to anticipate the yield of the *Jatropha* oilseeds necessary even for the small-scale local biodiesel production. However, it demonstrates in very transparent way how significant both total energy inputs and GHG emissions from *Jatropha* cultivation in the overall energy balance and greenhouse gases balance.

For Models a11, a12 and a21, the basic fuel input provided by fuel oil, coal and natural gas respectively. The total energy input in each of these cases is ~17.5% (Low and Best scenarios) and 24.1% (High) of the energy contained in the produced biodiesel. This numbers have not fluctuated significantly, just as little as 16.2-16.6% (Low and Best) and 22.8-23.3% (High) of the biodiesel energy in the more efficient Models f11 and f12 which elaborate Combined Heat and Power (CHP) option by means of diesel or natural gas fired gensets equipped with Heat Utilization Block (HUB) (Tables 5.10, 5.11 & 5.12).

Model g equipped with natural gas fired CHP Microturbine, have the total primary energy input of the energy contained in the produced biodiesel roughly the same as all previous models (16.5% (Low and Best) and 23.0% (High)).

Models h11 and h12 demonstrate minimal reduction in fossil energy inputs (by 14.0% - for Low, Best and High scenarios) due to the utilization of biomass such as fruits husks, seed shells and pruning material in the small-scale transesterification plant. However, both total fossil energy input (140.0% for Low, Best and High scenarios) and total primary energy input (166.3% for Low, Best and High scenarios) is significantly higher than in Models a11, a12 and a21 as exported electricity is again much higher, especially in the Models h11 and h12. This total energy input for the Models h11 and h12 in case of the Rainfed II Scenario even higher than for the biomass utilized Models in case of the Irrigated I and Irrigated II scenarios (by 30.2% (Low), 27.8% (Best) and 18.8% (High)), but lower by 7.2% (Low), 5.5% (Best) and higher by only 0.2% (High) scenarios than in equivalent Rainfed I Low, Best and High scenarios respectively with fertilizers and agro-chemicals applied. The total primary energy input in Models h11 and h12 is equal or even higher than the same for petrodiesel (116.0%) by 30%.

Table 5.10: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (before by-products credits). Low scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**0.140**	**0.140**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**1.663**	**1.663**	**1.16**
	GJp/t biodiesel		6.53	6.53	6.55	6.20	6.05	6.14	62.0	62.0	
Farming			3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**28.53**	**30.69**	**28.01**	**28.09**	**27.08**	**27.22**	**26.05**	**26.05**	**89.3**
	kg CO_2eq/t biodiesel		1063.24	1143.81	1044.10	1046.82	1009.40	1014.50	970.80	970.80	
Farming (CO_2)			396.36	396.36	396.36	396.36	396.36	396.36	396.36	396.36	
Farming (N_2O)			467.0	467.0	467.0	467.0	467.0	467.0	467.0	467.0	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table 5.11: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (before by-products credits). Best scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**0.140**	**0.140**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**1.66**	**1.66**	**1.16**
	GJp/t biodiesel		6.53	6.53	6.55	6.20	6.05	6.14	62.0	62.0	
Farming			3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**32.70**	**34.87**	**32.19**	**32.26**	**31.26**	**31.40**	**30.22**	**30.22**	**89.3**
	kg CO_2eq/t biodiesel		1218.90	1299.47	1199.75	1202.48	1165.06	1170.16	1126.45	1126.45	
Farming (CO_2)			396.36	396.36	396.36	396.36	396.36	396.36	396.36	396.36	
Farming (N_2O)			622.6	622.6	622.6	622.6	622.6	622.6	622.6	622.6	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table 5.12: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (before by-products credits). High scenario

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.241**	**0.241**	**0.241**	**0.232**	**0.228**	**0.230**	**0.14**	**0.14**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.241**	**0.241**	**0.241**	**0.232**	**0.228**	**0.230**	**1.663**	**1.663**	**1.16**
	GJp/t biodiesel		8.97	8.97	8.99	8.64	8.49	8.58	62.0	62.0	
Farming			6.26	6.26	6.26	6.26	6.26	6.26	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**57.05**	**59.21**	**56.54**	**56.61**	**55.60**	**55.74**	**34.40**	**34.40**	**89.3**
	kg CO_2eq/t biodiesel		2126.23	2206.79	2107.08	2109.81	2072.38	2077.49	1282.11	1282.11	
Farming (CO_2)			649.93	649.93	649.93	649.93	649.93	649.93	396.36	396.36	
Farming (N_2O)			1276.4	1276.4	1276.4	1276.4	1276.4	1276.4	778.3	778.3	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Total greenhouse emissions are not transparent variations per model, and fluctuate as little as from 27.08 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Models f12 to 59.21 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12. Models h11 and h12 in this case do not demonstrate reduction in GHG emissions compare to other cases and keeping it as low as 26.05-34.4 $kgCO_2eq/GJ_{biodiesel}$. However, this is an 30.7% increase in Low and 6.4% in Best scenarios, and significant 46.2% reduction in High scenario compare to Rainfed I scenario with fertilizers and agro-chemicals applied. However, this is a 47.0% increase in Low scenario, and reduction of 13.5% in Best and 50.7% in High scenarios compare to biomass utilized energy supply options (Models d1, d2 and e) in Irrigated I and Irrigated II scenarios (Tables 5.10, 5.11 & 5.12).

5.2 Net energy and GHG balances with electricity and glycerine credits

5.2.1 Credits for electricity

In all cases Models a11, a12 and a21 attracts no electricity credits, as in all these cases electricity consumed from the National electrical grid. As noticed by LowCVP (2004) "the debit due to electricity import is already factored into the gross balance calculations." However, electricity credits applied for energy balance calculations could vary for small-scale production from -0.001 $GJp/GJ_{biodiesel}$ in Model f12 (Rainfed I and Rainfed II scenarios) to as -0.53 $GJp/GJ_{biodiesel}$ in Model h11 (Rainfed I and Rainfed II scenarios). For industrial scale production these credits could vary from -0.02 $GJp/GJ_{biodiesel}$ in Model b21 (Irrigated II scenario) to -0.99 $GJp/GJ_{biodiesel}$ in Model c21 (Irrigated I scenario).

Electricity credits for the greenhouse gases (GHG) balance calculations vary for the small-scale production from -0.08 $kgCO_2eq/GJ_{biodiesel}$ in Model f12 to -36.34 $kgCO_2eq/GJ_{biodiesel}$ in Model h11 (Rainfed I and Rainfed II scenarios). For industrial scale production these credits could vary from -0.01 $kgCO_2eq/GJ_{biodiesel}$ in Model e (Irrigated II scenario) to -56.88 $kgCO_2eq/GJ_{biodiesel}$ in Model e (Irrigated I scenario).

5.2.2 Credits for glycerine

As a by-product of the biodiesel production, glycerine usage could be multifaceted. It could be purified and used as pharmaceutical grade glycerine in both pharmacy and food industries, used as animal fodder substitute or additive, being simply co-fired for the heat and electricity generation, or used in advanced energy technologies to produce hydrogen and/or syn gas for further use for energy generation. Assessing the contemporary glycerine market and development of the pharmaceutical and food industry in India, it is possible to make determination and proceed with credits calculation based on assumption that all glycerine in Industrial scale production (Irrigated I and Irrigated II scenarios) as being used as a pharma-grade glycerine. However, discretion for a small-scale production (Rainfed I and Rainfed II scenarios) is not that simple. Appropriate logistic network and glycerine collection from the local biodiesel producers are not established yet. As such, glycerine could be used locally rather as an additive to the animal fodder or co-fired for the biodiesel plant energy (heat and/or electricity) supply. Following LowCVP (2004) recommendations allocation by substitution method has been used and glycerine credits has been allocated for the displacement of conventionally produced glycerine.

Credits for glycerine applied for energy balance calculated as -0.06 $GJp/GJ_{biodiesel}$ for small-scale (Rainfed I and Rainfed II scenarios) and -0.05 $GJp/GJ_{biodiesel}$ for industrial scale production (Irrigated I and Irrigated II scenarios). Credits for glycerine applied for the greenhouse gases (GHG) balance calculated as -2.46 $kgCO_2eq/GJ_{biodiesel}$ for the small-scale production (Rainfed I and Rainfed II scenarios) and -2.21 $kgCO_2eq/GJ_{biodiesel}$ for industrial scale (Irrigated I and Irrigated II scenarios).

5.2.3 Credits for potassium phosphate

Potassium phosphate produced during glycerol purification could be utilized as a fertilizer displacing potassium phosphate fertilizer. However, economically feasible process for its recovery from waste water is still under development taking into consideration the small amount of the product recovered. For this reason credits for potassium phosphate were excluded from the current Model until recovery technology will be significantly improved.

5.2.4 Credits for press-cake

Jatropha press-cake has a value as an organic fertilizer (green manure), which appears to be the most common use, or it can be fermented in a biogas plant and subsequently used in energy generation substituting fuel oil. As such, a number of different scenarios of press cake usage are possible.

At present, the most commonly used biogas power systems are: up-flow anaerobioc sludge blanket (UASB), anaerobic fixed film reactor (AFFR), continuous stirred tank reactor (CSTR), covered in-ground anaerobic reactor (CIGAR), covered lagoon, *etc* (Balasankari & Arul: 2009). In case of biogas generation from *Jatropha* press-cake the data for the biogas (at 288.15 K and 101.325 kPa) are used for further calculations can be found in Appendix XI.

Noteworthy to mention that since the cow dung (liquid manure) is going to be utilized in either case, biogas generation from the same amount of cow dung (liquid manure) without *Jatropha* press-cake is considered as a reference system (Gartner & Reinhardt: 2003). As a consequence, *Jatropha* press-cake is credited with the difference in electrical energy and heat generation as well as in the quality of residue produced. The credit covers electrical power from grid and mineral fertilizer.

In terms of allocation, soya meal or rape meal could be considered as a substitute for press-cake but this approach could be challenged by the possible use of both soya beans and rape seeds as a source of biodiesel.

A soya bean meal is chosen as the fertilizer (green manure) in calculations of *Jatropha* press-cake credits. This is based on assumptions that:

❒ 0.311 GJp/GJ based on 0.83 kg soybean meal per 0.2 kg biodiesel or 1.04 kg dry soybeans (Sheehan, *et. al.*: 1998 cited by LowCVP: 2004);

❒ 32.6 kgCO_2eq/GJ (Beer, *et. al.*: no date) for Australia.

Another possible substitute for *Jatropha* press-cake is a rapeseed meal. In this case the following assumptions could be made for the *Jaropha* press-cake estimation:

❒ 0.238-0.567 GJp/GJ based on 0.58-0.63 $t_{rapemeal}/t_{oilseed}$ (Woods & Bauen: 2003) or 0.437 MJ/MJ for conventional production based on 1.575 $t_{rapemeal}/t_{biodiesel}$; 0.21 MJ/MJ for modified production based on 1.666 $t_{rapemeal}/t_{biodiesel}$ (Mortimer, *et. al.*: 2003);

❒ 15.0-29.7 kgCO_2eq/GJ (Woods & Bauen: 2003) or 41.0 kgCO_2eq/GJ for conventional production; 19.0 kgCO_2eq/GJ for modified production (Mortimer: 2003).

For *Jatropha* press-cake used as a fertilizer (green manure), a credits of -0.167 $GJp/GJ_{biodiesel}$ (-6.23 $GJp/t_{biodiesel}$) and -17.5 $kgCO_2eq/GJ_{biodiesel}$ (-652.88 $kgCO_2eq/t_{biodiesel}$) are applied for energy and GHG balance respectively.

For *Jatropha* press-cake used as co-fuel for power plant (biogas production) credits of -0.356 $GJp/GJ_{biodiesel}$ (-13.26 $GJp/t_{biodiesel}$) and -24.5 $kgCO_2eq/GJ_{biodiesel}$ (-913.11 $kgCO_2eq/t_{biodiesel}$) are applied for energy and GHG balance respectively.

5.2.5 Credits for set-aside land

Credits for set-aside land cultivation were not considered based on recommendations of the research completed by Jenkinson and Ayanaka from the Rothamstead Agri Research Station, UK in Nigeria. In their publication "Nigeria and Rothamstead. Organic matter decomposition." (1973, 1983, and 1989), authors argue that unlike in Temperate climatic zones, in Tropical climatic zones cultivation of set-aside land does not produce any credits. The authors' conclusion is that organic matter decomposition in tropics has only 45 days half-life cycle, so in a year 80-85% of organic matter (OM) is lost as CO_2. If 1 kg of OM contains 10 g of nitrogen (N) per annum, in temperate climate it will release 4 g of nitrogen, and in tropics conditions - 8 g of nitrogen. The curves which represent this difference are presented by formulas e^{-kt} - for temperate climate, and e^{-4kt} - for tropics (Chakarya: pers. comm.). Based on these theoretical approaches, there are no credits for use of set-aside land producing feedstock for biodiesel production.

5.3 *Jatropha* press-cake use as fertilizer (green manure)

The *Jatropha* press-cake credit reduces the net energy requirement and greenhouse gas (GHG) emissions even in larger extend. Tables in Appendix IV: "LCA results: Low, Best and High scenarios" show the Net balance including credits for surplus electricity and *Jatropha* press-cake use as fertilizer (green manure).

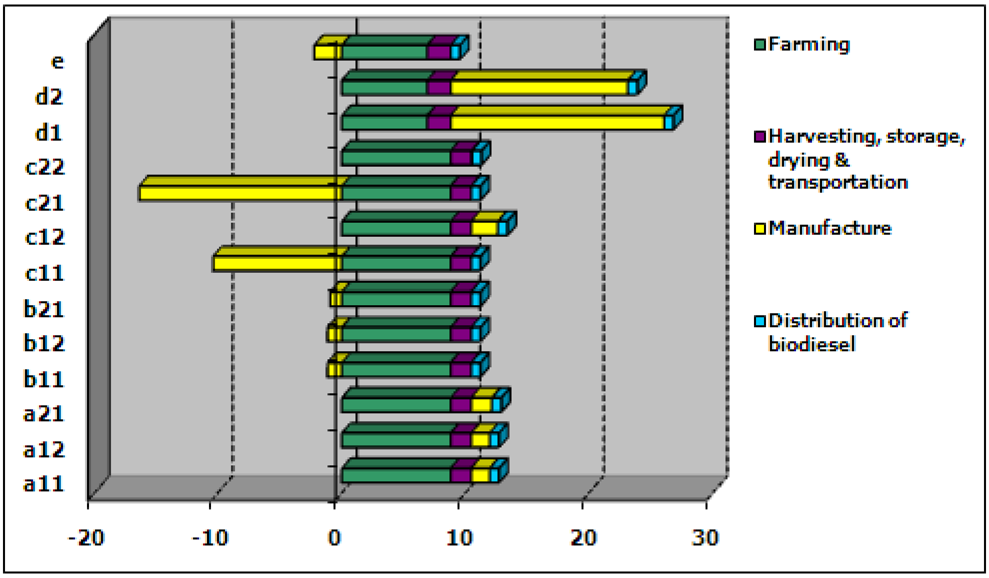
5.3.1 Irrigated Scenario I: Industrial scale production. One-stage Transesterification Process (90 bar, 240°C)

In terms of fossil energy usage the 13 models have a range from -0.222 GJ_f/GJ biodiesel (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 0.467 $GJ_f/GJ_{biodiesel}$ (High) in Model c12 which utilizes NG GT and co-fired HRSG.

Models d1, d2 and e which utilize biomass in the energy supply scenario make a special case from -0.876 $GJ_f/GJ_{biodiesel}$ (Low) in Model e to -0.16 $GJ_f/GJ_{biodiesel}$ (High) in Model d1 (Chart 5.1, Appendix IV: Tables IV.4, IV.16 & IV.28).

Also, Fossil energy saved in these Models has a range from 113.8% (High) in Model d1 to 175.5% (Low) in Model e which reflect that more than 100% of the biodiesel energy can be saved. It can be interpreted that through the utilization of by-products as an energy sources, large amounts of additional fossil energy can be saved (LowCVP: 2004).

Chart 5.1: Energy balance ($GJp/t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**



The results for the GHG emissions are similar, even though the savings are lover due to the contribution of the emissions from agriculture. For Models d1, d2 and e the GHG emissions have a range from -63.43 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model e where *Jatropha* pruning material used in the integrated biomass gasifier to 29.19 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model d1 where *Jatropha* pruning material used in the biomass boiler.

For other Models results for the GHG emissions have a range from -21.22 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 90.9 (High) in Models a12 & b12 which utilizes coal boiler and grid electricity, and coal boiler and BPSTG respectively (Charts 5.2 & 5.3, Appendix IV: Tables IV.4, IV.16 & IV.28).

Chart 5.2: GHG balance ($kgCO_2eq/t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

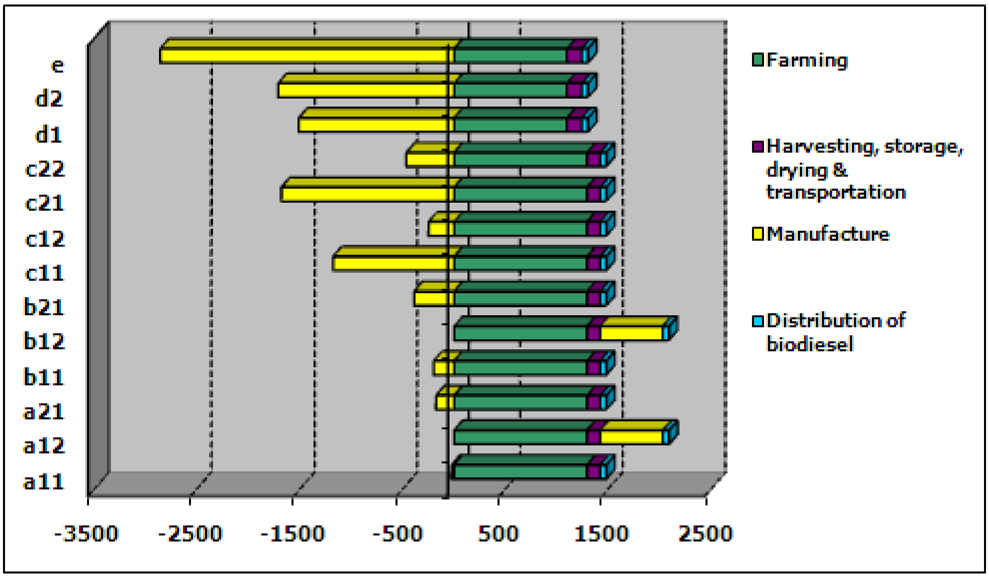
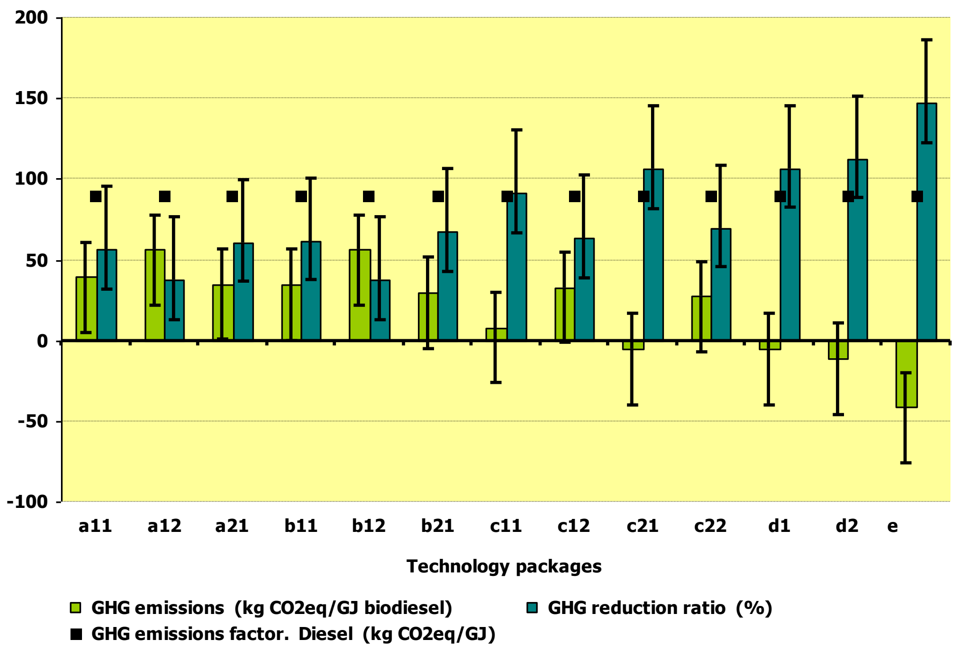


Chart 5.3: GHG emissions ($kgCO_2eq/GJ_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**



GHG reduction ratio (%) calculated as:

$$GHG\ reduction\ ratio\ (\%) = \frac{GHG\ emissions_{test\ case} - GHG\ emissions_{base\ case}}{GHG\ emissions_{base\ case}} \quad (5.1)$$

The results for the GHG avoided have a range from -1.8% (High) in Model a12 which utilizes coal boiler and grid electricity and in Model b12 which utilizes coal boiler and BPSTG to 130.4% (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPST.

The GHG avoided for Models d1, d2 and e have a range from 67.3% in Model d1 where *Jatropha* pruning material used in the biomass boiler to 171.0% (Low) in Model e where *Jatropha* pruning material used in the integrated biomass gasifier. The fossil energy saved and GHG avoided calculated as a percentage of energy used and emissions released when using Diesel (India specific): Primary energy factor: 1.16 GJp/GJ; GHG emissions factor: 89.3 $kgCO_2eq/GJ$ instead of biodiesel (LowCVP: 2004) (Chart 5.3).

5.3.2 Irrigated Scenario II: Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C)

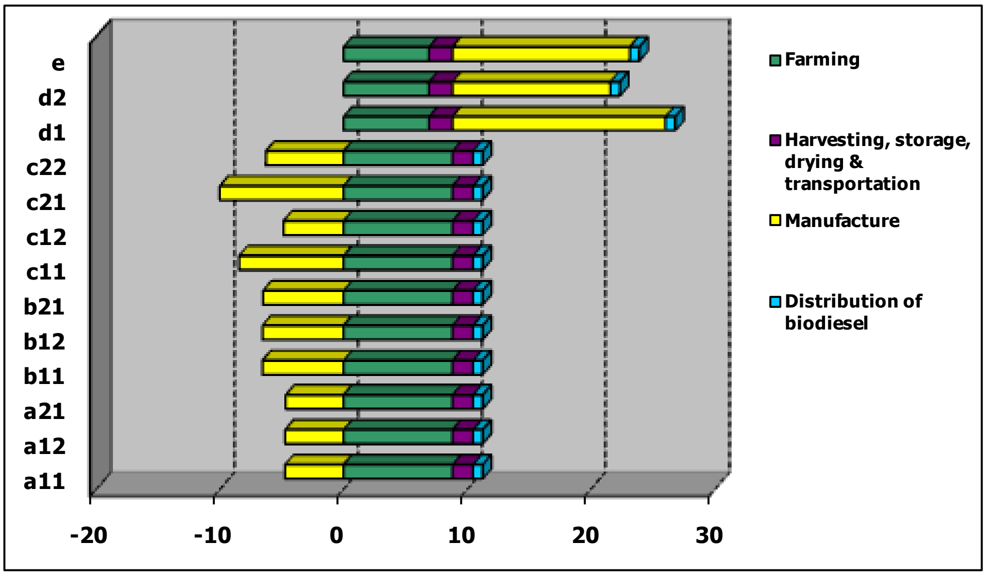
In this scenario, in terms of fossil energy usage the 13 models have a range from -0.052 $GJ_f/GJ_{biodiesel}$ (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 0.284 $GJ_f/GJ_{biodiesel}$ (High) in Model a21 which utilizes NG boiler and grid electricity. Models d1, d2 and e which utilize biomass in the energy supply scenario have a range from -0.473 $GJ_f/GJ_{biodiesel}$ (Low) in Model d2 to -0.011 $GJ_f/GJ_{biodiesel}$ (High) in Model d1.

Also, Fossil energy saved in these Models has a range from 100.9% (High) in Model d1, to 140.8% (Low) in Model d2, which reflects that more than 100% of the biodiesel energy can be saved (Chart 5.4, Appendix IV: Tables IV.7, IV.19 & IV.31).

The GHG emissions for Models d1, d2 and e have a range from -7.33 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model d2 to 50.01 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model e respectively.

For other Models GHG emissions has a range from 2.19 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model b21 which utilizes NG boiler and BPSTG to 66.59 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and grid electricity (Chart 5.5 & 5.6, Appendix IV: Tables IV.7, IV.19 & IV.31).

Chart 5.4: Energy balance (GJp/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake as fertilizer (green manure). Best scenario**



In Models d1, d2 and e where *Jatropha* pruning material used in the biomass boiler or integrated biomass gasifier, the results for GHG avoided have a range from 44.6% (High) in Model d1 to 108.2% (Low) in Model d2.

For other Models results for the GHG avoided have a range from 25.5% (High) in Model a12 which utilizes coal boiler and grid electricity to 97.5% (Low) in Model b21 which utilizes NG boiler and BPSTG (Chart 5.6).

Chart 5.5: GHG balance (kgCO_2eq/t$_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting (60 bar, 260°C) and Esterification. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

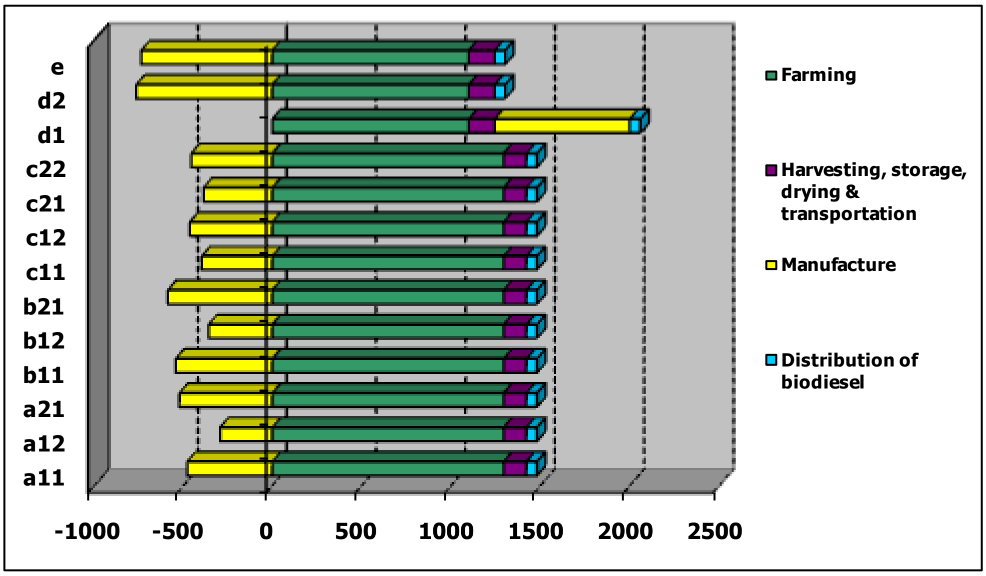
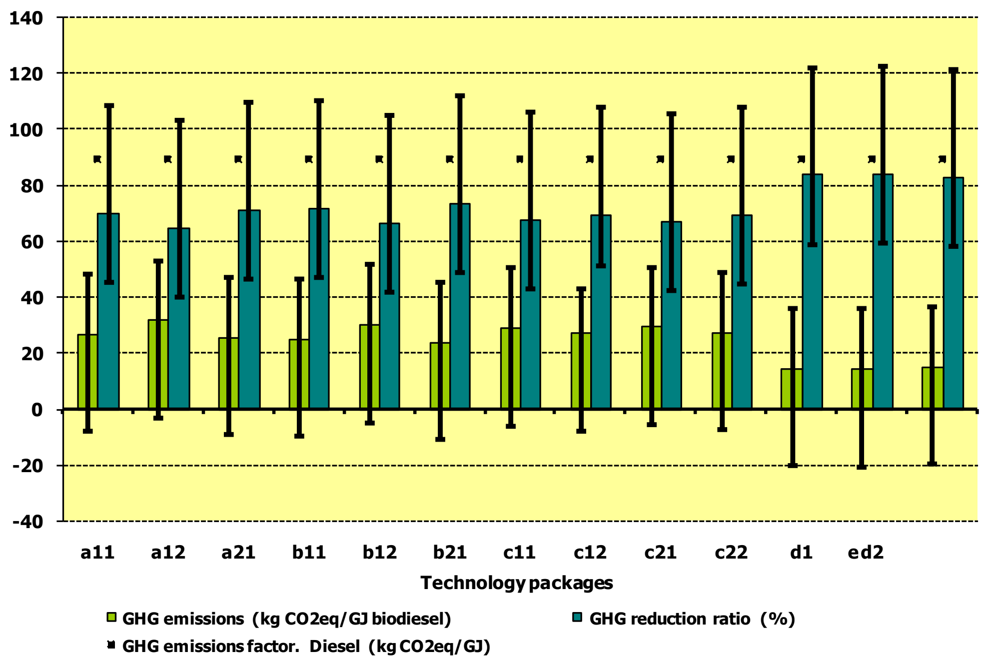


Chart 5.6: GHG emissions GHG emissions (kgCO_2eq/GJ$_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake as fertilizer (green manure)**



Charts 5.1. 5.2, 5.3, 5.4, 5.5 and 5.6 represent a juxtaposition of the energy and GHG balances for Industrial scale biodiesel production: Irrigated scenario I, "One-stage Transesterification Process (90 bar, 240°C)" and Irrigated scenario II, "Two-stage process.

Fat-splitting (60 bar, 260°C) and Esterification (10 bar, 240°C)". Charts show the total energy use for the supply of biodiesel including the energy content of the feedstock (*Jatropha* oilseeds). It could be concluded from these charts analysis that Two-stage process requires much less energy inputs and generate much less GHG emissions compare to the One-stage transesterification process. However, the One-stage process attracts more credits to the GHG balance when energy (heat and electricity) is produced utilizing either biomass boilers or integrated biomass gasifier (Models d1, d2 and e).

5.3.3 Rainfed Scenario I: Small-scale production. Organic, chemical fertilizers and agro-chemicals applied. Transesterification Process (1.4 bar, 60 °C)

In this scenario, in terms of fossil energy usage the 8 models have almost no fluctuations and vary as little as from -0.108 $GJ_f/GJ_{biodiesel}$ (High) in Model a11 which utilizes oil boiler and grid electricity, Model a12 which utilizes coal boiler and grid electricity, and Model a21 which utilizes NG boiler and grid electricity to -0.036 $GJ_f/GJ_{biodiesel}$ (Low) in Model f11 which utilizes Diesel genset with Heat Utilization Block (HUB).

Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier once again make a special case for the fossil energy usage which has a range from -0.687 $GJ_f/GJ_{biodiesel}$ (Low) in Model h11 to -0.216 GJf/GJbiodiesel (High) in Model h12.

Also, Fossil energy saved 148.7-152.3% in Model h11 and 118.6-129.2% in Model h12 reflect that more than 100% of the biodiesel energy can be saved, the reason of which has been explained earlier.

In all other "Low" scenarios: a11 (101.8%), a12 (101.8%), a21 (101.7%), f11 (103.1%), f12 (103.0%), g (102.8%) and several "Best" scenarios: f11 (100.8%), f12 (100.6%) and g (100.5%) the Fossil energy saved is slightly higher than 100% which shows that no any Fossil energy can be saved in these cases (Charts 5.7, 5.8 & 5.10, Appendix IV: Tables IV.10, IV.22 & IV.34).

Chart 5.7: Energy balance (GJp/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

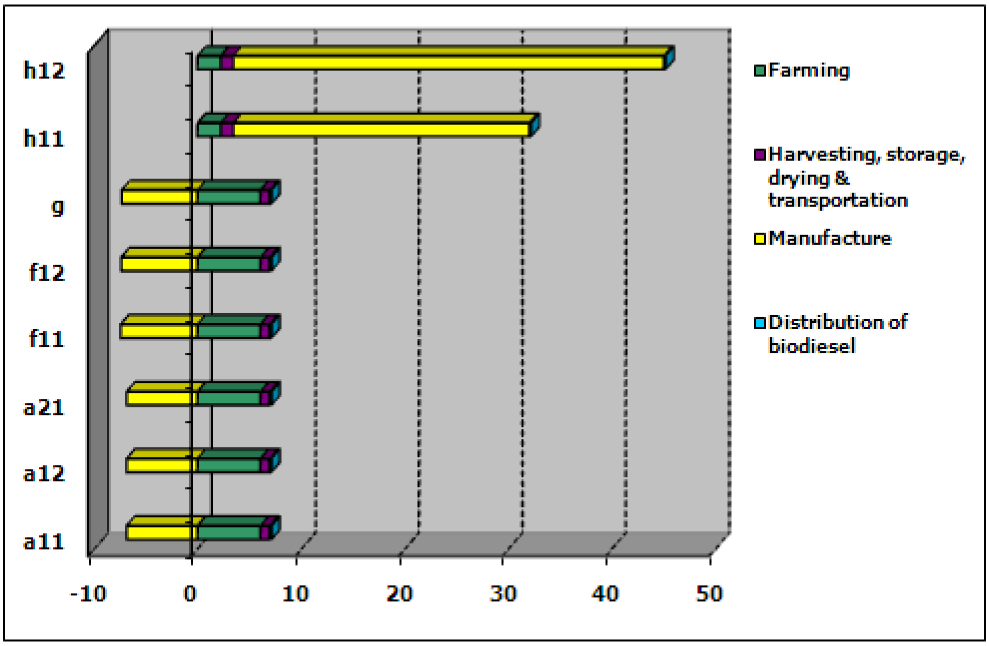


Chart 5.8: Primary total energy input (GJp/$GJ_{biodiesel}$/a). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**

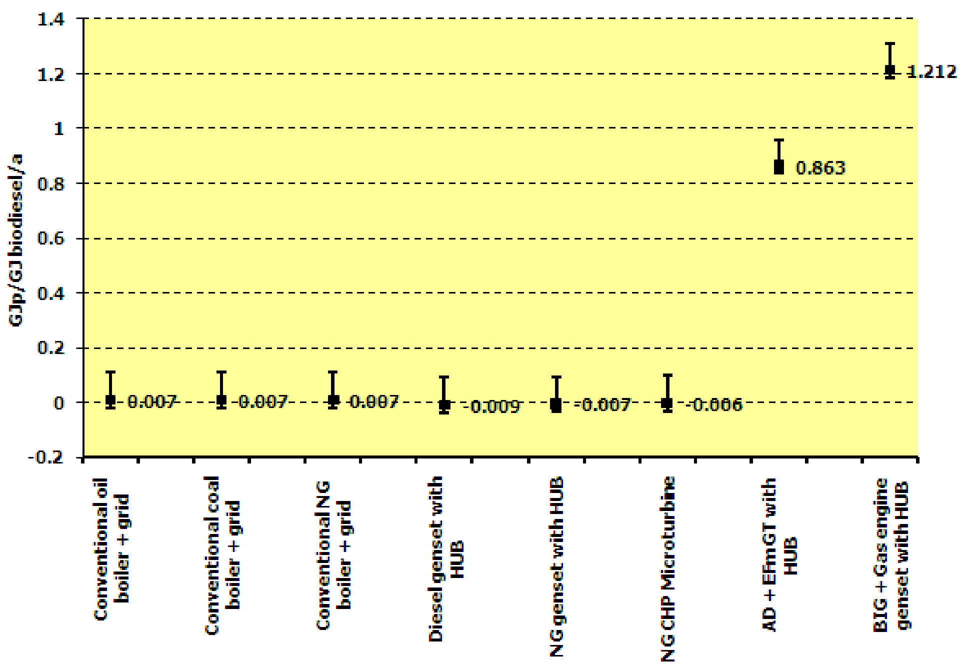


Chart 5.9: GHG balance. (%) *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

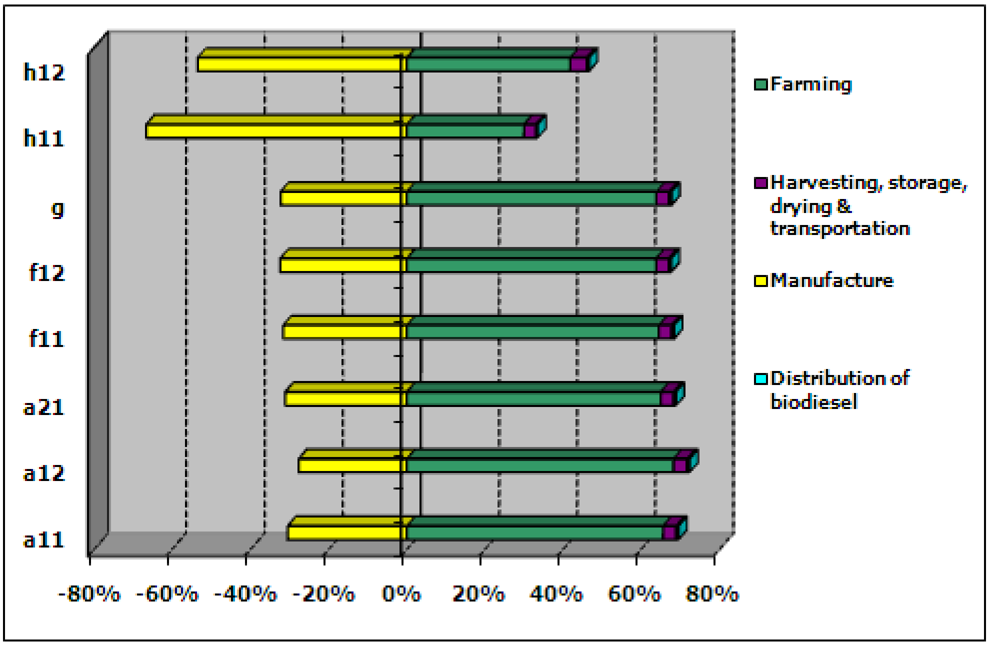
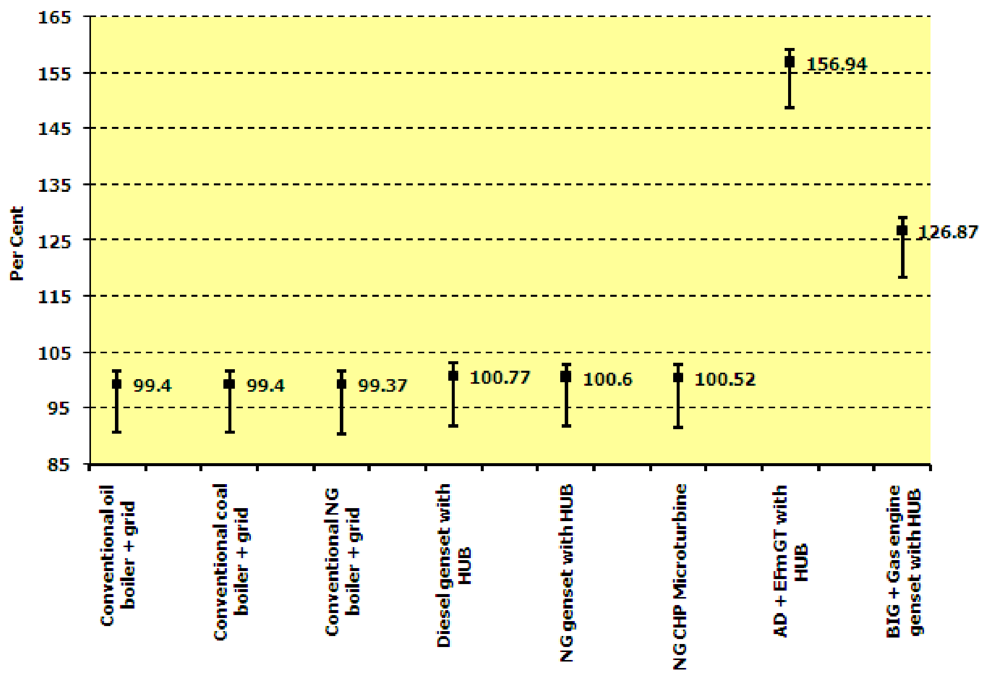


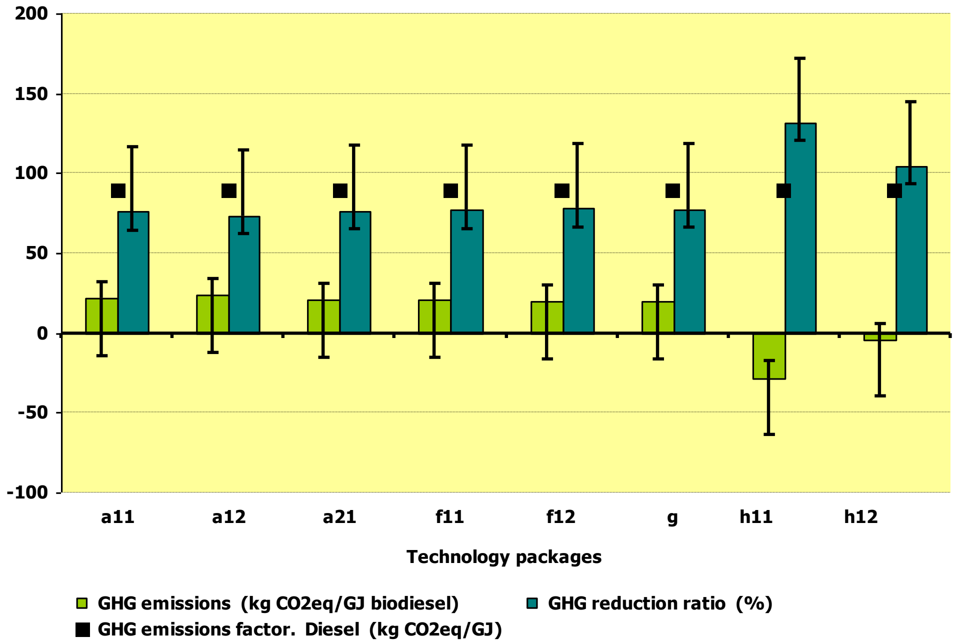
Chart 5.10: Fossil energy saved (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**



The results for the GHG emissions are similar, and have a range from -38.42 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model h11 which utilize anaerobic digester to 31.54 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model h12 which utilize integrated biomass gasifier.

For other Models GHG emissions have a range from 9.63 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) to 59.67 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and electricity from grid (Charts 5.9 & 5.11, Appendix IV: Tables IV.10, IV.22 & IV.34).

Chart 5.11: GHG emissions GHG emissions ($kgCO_2eq/GJ_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure)**



Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier has a range for the GHG avoided from 64.7% (High) in Model h12 which utilize integrated biomass gasifier to 143.0% (Low) in Model h11 which utilize anaerobic digester.

For other Models the results for the GHG avoided have a range from 33.2% (High) in Model a12 which utilizes coal boiler and grid to 89.2% (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) and Model g which utilizes NG CHP and Microturbine.

5.3.4 Rainfed Scenario II: Small-scale production. No fertilizers and agro-chemicals used. Transesterification Process (1.4 bar, 60°C)

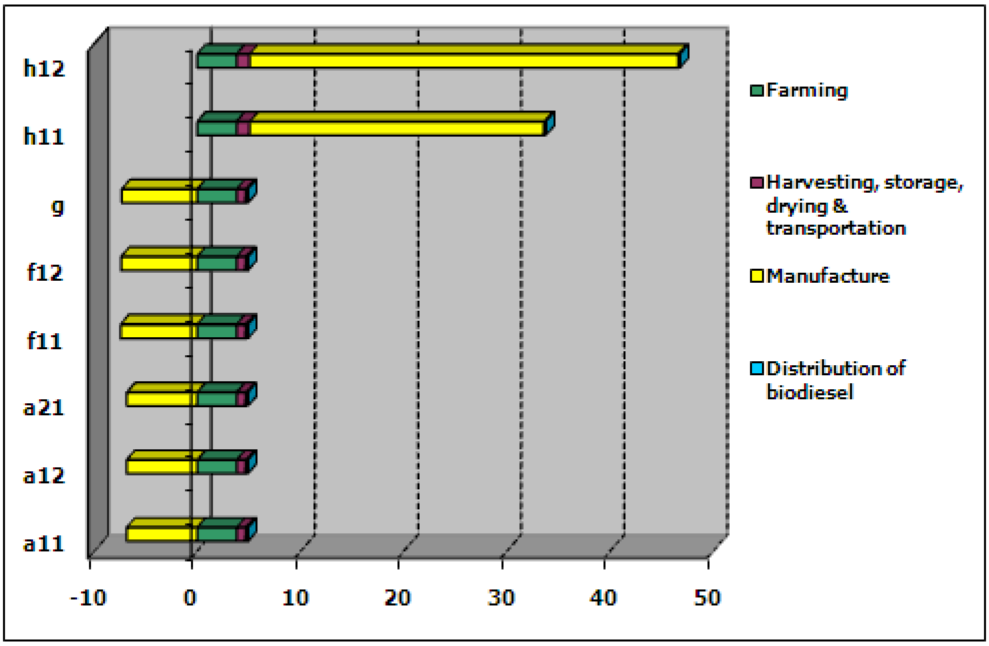
In this scenario, in terms of fossil energy usage the 8 models have almost no fluctuations and vary as little as from -0.069 $GJ_f/GJ_{biodiesel}$ (Low and Best) in Model f11 which utilizes Diesel genset with Heat Utilization Block (HUB) to 0.013 $GJ_f/GJ_{biodiesel}$ (High) in Model a11 which utilizes oil boiler and grid electricity, Model a12 which utilizes coal boiler and grid electricity) and Model a21 which utilizes NG boiler and grid electricity.

Model h11 which utilizes anaerobic digester, and Model h12 which utilizes integrated biomass gasifier once again make a special case demonstrating the range from -0.618 $GJ_f/GJ_{biodiesel}$ (Low, Best and High) in Model h11 to -0.269 $GJ_f/GJ_{biodiesel}$ (Low, Best and High) in Model h12 (Chart 5.12, Appendix IV: Tables IV.13, IV.25 & IV.37).

Also, Fossil energy saved in all Models have a range from 104.5% (Low and Best) in Model a21 to 153.3% (Low, Best and High) in Model h11 reflect that more than 100% of the biodiesel energy can be saved the reason of which has been explained earlier.

Also, in all other "High" scenarios: a11 (98.9%), a12 (98.9%), a21 (98.9%), f11 (100.3%), f12 (100.1%), g (100.0%) the Fossil energy saved is very close or equal to 100% which shows that no Fossil energy can be saved in these cases.

Chart 5.12: Energy balance ($GJp/t_{biodiesel}$). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**



The results for the GHG emissions are similar and have a range from -30.4 kgCO_2eq/$GJ_{biodiesel}$ (Low) in Model h11 which utilize anaerobic digester to 2.0 kgCO_2eq/$GJ_{biodiesel}$ (High) in Model h12 which utilize integrated biomass gasifier.

For other Models GHG emissions have a range from 7.0 kgCO_2eq/$GJ_{biodiesel}$ (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) to 39.2 kgCO_2eq/$GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and grid electricity (Charts 5.13 & 5.14, Appendix IV: Tables IV.13, IV.25 & IV.37).

Chart 5.13: GHG balance (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure). Best scenario**

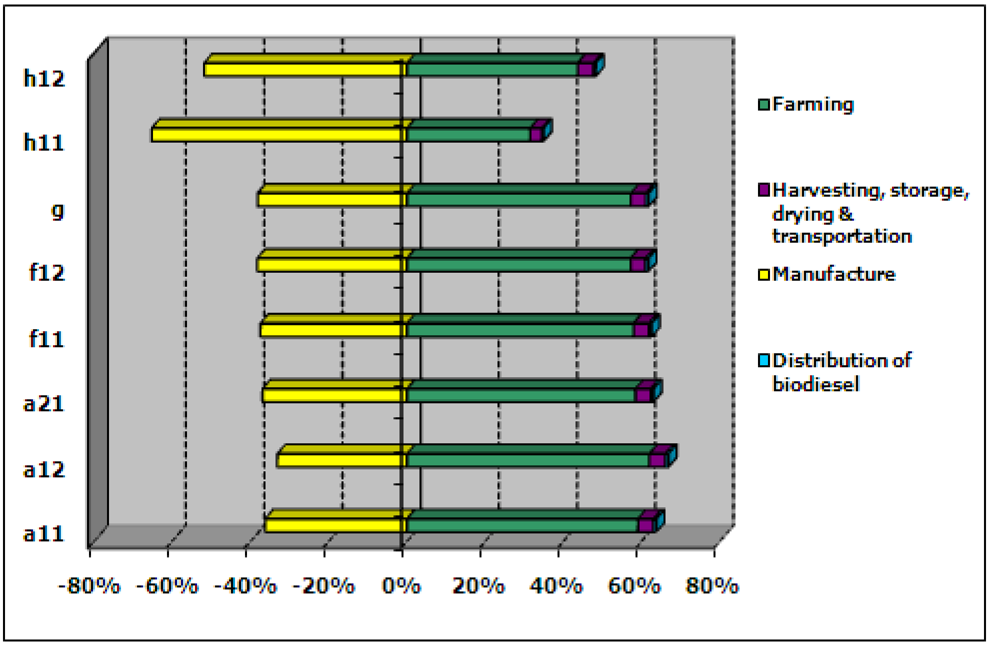


Chart 5.14: GHG emissions ($kgCO_2eq/GJ_{biodiesel}/a$). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure).**

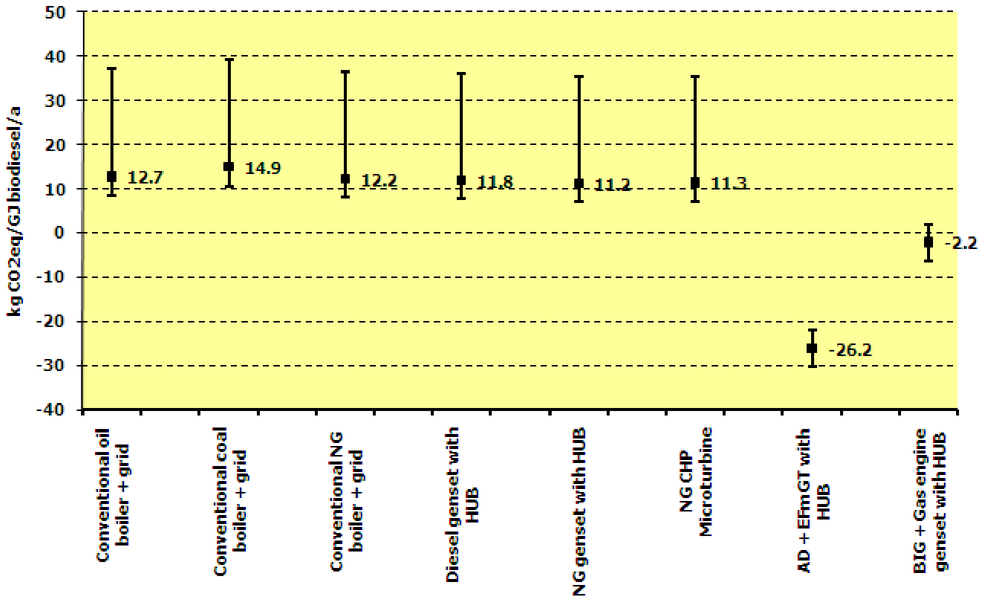
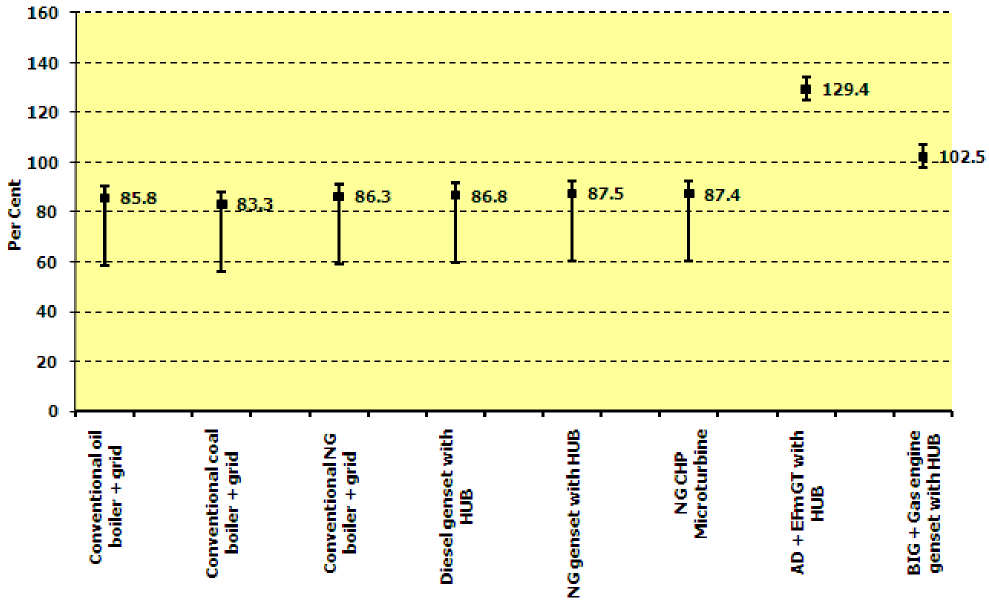


Chart 5.15: GHG avoided (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake as fertilizer (green manure).**



Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier has a range for the GHG avoided from 97.8% (High) in Model h12 which utilize integrated biomass gasifier to 134.0% (Low) in Model h11 which utilize anaerobic digester.

For other Models the results for the GHG avoided have a range from 56.1% (High) in Model a12 which utilizes coal boiler and grid to 92.1% (Low) in Model g which utilizes NG CHP and Microturbine and Model f12 which utilizes NG genset and Heat Utilization Block (HUB) (Chart 5.15).

5.4 *Jatropha* press-cake use as co-fuel for power plant

Similar to scenario "Jatropha press-cake use a fertilizer (green manure)" presented in subchapter 5.3, in this case the *Jatropha* press-cake credit reduces the net energy requirement and greenhouse gas (GHG) emissions as well. Tables in Appendix IV: "LCA results: Low, Best and High scenarios" show the Net balance including credits for surplus electricity and *Jatropha* press-cake use as co-fuel for power plant.

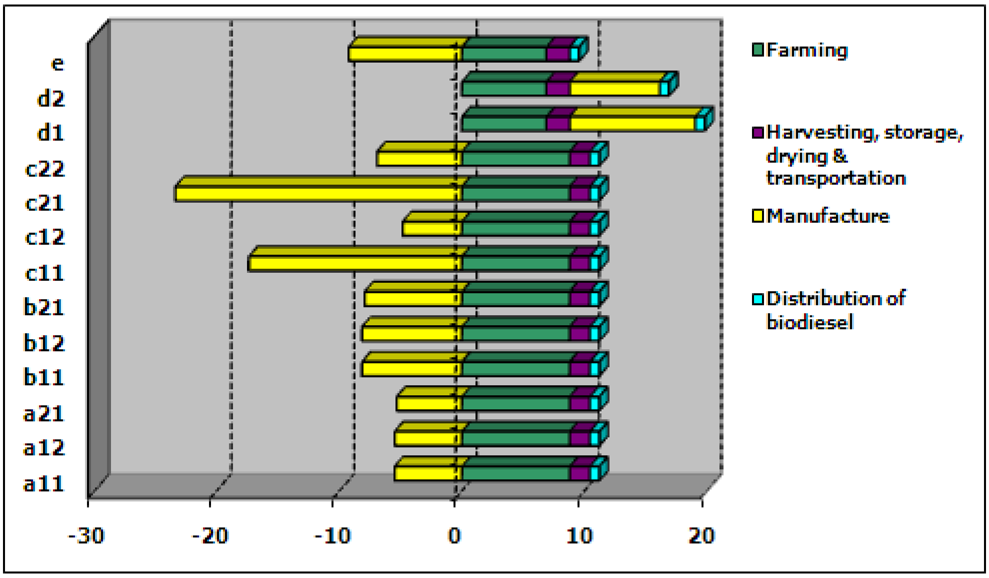
5.4.1 Irrigated Scenario I: Industrial scale production. One-stage Transesterification Process (90 bar, 240^{o}C)

In terms of fossil energy usage the 13 models have a range from -0.41 $GJ_f/GJ_{biodiesel}$ (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 0.28 $GJ_f/GJ_{biodiesel}$ (High) in Model c12 which utilizes NG GT and co-fired HRSG.

Models d1, d2 and e which utilize biomass in the energy supply scenario have a range from -1.06 $GJ_f/GJ_{biodiesel}$ (Low) in Model e which utilize integrated biomass gasifier to -0.348 $GJ_f/GJ_{biodiesel}$ (High) in Model d1 which utilizes biomass boiler.

Also, Fossil energy saved 130.0-146.6% in Model d1, 136.7-153.3% in Model d2 and 175.1-191.7% in Model e reflect that more than 100% of the biodiesel energy can be saved. Once again, it can be interpreted that through the utilization of by-products as an energy sources, large amounts of additional fossil energy can be saved (LowCVP: 2004) (Chart 5.16, Appendix IV: Tables IV.5, IV.17 & IV.29).

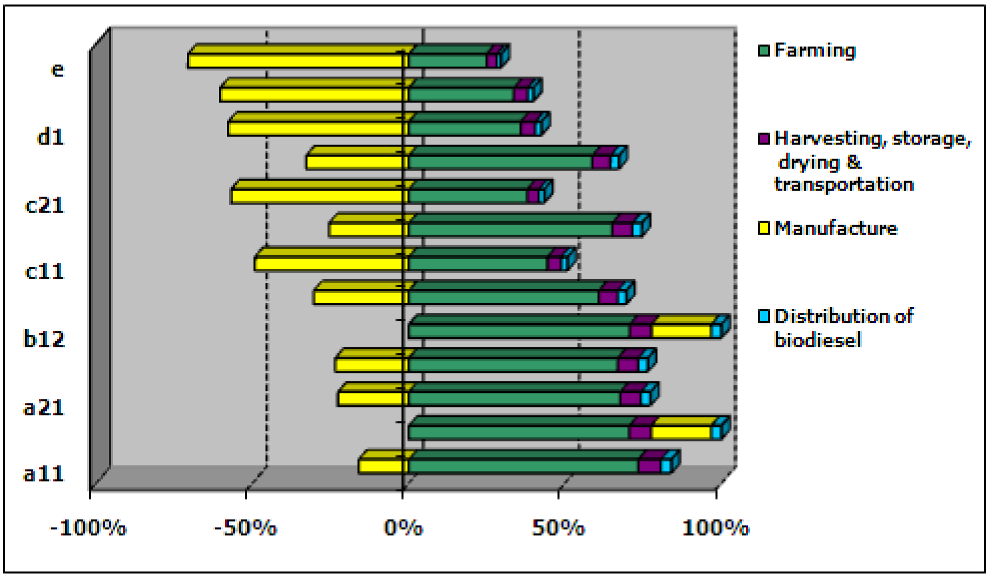
Chart 5.16: Energy balance (GJp/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant. Best scenario**



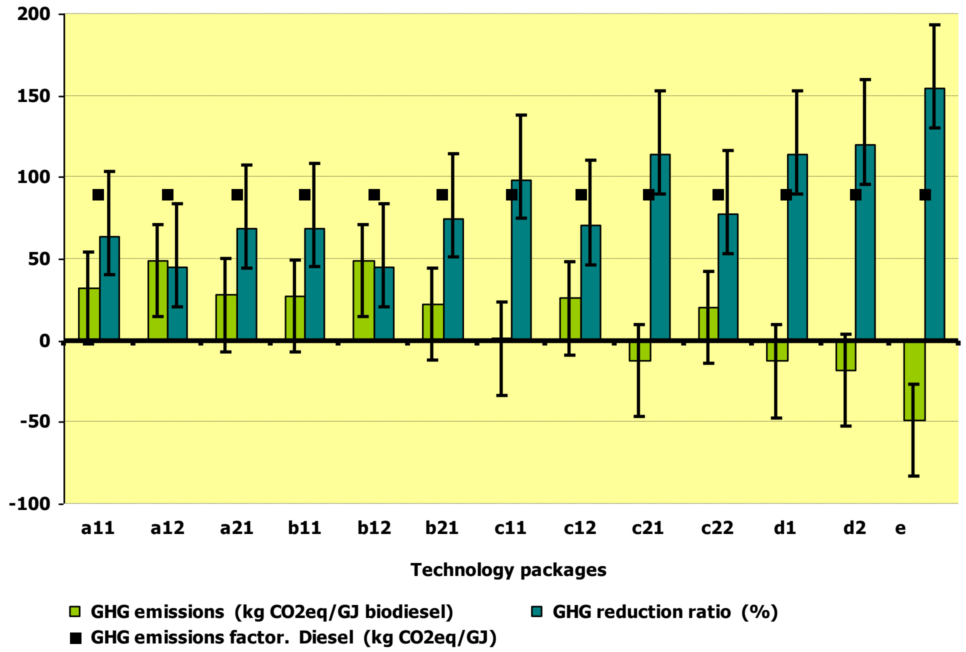
The results for the GHG emissions are similar, even though the savings are lover due to the contribution of the emissions from agriculture. For Models d1, d2 and e the GHG emissions have a range from -70.36 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model e where *Jatropha* pruning material used in integrated biomass gasifier to 22.26 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model d1 where *Jatropha* pruning material used in the biomass boiler.

For other models results for GHG emissions have a range from -34.05 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 83.9-83.99 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and grid electricity and Model b12 which utilizes coal boiler and BPSTG) (Charts 5.17 & 5.18, Appendix IV: Tables IV.5, IV.17 & IV.29).

Chart 5.17: GHG balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant. Best scenario**



Char 5.18: GHG emissions ($kgCO_2eq/GJ_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). One-stage Henkel Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**



For Models d1, d2 and e where *Jatropha* pruning material used in the biomass boiler or integrated biomass gasifier, the results for GHG avoided have a range from 75.1% (High) in Model d1 to 178.8% (Low) in Model e.

For other Models results for the GHG avoided have a range from -6.0% (High) in Model a12 which utilizes coal boiler and grid electricity and 6.1 (High) in Model b12 which utilizes coal boiler and BPSTG to 113.8% (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG (Chart 5.18).

5.4.2 Irrigated Scenario II: Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260^{o}C) and Esterification (10 bar, 240^{o}C)

In this scenario, in terms of fossil energy usage the 13 models have a range from -0.240 $GJ_f/GJ_{biodiesel}$ (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 0.096 $GJ_f/GJ_{biodiesel}$ (High) in Model a21 which utilizes NG boiler and grid electricity.

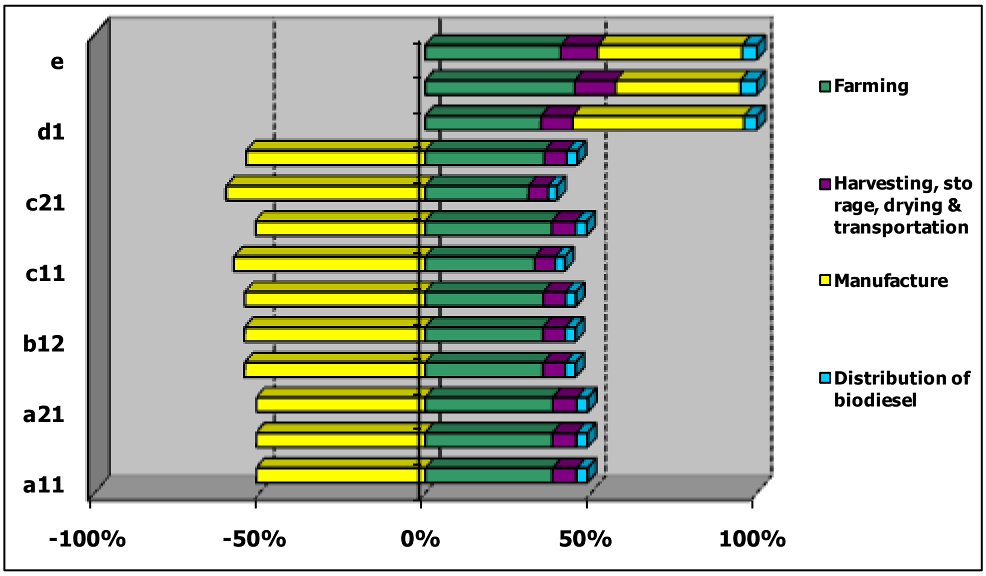
Models d1, d2 and e which utilize biomass in the energy supply scenario make a special case from-0.661 $GJ_f/GJ_{biodiesel}$ (Low) in Model d2 to -0.016 $GJ_f/GJ_{biodiesel}$ (High) in Model d1 (Charts 5.19 & 5.20, Appendix IV: Tables IV.8, IV.20 & IV.32).

Also, Fossil energy saved in all models in Low and Best scenarios, and some models in High scenario, e.g. 100.5% in Model c11, 104.1% in Model c21, 101.4% in Model d1, 140.4% in Model d2, and 136.8% in Model e reflect that more than 100% of the biodiesel energy can be saved (Chart 5.21).

For Models d1, d2 and e the GHG emissions have a range from -14.26 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model d2 to 43.08 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model e respectively where *Jatropha* pruning material used in the biomass boiler or integrated biomass gasifier.

For other Models GHG emissions have a range from -4.74 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model b21 which utilizes NG boiler and BPSTG to 59.66 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and grid electricity (Charts 5.22 & 5.23, Appendix IV: Tables IV.8, IV.20 & IV.32).

Chart 5.19: Energy balance (%). *Jatropha* to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. **Net balance: Press-cake use as co-fuel for power plant. Best scenario**



For Models d1, d2 and e where *Jatropha* pruning material used in the biomass boiler or integrated biomass gasifier, the results for GHG avoided have a range from 51.8% (High) in Model e to 116.0% (Low) in Model d2.

For other Models results for the GHG avoided have a range from 33.2% (High) in Model a12 which utilizes coal boiler and grid electricity to 105.3% (Low) in Model b21 which utilizes NG boiler and BPSTG).

Fossil energy saved 115.7% (Low) in Model d1 and 116.0% in Model d2 where *Jatropha* pruning material used in the biomass boiler, and 115.1% in Model e where *Jatropha* pruning material used in integrated biomass gasifier reflects that more than 100% of the biodiesel energy can be saved (Chart 5.23).

Also, in the following "Low" scenarios: 102.0% (Low) in Model a11 which utilizes oil boiler and grid electricity, 103.3% (Low) in Model a21 which utilizes NG boiled and grid electricity, 104.0% (Low) in Model b11 which utilizes oil boiler and BPSTG, 105.3% (Low) in Model b21 which utilizes NG boiler and BPSTG, 101.6% (Low) in Model c12 which utilizes NG GT and co-fired HRSG, 101.4% in Model c22 which utilizes NG GT, co-fired HRSG and BPSTG the Fossil energy saved is very close or equal to 100% which shows that no Fossil energy can be saved in these cases.

Chart 5.20: Primary total energy input (GJp/GJ$_{biodiesel}$). Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. Net balance: Press-cake used as co-fuel for power plant

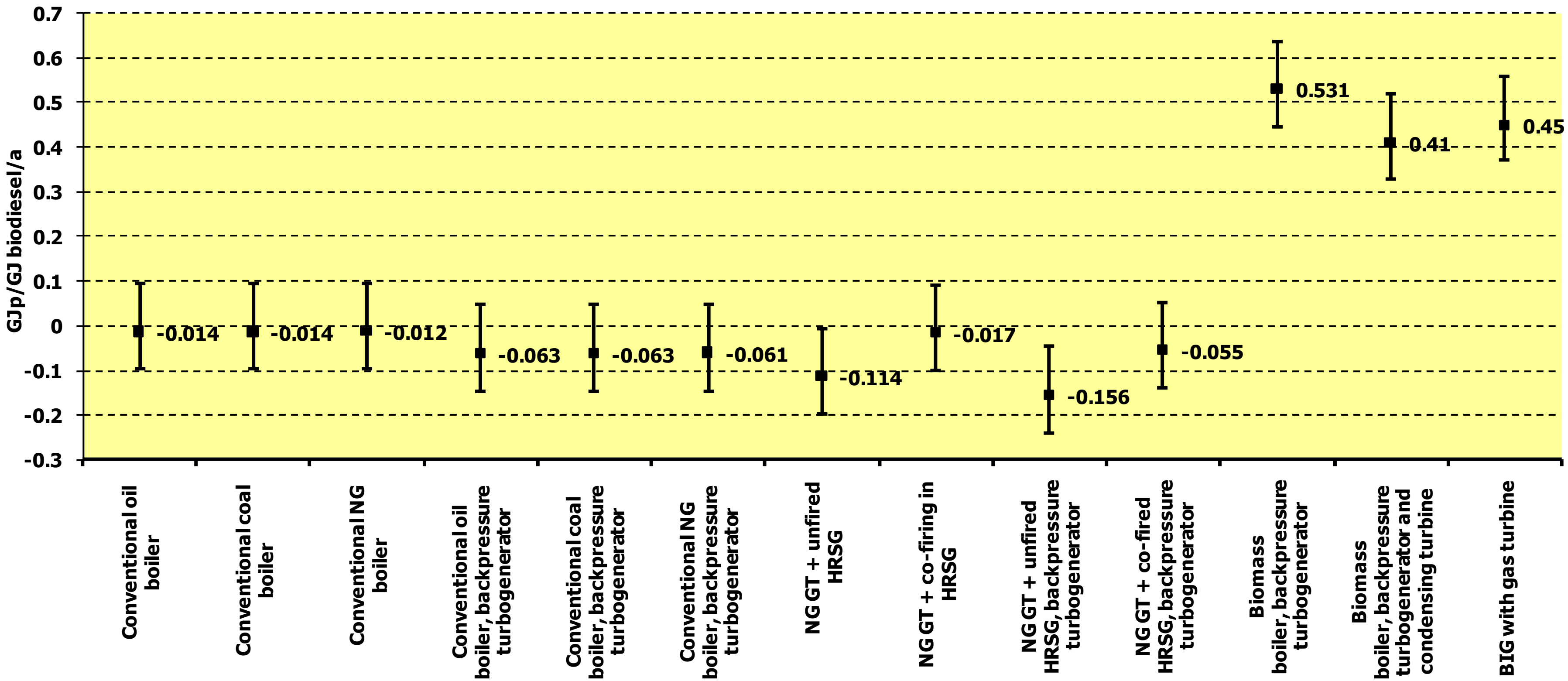


Chart 5.21: Fossil energy saved (%). Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. Net balance: Press-cake used as co-fuel for power plant

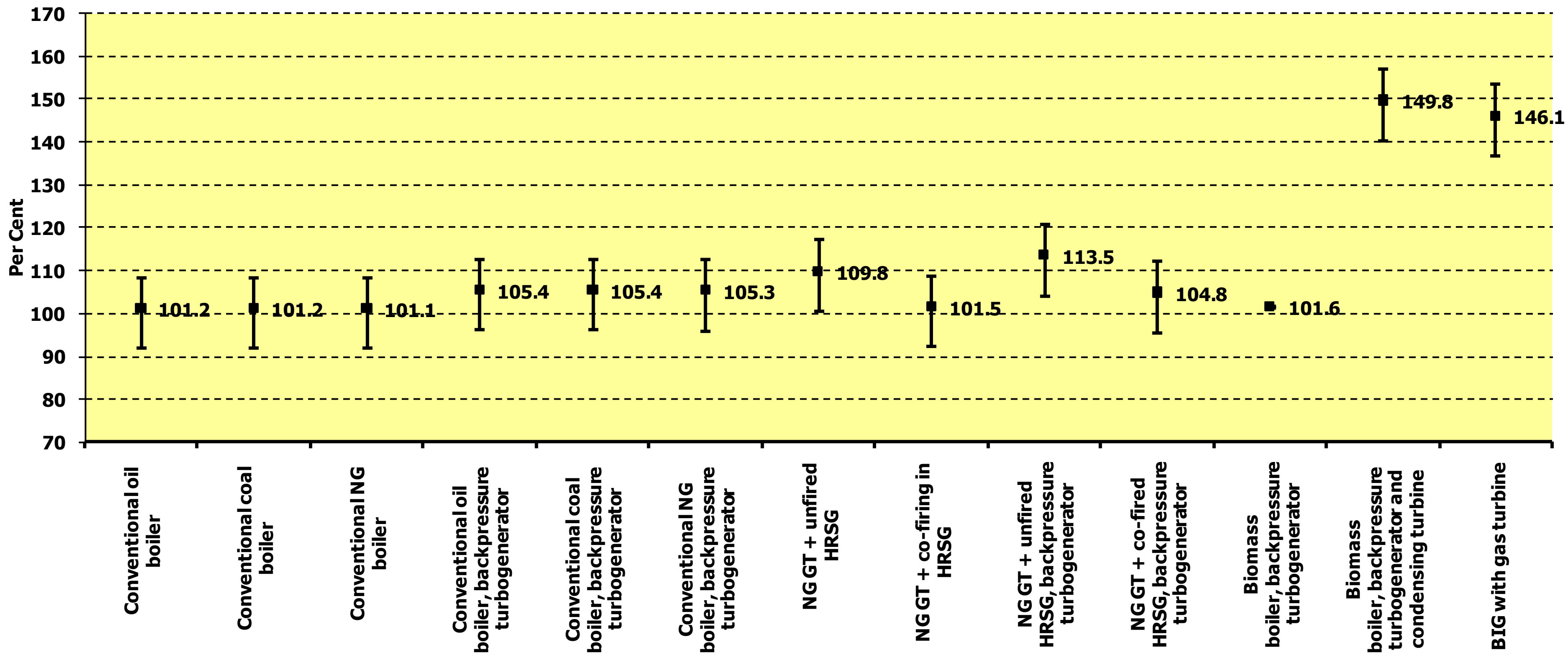


Chart 5.22: GHG emissions (kg CO_2eq/$GJ_{biodiesel}$/a). Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-Splitting and Esterification. Net balance: Press-cake used as co-fuel for power plant

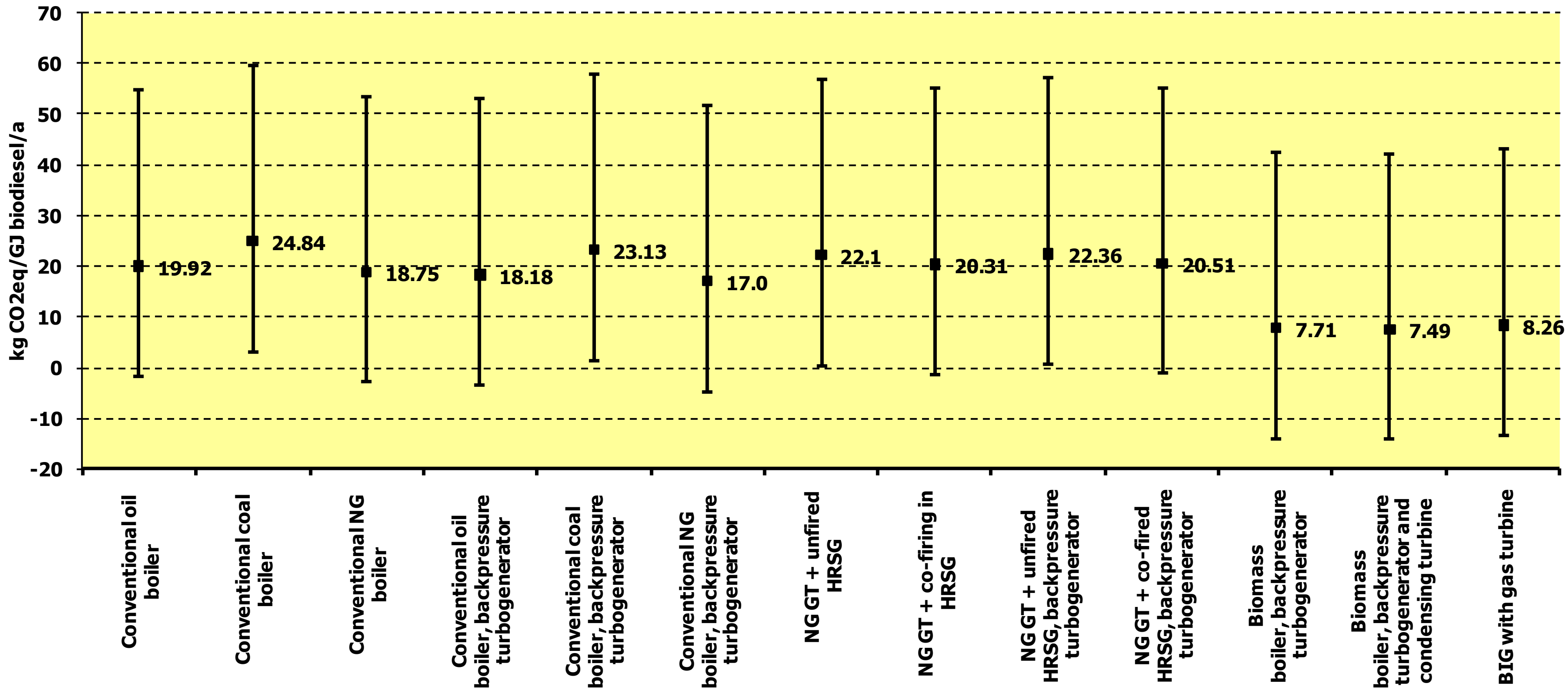
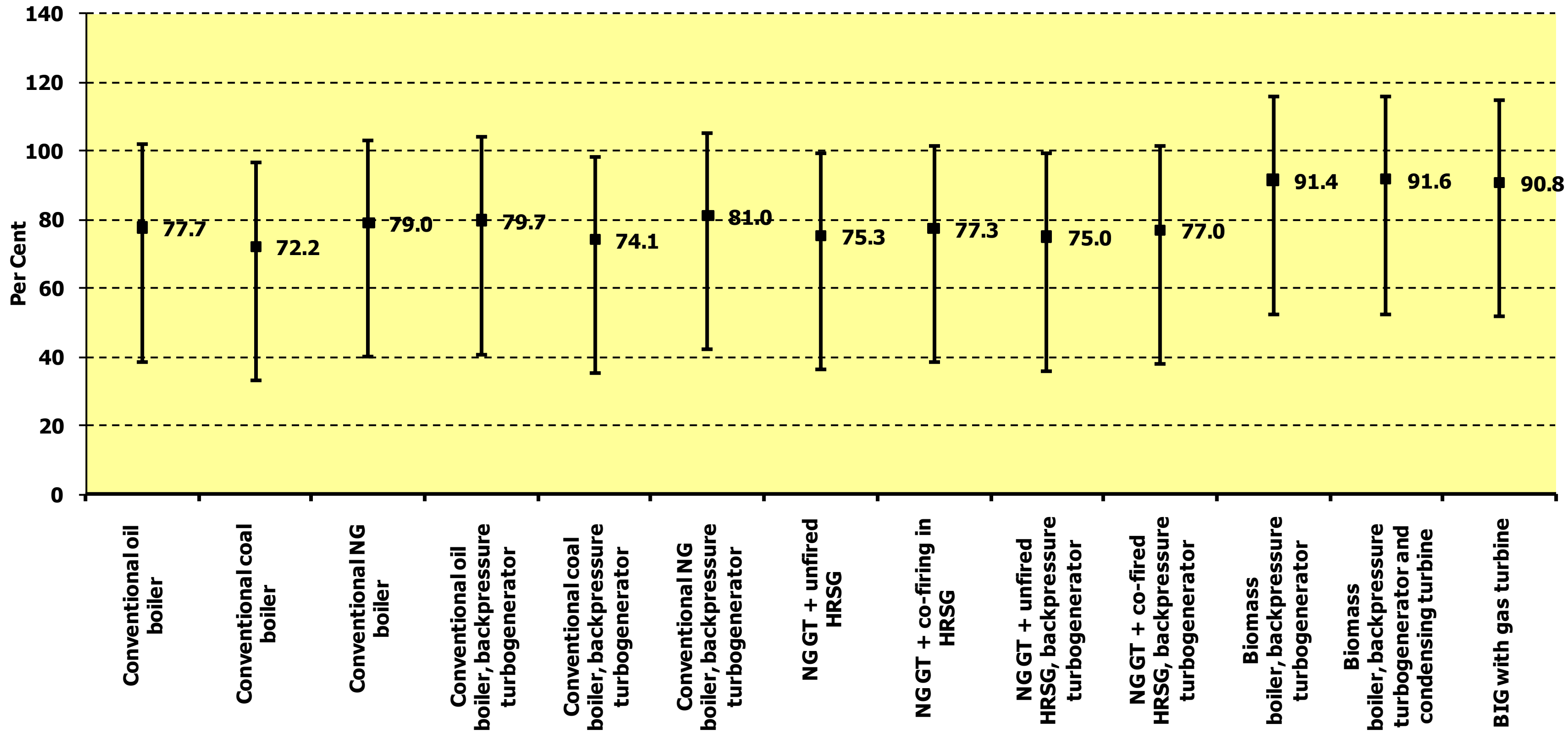


Chart 5.23: GHG avoided (%). Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha). Two-stage process. Fat-splitting and Esterification. Net balance: Press-cake used as co-fuel for power plant



5.4.3 Rainfed Scenario I: Small-scale production. Organic, chemical fertilizers and agro-chemicals applied. Transesterification Process (1.4 bar, 60°C)

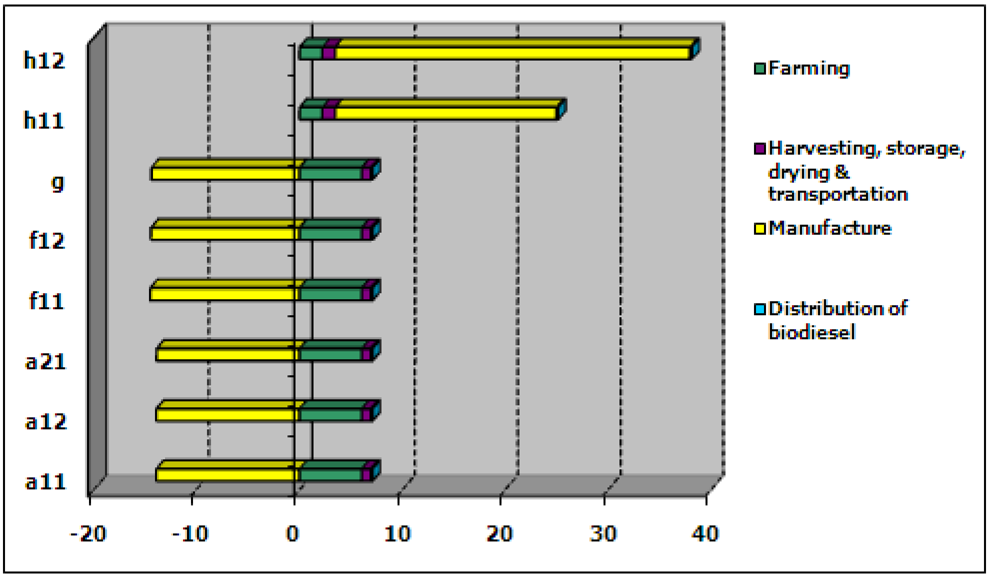
In this scenario, in terms of fossil energy usage the 8 models have almost no fluctuations and vary as little as from -0.225 $GJ_f/GJ_{biodiesel}$ (Low) in Model f11 which utilizes Diesel genset with Heat Utilization Block (HUB) to -0.008 $GJ_f/GJ_{biodiesel}$ (High) in Model a11 which utilizes oil boiler and grid electricity, Model a12 which utilizes coal boiler and grid electricity, and Model a21 which utilizes NG boiler and grid electricity.

Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier once again make a special case for the fossil energy usage which has a range from -0.876 $GJ_f/GJ_{biodiesel}$ (Low) in Model h11 to -0.405 GJf/GJbiodiesel (High) in Model h12.

Also, Fossil energy saved 165.0-175.5% in Model h11 and 134.9-145.5% in Model h12 reflects that more than 100% of the biodiesel energy can be saved, the reason of which has been explained earlier.

In all other Models: a11 (106.9-118.0%), a12 (106.9-118.0%), a21 (106.9-118.0%), f11 (108.3-119.4%), f12 (108.1-119.2%), g (108.0-119.1%) the Fossil energy saved is higher than 100% which shows that more than 100% of the biodiesel energy can be saved (Chart 5.24, Appendix IV: Tables IV.11, IV.23 & IV.35).

Chart 5.24: Energy balance ($GJp/t_{biodiesel}$). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake used as co-fuel for power plant. Best scenario**



The results for the GHG emissions are similar, and have a range from -45.4 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model h11 which utilize anaerobic digester to 24.56 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model h12 which utilize integrated biomass gasifier.

For other Models GHG emissions have a range from 2.65 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) to 52.69 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and electricity from grid (Charts 5.25 & 5.26, Appendix IV: Tables IV.11, IV.23 & IV.35).

Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier has a range for the GHG avoided from 75.2% (High) in Model h12 which utilize integrated biomass gasifier to 150.8% (Low) in Model h11 which utilize anaerobic digester.

For other Models the results for the GHG avoided have a range from 41.0% (High) in Model a12 which utilizes coal boiler and grid to 97.0% (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) and Model g which utilizes NG CHP and Microturbine (Chart 5.26).

Chart 5.25: GHG balance (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake used as co-fuel for power plant. Best scenario**

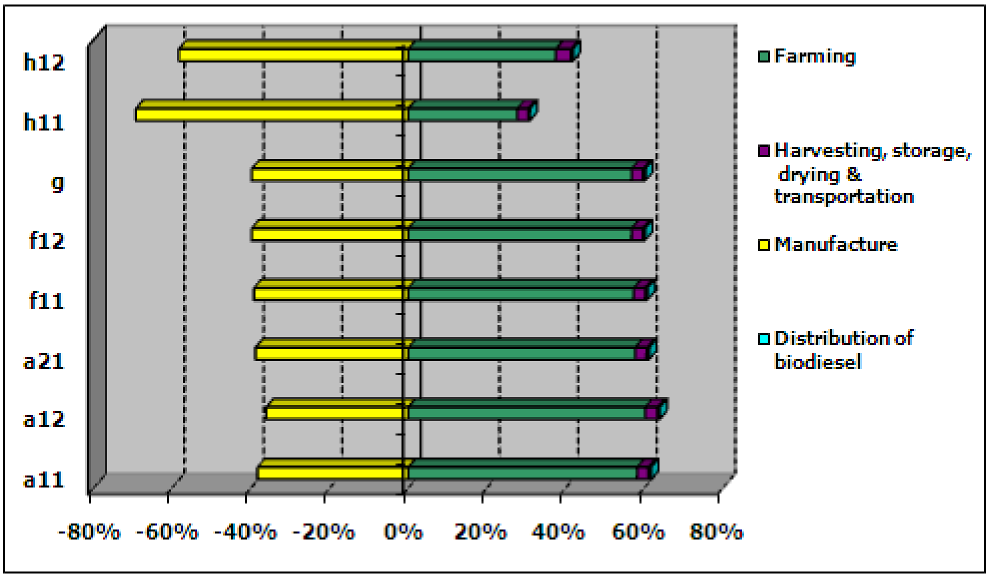
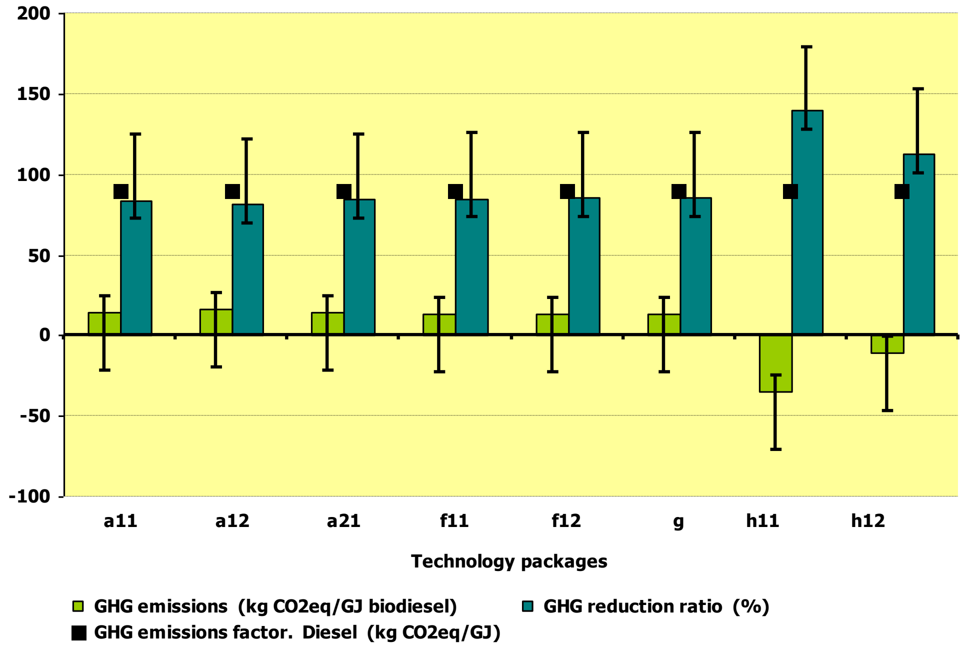


Chart 5.26: GHG emissions GHG emissions (kgCO_2eq/$GJ_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Small-scale Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**



5.4.4 Rainfed Scenario II: Small-scale production. No fertilizers and agro-chemicals used. Transesterification Process (1.4 bar, 60°C)

In this scenario, in terms of fossil energy usage the 8 models have almost no fluctuations and vary as little as from -0.257 $GJ_f/GJ_{biodiesel}$ (Low and Best) in Model f11 which utilizes Diesel genset with Heat Utilization Block (HUB) to -0.176 $GJ_f/GJ_{biodiesel}$ (High) in Model a11 which utilizes oil boiler and grid electricity, Model a12 which utilizes coal boiler and grid electricity) and Model a21 which utilizes NG boiler and grid electricity.

Model h11 which utilizes anaerobic digester and Model h12 which utilizes integrated biomass gasifier once again make a special case demonstrating the range from -0.807 $GJ_f/GJ_{biodiesel}$ (Low, Best and High) in Model h11 to -0.458 $GJ_f/GJ_{biodiesel}$ (Low, Best and High) in Model h12 (Chart 5.27, Appendix IV: Tables IV.14, IV.26 & IV.38).

Also, Fossil energy saved 169.5% in Model h11 and 139.5% in Model h12 reflects that more than 100% of the biodiesel energy can be saved, the reason of which has been explained earlier.

In all other Models: a11 (115.2-120.8%), a12 (115.2-120.8%), a21 (115.2-120.8%), f11 (116.5-122.2%), f12 (116.4-122.1%), g (116.3-121.9%) the Fossil energy saved is higher than 100% which shows that more than 100% of the biodiesel energy can be saved (Chart 5.28, Appendix IV: Tables IV.14, IV.26 & IV.38).

Chart 5.27: Energy balance (GJp/$t_{biodiesel}$). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake used as co-fuel for power plant. Best scenario**

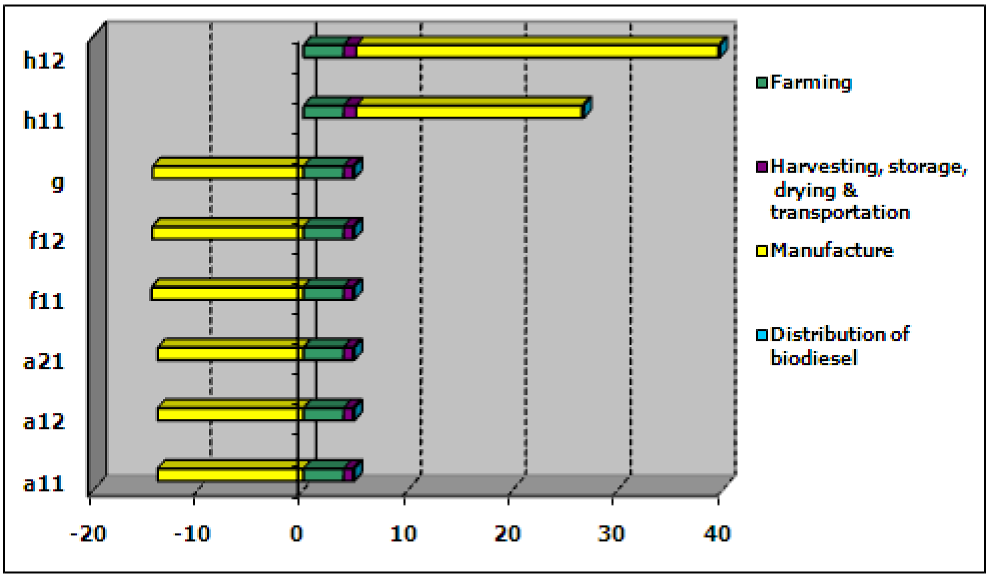
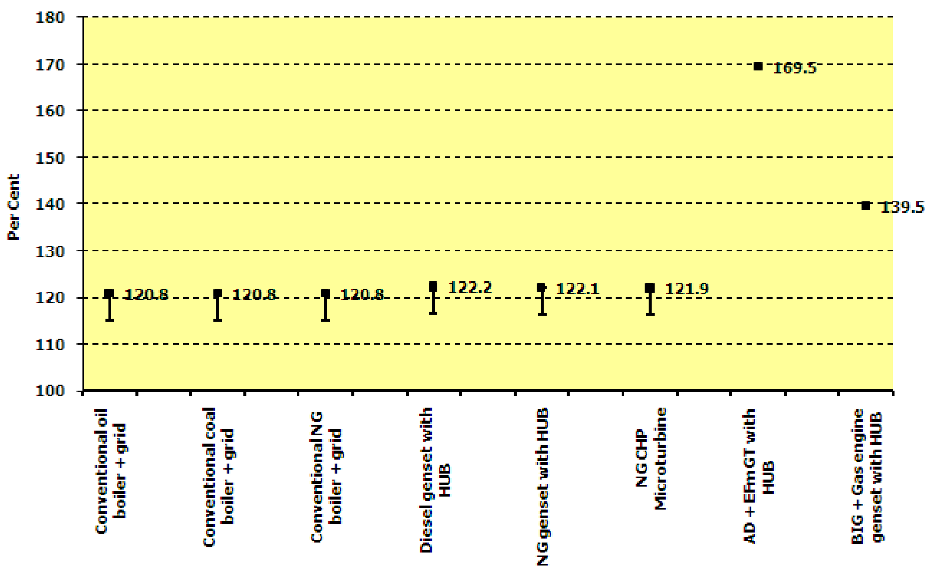


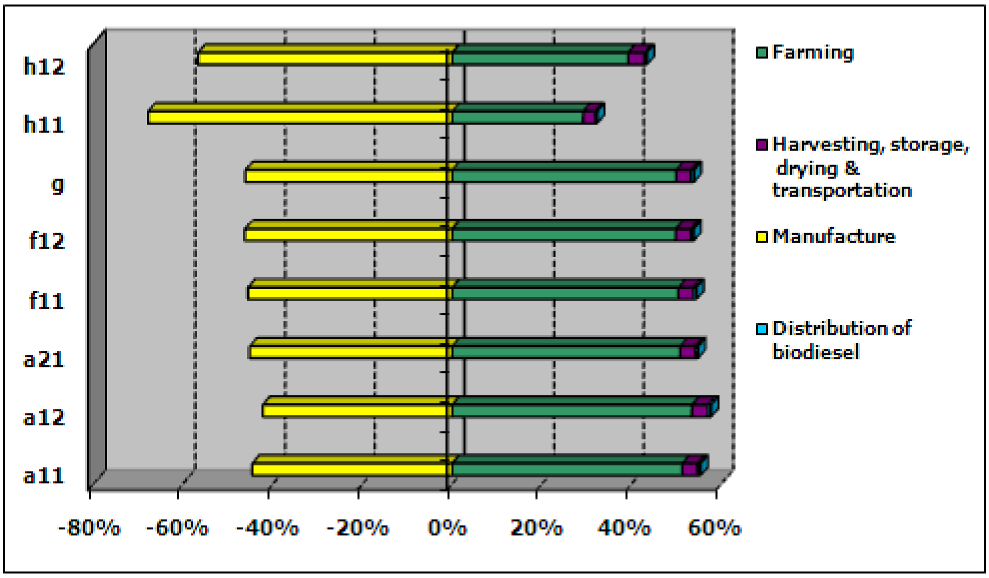
Chart 5.28: Fossil energy saved (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**



The results for the GHG emissions are similar and have a range from -37.38 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model h11 which utilize anaerobic digester to 5.01 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model h12 which utilize integrated biomass gasifier.

For other Models GHG emissions have a range from 0.04 $kgCO_2eq/GJ_{biodiesel}$ (Low) in Model f12 which utilizes NG genset and Heat Utilization Block (HUB) to 32.25 $kgCO_2eq/GJ_{biodiesel}$ (High) in Model a12 which utilizes coal boiler and grid electricity (Charts 5.29 & 5.31, Appendix IV: Tables IV.14, IV.26 & IV.38).

Chart 5.29: GHG balance (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake used as co-fuel for power plant. Best scenario**



Models h11 which utilizes anaerobic digester and h12 which utilizes integrated biomass gasifier has a range for the GHG avoided from 105.6% (High) in Model h12 which utilize integrated biomass gasifier to 141.8% (Low) in Model h11 which utilize anaerobic digester.

For other Models the results for the GHG avoided have a range from 63.9% (High) in Model a12 which utilizes coal boiler and grid to 100% (Low) in Model g which utilizes NG CHP and Microturbine and Model f12 which utilizes NG genset and Heat Utilization Block (HUB) (Charts 5.30 & 5.31).

Chart 5.30: GHG avoided (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**

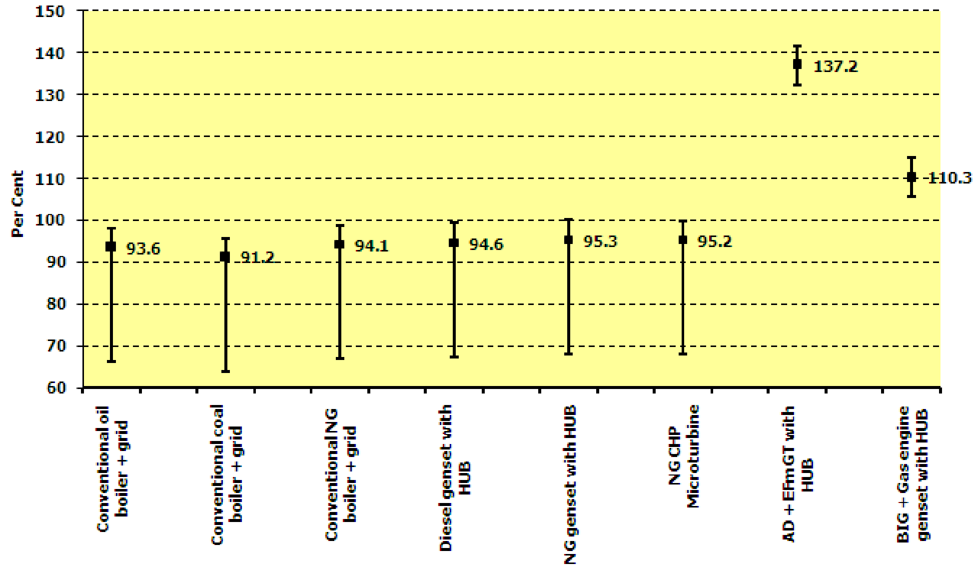
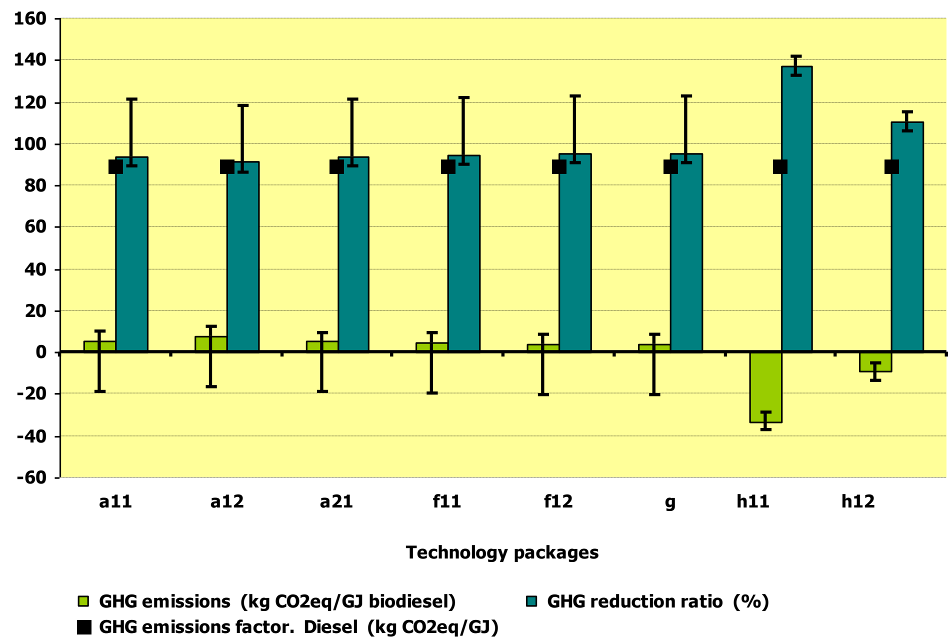


Chart 5.31: GHG emissions (kgCO_2eq/GJ$_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. 2,500 trees/ha. No fertilizers and agro-chemicals used). Small-scale Transesterification Process. **Net balance: Press-cake use as co-fuel for power plant**



5.5 Results of preliminary cost-effectiveness analysis

Tables 5.13, 5.14, 5.15 and 5.16 show the plant margin calculation as well as the cost of CO_2eq avoided for the case where press-cake is used as substitution for chemical fertilizer. The cost calculation for the case where press-cake is used as co-fuel for power plant is not presented here, since predicting the economic value of press-cake as a fuel is difficult.

The calculation credits the biodiesel with the value of an equivalent amount of petrodiesel, on an energy basis. In reality, of course, biodiesel is more costly than petrodiesel, so the calculation generates a net loss for the process: the size of the deficit is an indicator of the relative costs for the different models (LowCVP: 2004).

5.5.1 Irrigated Scenario I: Industrial scale production. One-stage Transesterification Process (90 bar, 240°C)

In terms of gross margin the 13 models have a range from 11.88 MGBP/a (Low, Best and High) in Model a11 which utilizes oil boiler and electricity from grid to 30.81 MGBP/a (Low, Best and High) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG, Models d1, d2 and e which utilize biomass in the energy supply scenario, demonstrate a gross margin rande of 19.75-21.25 MGBP/a (Low, Best and High).

Irrigated I scenario has positive net margin of 0.31 MGBP/a (Low, Best and High) in Model c21 only. All other Models produce negative net margin, which represents current economic reality, and require heavy subsidies for biodiesel production from *Jatropha* oilseeds to become profitable fuel for road transport.

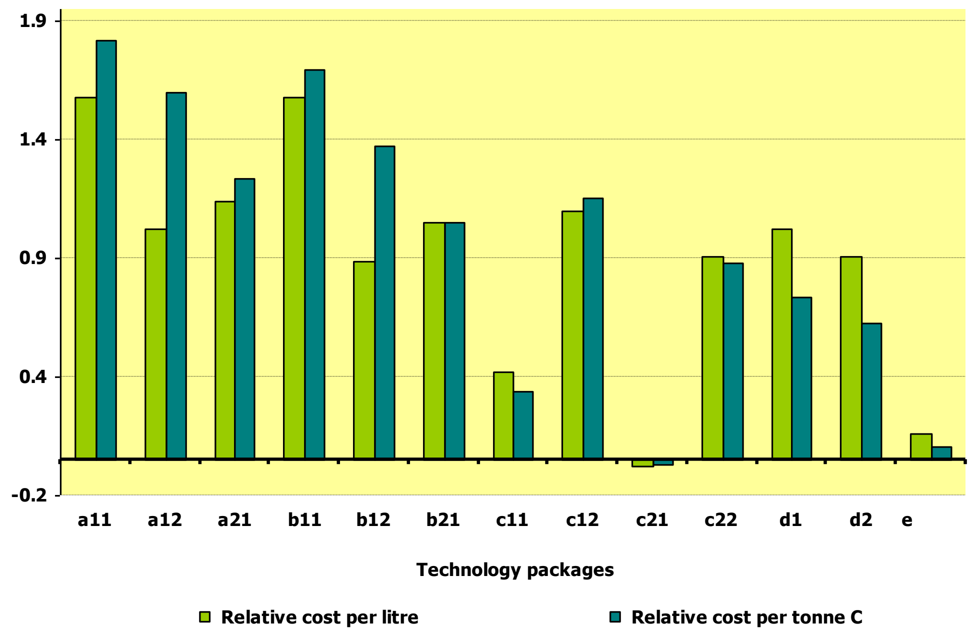
In terms of cost per tonne of carbon the 13 models have a range from -2.71 GBP/tCeq (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 266.3 GBP/tCeq (High) in Model a11 which utilizes oil boiler and electricity from grid.

Models d1, d2 and e reveal the cost per tonne of carbon from 8.6 GBP/tCeq (Low) in Model e which utilize integrated biomass gasifier to 103.5 GBP/tCeq (High) in Model d1 which utilize biomass boiler (Table 5.13).

Table 5.13: Economic margin and cost of GHG avoided: Press-cake as fertilizer (green manure). Irrigated I scenario. Best scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT + unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT + unfired HRSG +BPSTG**	**c22 NG GT + co-fired HRSG +BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/ cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**
Biodiesel plant margin															
Press-cake as fertilizer (Chemical fertilizer substitution)															
Total in	MGBP/a														
Oilseed			-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0
NG					-2.545			-3.229	-6.00	-4.70	-7.85	-6.15	0.0	0.0	0.0
Carbon Oil			-7.67			-9.73									
Coal				-1.32			-1.68								
Grid electricity			-0.34	-0.34	-0.34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
In-field residues (biomass)			0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-5.9	-5.9	-5.9
Total out															
Biodiesel			32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
Press-cake			5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Crude glycerine			3.2	3.2	3.16	3.16	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Electricity			0.0	0.0	0.0	2.27	2.27	2.27	12.3	3.4	18.8	7.2	5.76	7.3	15.73
Gross margin			**11.88**	**18.22**	**17.00**	**12.43**	**20.48**	**18.93**	**26.16**	**18.62**	**30.81**	**20.94**	**19.75**	**21.25**	**29.72**
Capex	MGBP		8.0	8.5	9.0	11.5	13.0	15.0	16.0	16.5	17.0	17.5	18.5	20.0	20.3
Capital charge	MGBP/a	15%	1.2	1.3	1.4	1.7	2.0	2.3	2.4	2.5	2.6	2.6	2.8	3.0	3.0
Opex (including feedstock costs)	% of capex /a		349.3%	328.8%	310.5%	243.0%	215.0%	186.3%	174.7%	169.4%	164.4%	159.7%	151.1%	139.7%	137.7%
	MGBP/a		27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Annual cost	MGBP/a		-29.15	-29.22	-29.30	-29.67	-29.90	-30.20	-30.35	-30.42	-30.50	-30.57	-30.72	-30.95	-30.99
Net margin	MGBP/a		**-17.27**	**-11.00**	**-12.29**	**-17.24**	**-9.42**	**-11.27**	**-4.19**	**-11.80**	**0.31**	**-9.63**	**-10.97**	**-9.70**	**-1.27**
	p/l		-13.43	-8.56	-9.57	-13.42	-7.33	-8.77	-3.26	-9.19	0.24	-7.49	-8.54	-7.55	-0.99
	Rs./l		-10.65	-6.78	-7.579	-10.63	-5.81	-6.95	-2.58	-7.28	0.19	-5.94	-6.76	-5.98	-0.78
Cost relative to b21			1.53	0.98	1.091	1.530	0.84	1.00	0.37	1.05	-0.03	0.855	0.974	0.861	0.113
GHG avoided	**kt/a CO_2eq**		**246.2**	**181.7**	**261.6**	**263.8**	**181.9**	**283.3**	**363.3**	**269.0**	**414.3**	**290.9**	**397.2**	**417.7**	**533.6**
Cost of GHG avoided	**GBP/tCeq**		**257.1**	**221.9**	**172.3**	**239.6**	**189.8**	**145.8**	**42.2**	**160.9**	**-2.766**	**121.4**	**101.3**	**85.1**	**8.7**
	Rs./tCO_2eq		**5556.16**	**4795.91**	**3723.93**	**5178.68**	**4101.89**	**3151.45**	**912.87**	**3477.57**	**-59.77**	**2623.21**	**2188.26**	**1839.85**	**188.51**
Relative cost of GHG avoided			1.76	1.52	1.18	1.64	1.30	1.00	0.29	1.10	-0.02	0.83	0.69	0.58	0.06

Chart 5.32: Relative costs. Scenario IRR I. Press-cake use as fertilizer



In terms of relative cost of GHG avoided (Chart 5.32) the 13 models have a range from -0.02-0.06 (Low, Best and High) in Models c21 which utilizes NG GT, unfired HRSG and BPSTG, and Model e which utilizes Integrated biomass gasifier, GT, unfired HRSG and BP/condensing STG) to 1.77 (High) in Model a11 which utilizes oil boiler and electricity from grid, indicating that even though some other models have higher emission reductions from 422.2 ktCO_2eq/a (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 533.6 ktCO_2eq/a (Best) in Model e which utilizes integrated biomass gasifier, the additional costs may not be justifiable (LowCVP: 2004). The relative costs of GHG avoided, were determined using Irrigated I (large scale) b21 scenario (NG boiler and BPSTG) as a baseline for costs of GHG avoided (Table 5.13).

5.5.2 Irrigated Scenario II: Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C)

In terms of gross margin the 13 models have a range from 17.2 MGBP/a (Low, Best and High) in Model a11 which utilizes oil boiler and electricity from grid to 24.7-25.5 MGBP/a (Low, Best and High) in Model d2 which utilizes biomass boilers and Model e which utilize integrated biomass gasifier. All models in Irrigated II scenario produce negative net margin, which represents current economic reality, and require heavy subsidies for biodiesel production from *Jatropha curcas* oilseeds to become profitable fuel for road transport.

In terms of cost per tonne of carbon the 13 models have a range from 85.9 GBP/tCeq (Low) in Model c21 which utilizes NG GT, unfired HRSG and BPSTG to 154.3 GBP/tCeq (High) in Model a11 which utilizes oil boiler and electricity from grid. Models d1, d2 and e reveal the cost per tonne of carbon vary from 45.6 GBP/tCeq (Low) in Model d2 to 70.6 GBP/tCeq (High) in Model d1 both of which utilize biomass boilers (Table 5.14).

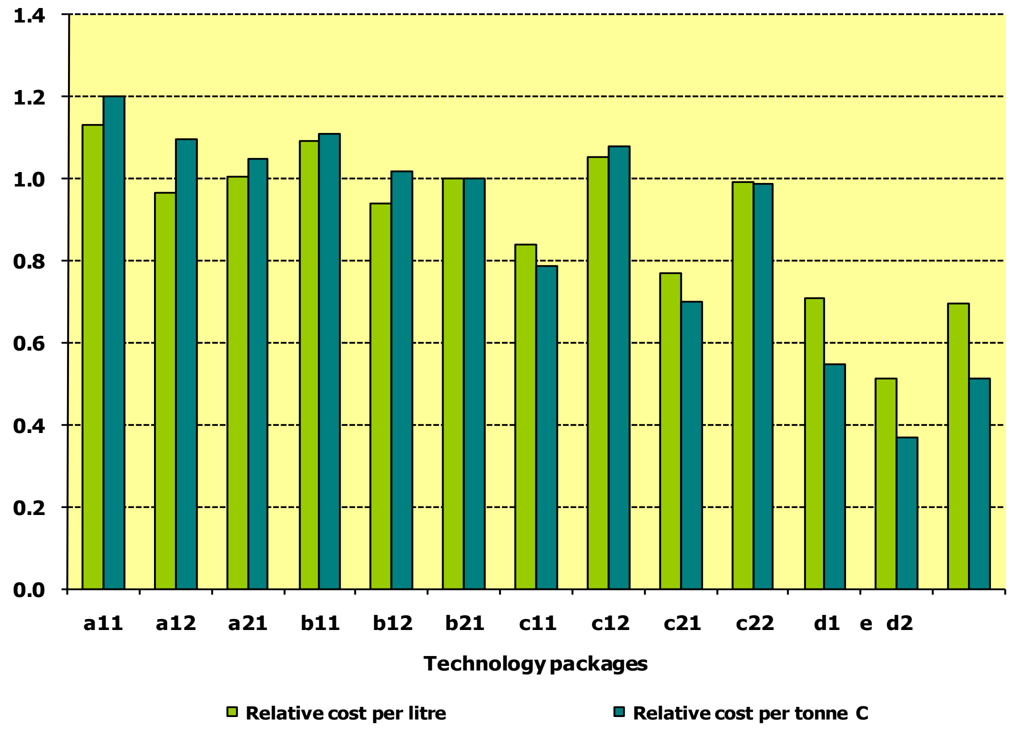
In terms of relative cost of GHG avoided (Chart 5.33) the same models have a range from 0.374 (Low) in Model d2 which utilizes biomass boiler to 1.198 (Low) in Model a11 which utilizes oil boiler and electricity from grid. Models c11, c12 and c21 equipped with unfired or co-fires Heat Recovery Steam Generator (HRSG) demonstrate a range of 0.791-1.1081.

The relative costs of GHG avoided, were determined using Irrigated II (large scale) b21 scenario which utilizes NG boiler and BPSTG as a baseline for costs of GHG avoided.

Table 5.14: Economic margin and cost of GHG avoided: Press-cake as fertilizer (green manure). Irrigated II scenario. Best scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Biodiesel plant margin															
Press-cake as fertilizer (Chemical fertilizer substitution)															
Total in	MGBP/a														
Oilseed			-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0	-21.0
NG					-0.734			-0.739	-1.732	-1.355	-1.796	-1.406	0	0	0
Carbon Oil			-2.21			-2.23									
Coal				-0.38			-0.38								
Grid electricity			-0.48	-0.48	-0.48	0	0	0	0	0	0	0	0	0	0
In-field residues (biomass)			0	0	0	0	0	0	0	0	0	0	-2.45	-2.45	-2.45
Total out															
Biodiesel			32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
Press-cake			5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7
Crude glycerine			3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Electricity			0	0	0	0.47	0.47	0.47	3.3	0.8	4.2	1.6	5.79	8.1	7.26
Gross margin			**17.20**	**19.03**	**18.68**	**18.13**	**19.97**	**19.62**	**21.48**	**19.31**	**22.34**	**20.08**	**23.23**	**25.51**	**24.70**
Capex	MGBP		8.0	8.5	9.0	11.5	13.0	15.0	16.0	16.5	17.0	17.5	18.5	20.0	20.3
Capital charge	MGBP/a	15%	1.2	1.3	1.4	1.7	2.0	2.3	2.4	2.5	2.6	2.6	2.8	3.0	4.1
Opex (including feedstock costs)	% of capex /a		349.3%	328.8%	310.5%	243.0%	215.0%	186.3%	174.7%	169.4%	164.4%	159.7%	151.1%	139.7%	137.7%
	MGBP/a		27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Annual cost	MGBP/a		-29.15	-29.22	-29.30	-29.67	-29.90	-30.20	-30.35	-30.42	-30.50	-30.57	-30.72	-30.95	-32.05
Net margin	MGBP/a		**-11.95**	**-10.19**	**-10.62**	**-11.54**	**-9.92**	**-10.58**	**-8.86**	**-11.11**	**-8.16**	**-10.49**	**-7.50**	**-5.44**	**-7.35**
	p/l		-9.30	-7.93	-8.26	-8.98	-7.72	-8.23	-6.90	-8.65	-6.35	-8.16	-5.83	-4.23	-5.72
	Rs./l		-7.37	-6.28	-6.55	-7.11	-6.12	-6.52	-5.46	-6.85	-5.03	-6.47	-4.62	-3.35	-4.53
Cost relative to b21			1.13	0.96	1.004	1.091	0.94	1.00	0.84	1.05	0.77	0.992	0.709	0.514	0.695
GHG avoided	**kt/a CO_2eq**		**292.4**	**273.7**	**296.8**	**305.2**	**286.5**	**309.6**	**328.4**	**301.2**	**339.6**	**311.4**	**397.6**	**428.7**	**417.7**
Cost of GHG avoided	**GBP/tCeq**		**149.8**	**136.5**	**131.2**	**138.6**	**127.0**	**125.2**	**99.0**	**135.3**	**88.1**	**123.5**	**69.1**	**46.5**	**64.5**
	Rs./tCO_2eq		**3237.64**	**2949.90**	**2834.93**	**2995.59**	**2744.43**	**2706.37**	**2138.68**	**2924.15**	**1903.52**	**2669.58**	**1493.80**	**1005.46**	**1393.73**
Relative cost of GHG avoided			1.20	1.09	1.05	1.11	1.01	1.00	0.79	1.08	0.70	0.99	0.55	0.37	0.51

Chart 5.33: Relative costs. Scenario IRR II. Press-cake use as fertilizer



In terms of GHG avoided Models d1 (389.0-406.1 kt CO_2eq/a) and d2 (420.2-437.3 kt CO_2eq/a) which utilize biomass boilers, Model e (409.2-426.2 ktCO_2eq/a) which utilizes integrated biomass gasifier, and Model c21 (331.1-348.1 ktCO_2eq/a) which utilizes NG GT, unfired HRSG and BPSTG demonstrate the best results in Irrigated II scenario (Table 5.14).

5.5.3 Rainfed Scenario I: Small-scale production. Organic, chemical fertilizers and agro-chemicals applied. Transesterification Process (1.4 bar, 60°C)

In terms of gross margin the 8 models have a range from 0.146 MGBP/a (Low, Best and High) in Model h12 which utilizes integrated biomass gasifier to 0.200-0.212 MGBP/a (Low, Best and High) in Model h11 which utilizes anaerobic digester and Model f12 (NG genset and Heat Utilization Block (HUB)). All models in Rainfed I scenario produce negative net margin, which represents current economic reality, and require heavy subsidies for biodiesel production from *Jatropha curcas* oilseeds to become profitable fuel for road transport (Table 5.15).

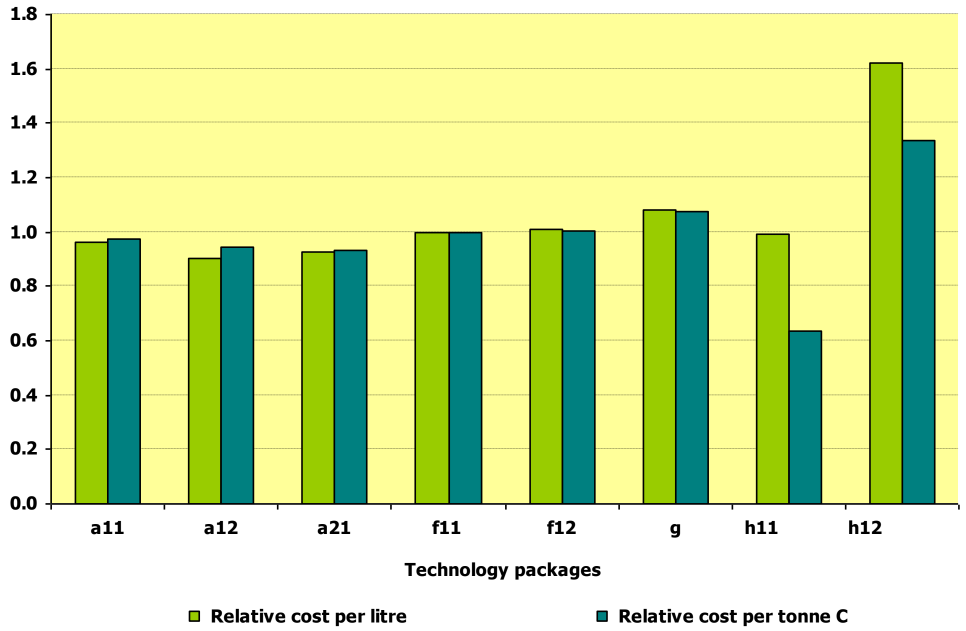
Table 5.15: Economic margin and cost of GHG avoided: Press-cake as fertilizer (green manure). Rainfed I scenario. Best scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**
Biodiesel plant margin										
Press-cake as fertilizer (Chemical fertilizer substitution)										
Total in	MGBP/a									
Oilseed			-0.21	-0.21	-0.21	-0.21	-0.21	-0.21	-0.21	-0.21
NG					-0.003226		-0.00326	-0.003515		
Carbon Oil			-0.0097							
Coal				-0.00168						
Diesel						-0.0104				
Grid electricity			-0.00263	-0.00263	-0.00263	0.0	0.0	0.0	0.0	0.0
In-field residues (biomass)									-0.091	-0.091
Total out										
Biodiesel			0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Press-cake			0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057
Crude glycerine			0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Electricity			0.0	0.0	0.0	0.0013	0.0002	0.0004	0.101	0.034
Gross margin			**0.190**	**0.198**	**0.197**	**0.193**	**0.200**	**0.199**	**0.212**	**0.146**
Capex	MGBP		0.11	0.12	0.13	0.16	0.21	0.26	0.28	0.3
Capital charge	MGBP/a	15%	0.017	0.018	0.020	0.024	0.03	0.04	0.04	0.05
Opex (including feedstock costs)	% of capex /a		254.1%	232.9%	215.0%	174.7%	133.1%	107.5%	99.8%	93.2%
	MGBP/a		0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279
Annual cost	MGBP/a		-0.30	-0.30	-0.30	-0.30	-0.31	-0.32	-0.32	-0.32
Net margin	MGBP/a		**-0.11**	**-0.10**	**-0.10**	**-0.11**	**-0.11**	**-0.12**	**-0.11**	**-0.18**
	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88
	Rs./l		-6.520	-6.12	-6.305	-6.784	-6.871	-7.336	-6.72	-11.00
Cost relative to f11			0.96	0.90	0.93	1.00	1.01	1.08	0.99	1.62
GHG avoided	**kt/a CO_2eq**		**2.7**	**2.7**	**2.8**	**2.8**	**2.8**	**2.8**	**4.2**	**3.3**
Cost of GHG avoided	**GBP/tCeq**		**141.3**	**136.7**	**135.7**	**145.2**	**145.9**	**155.9**	**94.2**	**196.1**
	Rs./tCO_2eq		**3053.98**	**2953.13**	**2932.30**	**3138.42**	**3152.02**	**3368.15**	**2034.91**	**4237.67**
Relative cost of GHG avoided			0.97	0.94	0.93	1.000	1.004	1.07	0.65	1.35

In terms of cost per tonne of carbon the 8 models have a range from 94.2 GBP/tCeq (Best) in Model h11 which utilizes anaerobic digester to 215.8 GBP/tCeq (Low) in Model h12 which utilizes integrated biomass gasifier.

In terms of relative cost of GHG avoided (Chart 5.34) the same models have a range from 0.63 (High) in Model h11 which utilizes anaerobic digester to 1.34 (High) in Model h12 which utilizes integrated biomass gasifier. The relative costs of GHG avoided, were determined using Rainfed I (small-scale) f11 scenario which utilizes Diesel genset with Heat Utilization Block (HUB) as a baseline for costs of GHG avoided.

Chart 5.34: Relative costs. Scenario RAIN I. Press-cake use as fertilizer



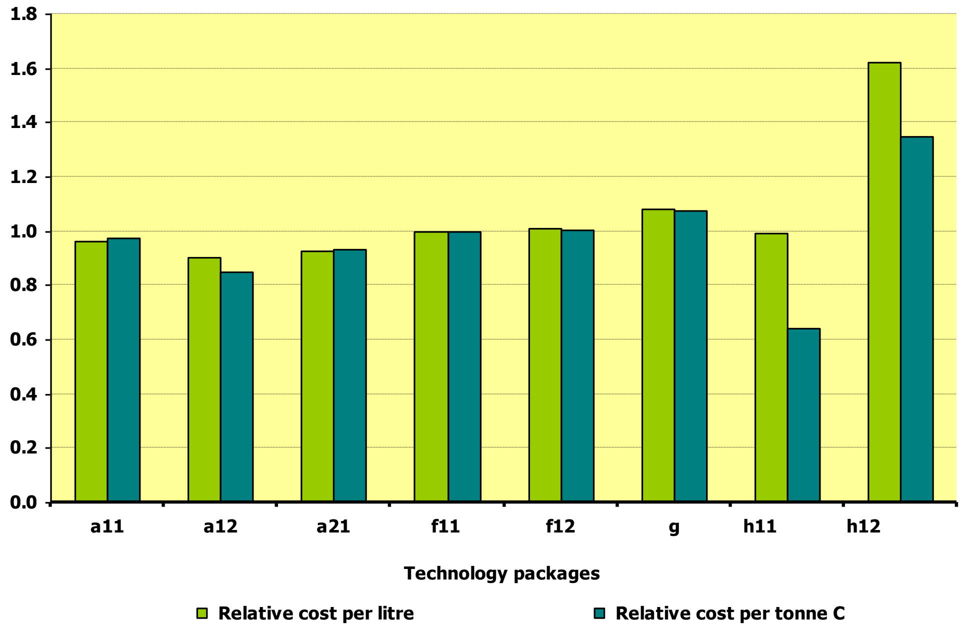
In terms of GHG avoided Models h11 (4.1-4.4 ktCO_2eq/a) and h12 (3.2-3.5 ktCO_2eq/a) which utilize biomass boilers, Model f12 (2.6-3.0 ktCO_2eq/a) which utilizes NG genset and Heat Utilization Block (HUB), and Model g (2.6-3.0 ktCO_2eq/a) which utilizes NG CHP and Microturbine demonstrate the best results for Rainfed I scenario (Table 5.15).

5.5.4 Rainfed Scenario II: Small-scale production. No fertilizers and agro-chemicals used. Transesterification Process (1.4 bar, 60°C)

In terms of gross margin the 8 models have a range from 0.146 MGBP/a (Low, Best and High) in Model h12 which utilizes integrated biomass gasifier to 0.200-0.212 MGBP/a (Low, Best and High) in Model h11 which utilizes anaerobic digester and Model f12 which utilizes NG genset and Heat Utilization Block (HUB). All models in Rainfed II scenario produce negative net margin, which represents current economic reality, and require heavy subsidies for biodiesel production from *Jatropha curcas* oilseeds to become profitable fuel for road transport.

In terms of cost per tonne of carbon the 8 models have a range from 88.6 GBP/tCeq (Low) in Model h11 which utilize anaerobic digester to 198.9 GBP/tCeq (High) in Model h12 which utilizes integrated biomass gasifier.

Chart 5.35: Relative costs. Scenario RAIN II. Press-cake use as fertilizer



In terms of relative cost of GHG avoided (Chart 5.35) the same models have a range from 0.64 (High) in Model h11 which utilizes anaerobic digester to 1.37 (Low) in Model h12 which utilizes integrated biomass gasifier. The relative costs of GHG avoided, were determined using Rainfed II (small-scale) f11 scenario which utilizes Diesel genset with Heat Utilization Block (HUB) as a baseline for costs of GHG avoided.

Table 5.16: Economic margin and cost of GHG avoided: Press-cake as fertilizer (green manure). Rainfed II scenario. Best scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Biodiesel plant margin										
Press-cake as fertilizer (Chemical fertilizer substitution)										
Total in	MGBP/a									
Oilseed			-0.21	-0.21	-0.21	-0.21	-0.21	-0.21	-0.21	-0.21
NG					-0.003226		-0.00326	-0.003515		
Carbon Oil			-0.01							
Coal				-0.00168						
Diesel						-0.0104				
Grid electricity			-0.00263	-0.00263	-0.00263	0.0	0.0	0.0	0.0	0.0
In-field residues (biomass)			0.0	0.0	0.0	0.0	0.0	0.0	-0.091	-0.091
Total out										
Biodiesel			0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Press-cake			0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.057
Crude glycerine			0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Electricity			0.0	0.0	0.0	0.00129	0.00022	0.00043	0.101	0.034
Gross margin			**0.190**	**0.198**	**0.197**	**0.193**	**0.200**	**0.199**	**0.212**	**0.146**
Capex	MGBP		0.11	0.12	0.13	0.16	0.21	0.26	0.28	0.3
Capital charge	MGBP/a	15%	0.017	0.018	0.020	0.024	0.03	0.039	0.042	0.05
Opex (including feedstock costs)	% of capex /a		254.1%	232.9%	215.0%	174.7%	133.1%	107.5%	99.8%	93.2%
	MGBP/a		0.279	0.279	0.279	0.279	0.279	0.279	0.279	0.279
Annual cost	MGBP/a		-0.30	-0.30	-0.30	-0.30	-0.31	-0.32	-0.32	-0.32
Net margin	MGBP/a		**-0.11**	**-0.10**	**-0.10**	**-0.11**	**-0.11**	**-0.12**	**-0.11**	**-0.18**
	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88
	EUR/l		-0.10	-0.10	-0.10	-0.11	-0.11	-0.12	-6.72	-0.18
Cost relative to f11			0.96	0.90	0.93	1.00	1.01	1.08	0.99	1.62
GHG avoided	**kt/a CO_2eq**		**2.9**	**3.0**	**2.9**	**2.9**	**2.9**	**2.9**	**4.4**	**3.4**
Cost of GHG avoided	**GBP/tCeq**		**135.8**	**120.8**	**130.5**	**139.7**	**140.3**	**149.9**	**91.8**	**189.8**
	Rs./tCO_2eq		**2935.28**	**2609.68**	**2819.10**	**3017.88**	**3031.94**	**3239.73**	**1983.07**	**4101.28**
Relative cost of GHG avoided			0.97	0.86	0.93	1.000	1.005	1.07	0.66	1.36

In terms of GHG avoided Models h11 (4.2-4.5 ktCO_2eq/a) which utilizes anaerobic digester, and h12 (3.3-3.6 ktCO_2eq/a) which utilize integrated biomass gasifier, demonstrate the best results in Rainfed I scenario. All other models produce very similar results for GHG avoided with the range of 2.8-3.1 ktCO_2eq/a (Table 5.16).

Tables from 5.17 to 5.28 summarise the main figures.

Table 5.17: Summary of main results and indicators. Irrigated I scenario. High scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT + unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT + unfired HRSG+ BPSTG**	**c22 NG GT + co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Fossil energy balance	GJf/GJ road fuel															
Gross			0.67	0.67	0.68	0.72	0.72	0.73	1.00	0.87	1.18	1.01	0.36	0.36	0.36	1.16
Net of credits																
Press-cake as fertilizer			0.45	0.45	0.45	0.38	0.38	0.38	0.13	0.47	-0.03	0.41	-0.16	-0.24	-0.68	
Perss-cake use as co-fuel for power plant			0.26	0.26	0.27	0.19	0.19	0.20	-0.06	0.28	-0.22	0.22	-0.35	-0.43	-0.87	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			93.59	110.64	89.54	97.15	118.79	92.01	107.03	99.97	117.05	107.82	69.74	69.74	69.74	89.3
Net of credits																
Press-cake as fertilizer			73.87	90.92	69.81	69.22	90.86	64.08	42.92	67.86	29.44	62.06	29.19	23.78	-6.87	
Press-cake used as co-fuel for power plant			66.94	83.99	62.88	62.29	83.93	57.15	35.99	60.93	22.51	55.13	22.26	16.85	-13.79	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			15.47	-1.58	19.53	20.12	-1.52	25.26	46.42	21.48	59.90	27.28	60.15	65.56	96.20	
Press-cake used as co-fuel for power plant			22.40	5.35	26.45	27.05	5.41	32.19	53.35	28.41	66.83	34.21	67.08	72.49	103.13	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-13.43	-8.56	-9.57	-13.42	-7.33	-8.77	-3.26	-9.19	0.24	-7.49	-8.54	-7.55	-0.99	
Cost relative to b21			1.53	0.98	1.09	1.53	0.84	1.00	0.37	1.05	-0.03	0.85	0.97	0.86	0.11	
Cost of GHG avoided	GBP/t Ceq		266.33	232.85	178.13	247.64	199.14	150.36	43.26	166.19	-2.82	125.05	103.48	86.91	8.87	
Relative cost of GHG avoided			1.77	1.55	1.18	1.65	1.32	1.00	0.29	1.11	-0.02	0.83	0.69	0.58	0.06	

Table 5.18: Summary of main results and indicators. Irrigated II scenario. High scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Fossil energy balance	GJf/GJ road fuel															
Gross			0.50	0.50	0.51	0.48	0.48	0.48	0.58	0.54	0.59	0.55	0.64	0.64	1.05	1.16
Net of credits																
Press-cake as fertilizer			0.28	0.28	0.28	0.23	0.23	0.23	0.18	0.28	0.14	0.24	-0.01	-0.28	-0.24	
Perss-cake use as co-fuel for power plant			0.09	0.09	0.10	0.05	0.05	0.05	-0.01	0.09	-0.05	0.05	-0.02	-0.47	-0.43	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			81.40	86.32	80.23	79.70	84.65	78.52	83.90	81.87	84.25	82.14	69.74	69.74	69.74	89.34
Net of credits																
Press-cake as fertilizer			61.67	66.59	60.50	59.93	64.88	58.75	63.85	62.06	64.12	62.26	49.46	49.24	50.01	
Perss-cake use as co-fuel for power plant			54.74	59.66	53.57	53.00	57.95	51.82	56.92	55.14	57.19	55.33	42.53	42.31	43.08	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			27.67	22.75	28.84	29.41	24.46	30.59	25.49	27.27	25.22	27.08	39.88	40.10	39.33	
Perss-cake use as co-fuel for power plant			34.60	29.68	35.77	36.34	31.39	37.52	32.41	34.20	32.15	34.01	46.81	47.03	46.26	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-9.30	-7.93	-8.26	-8.98	-7.72	-8.23	-6.90	-8.65	-6.35	-8.16	-5.83	-4.23	-5.72	
Cost relative to b21			1.13	0.96	1.00	1.09	0.94	1.00	0.84	1.05	0.77	0.99	0.71	0.51	0.69	
Cost of GHG avoided	GBP/t Ceq		154.32	140.89	135.06	142.60	130.89	128.78	101.60	139.26	90.35	127.01	70.64	47.47	65.84	
Relative cost of GHG avoided			1.20	1.09	1.05	1.11	1.02	1.00	0.79	1.08	0.70	0.99	0.55	0.37	0.51	

Table 5.19: Summary of main results and indicators. Rainfed I scenario. High scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Fossil energy balance	GJf/GJ road fuel										
Gross			0.34	0.34	0.34	0.33	0.32	0.33	1.67	1.67	1.16
Net of credits											
Press-cake as fertilizer			0.11	0.11	0.11	0.09	0.09	0.10	-0.6	-0.22	
Perss-cake use as co-fuel for power plant			-0.08	-0.08	-0.08	-0.10	-0.09	-0.09	-0.8	-0.40	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			77.49	79.65	76.98	77.05	76.05	76.18	63.97	63.97	89.3
Net of credits											
Press-cake as fertilizer			57.51	59.67	57.00	56.60	55.98	56.04	7.52	31.54	
Perss-cake use as co-fuel for power plant			50.53	52.69	50.01	49.62	49.00	49.06	0.54	24.56	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			31.83	29.67	32.34	32.74	33.35	33.29	81.81	57.80	
Perss-cake use as co-fuel for power plant			38.81	36.65	39.33	39.72	40.34	40.28	88.80	64.78	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88	
Cost relative to f11			0.96	0.90	0.93	1.00	1.01	1.08	0.99	1.62	
Cost of GHG avoided	GBP/t Ceq		150.67	146.00	144.60	154.71	155.30	165.96	98.10	206.65	
Relative cost of GHG avoided			0.97	0.94	0.93	1.00	1.00	1.07	0.63	1.34	

Table 5.20: Summary of main results and indicators. Rainfed II scenario. High scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**	**Diesel**
Fossil energy balance	GJf/GJ road fuel										
Gross			0.24	0.24	0.24	0.23	0.23	0.23	0.14	0.14	1.16
Net of credits											
Press-cake as fertilizer			0.01	0.01	0.01	0.00	0.00	0.00	-0.62	-0.27	
Perss-cake use as co-fuel for power plant			-0.18	-0.18	-0.18	-0.19	-0.19	-0.19	-0.81	-0.46	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			57.05	59.21	56.54	56.61	55.60	55.74	34.40	34.40	89.3
Net of credits											
Press-cake as fertilizer			37.07	39.23	36.55	36.16	35.54	35.60	-22.04	1.97	
Perss-cake use as co-fuel for power plant			30.09	32.25	29.57	29.18	28.56	28.62	-29.03	-5.01	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			52.27	50.11	52.79	53.18	53.80	53.74	111.38	87.37	
Perss-cake use as co-fuel for power plant			59.25	57.09	59.77	60.16	60.78	60.72	118.37	94.35	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88	
Cost relative to f11			0.96	0.9	0.93	1.00	1.01	1.08	0.99	1.62	
Cost of GHG avoided	GBP/t Ceq		143.79	125.84	138.05	147.74	148.36	158.53	95.22	198.91	
Relative cost of GHG avoided			0.97	0.85	0.93	1.00	1.00	1.07	0.64	1.35	

Table 5.21: Summary of main results and indicators. Irrigated I scenario. Best scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG +BPSTG	c22 NG GT + co-fired HRSG +BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Fossil energy balance	GJf/GJ road fuel															
Gross			0.56	0.56	0.57	0.61	0.61	0.62	0.89	0.76	1.07	0.90	0.26	0.26	0.26	1.16
Net of credits																
Press-cake as fertilizer			0.34	0.34	0.35	0.27	0.27	0.28	0.02	0.36	-0.14	0.30	-0.27	-0.35	-0.79	
Perss-cake use as co-fuel for power plant			0.15	0.15	0.16	0.08	0.08	0.09	-0.17	0.17	-0.33	0.11	-0.46	-0.53	-0.98	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			58.77	75.82	54.72	62.33	83.97	57.19	72.21	65.15	82.23	72.99	34.93	34.93	34.93	89.3
Net of credits																
Press-cake as fertilizer			39.04	56.10	34.99	34.40	56.04	29.26	8.10	33.03	-5.38	27.24	-5.63	-11.04	-41.68	
Press-cake used as co-fuel for power plant			32.11	49.17	28.06	27.47	49.11	22.33	1.17	26.10	-12.31	20.31	-12.56	-17.97	-48.61	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			50.30	33.24	54.35	54.94	33.30	60.08	81.24	56.30	94.72	62.10	94.97	100.38	131.02	
Press-cake used as co-fuel for power plant			57.22	40.17	61.28	61.87	40.23	67.01	88.17	63.23	101.65	69.03	101.90	107.31	137.95	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-13.43	-8.56	-9.57	-13.42	-7.33	-8.77	-3.26	-9.19	0.24	-7.49	-8.54	-7.55	-0.99	
Cost relative to b21			1.53	0.98	1.09	1.53	0.84	1.00	0.37	1.05	-0.03	0.85	0.97	0.86	0.11	
Cost of GHG avoided	GBP/t Ceq		257.12	221.94	172.33	239.65	189.82	145.84	42.24	160.93	-2.77	121.39	101.26	85.14	8.72	
Relative cost of GHG avoided			1.76	1.52	1.18	1.64	1.30	1.00	0.29	1.10	-0.02	0.83	0.69	0.58	0.06	

Table 5.22: Summary of main results and indicators. Irrigated II scenario. Best scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Fossil energy balance	GJf/GJ road fuel															
Gross			0.40	0.40	0.40	0.37	0.37	0.37	0.47	0.43	0.48	0.44	0.53	0.53	0.94	1.16
Net of credits																
Press-cake as fertilizer			0.17	0.17	0.18	0.13	0.13	0.13	0.07	0.17	0.03	0.13	-0.01	-0.39	-0.35	
Perss-cake use as co-fuel for power plant			-0.01	-0.01	-0.01	-0.06	-0.06	-0.06	-0.11	-0.02	-0.16	-0.06	-0.02	-0.58	-0.53	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			46.57	51.49	45.41	44.88	49.83	43.70	49.08	47.04	49.43	47.32	34.93	34.93	34.93	89.34
Net of credits																
Press-cake as fertilizer			26.85	31.77	25.68	25.11	30.06	23.93	29.03	27.24	29.29	27.44	14.64	14.42	15.19	
Perss-cake use as co-fuel for power plant			19.92	24.84	18.75	18.18	23.13	17.00	22.10	20.31	22.36	20.51	7.71	7.49	8.26	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			62.49	57.57	63.66	64.23	59.28	65.41	60.31	62.10	60.05	61.90	74.70	74.92	74.15	
Perss-cake use as co-fuel for power plant			69.42	64.50	70.59	71.16	66.21	72.34	67.24	69.03	66.98	68.83	81.63	81.85	81.08	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-9.30	-7.93	-8.26	-8.98	-7.72	-8.23	-6.90	-8.65	-6.35	-8.16	-5.83	-4.23	-5.72	
Cost relative to b21			1.13	0.96	1.00	1.09	0.94	1.00	0.84	1.05	0.77	0.99	0.71	0.51	0.69	
Cost of GHG avoided	GBP/t Ceq		149.82	136.51	131.19	138.62	127.00	125.24	98.97	135.32	88.09	123.54	69.13	46.53	64.50	
Relative cost of GHG avoided			1.20	1.09	1.05	1.11	1.01	1.00	0.79	1.08	0.70	0.99	0.55	0.37	0.51	

Table 5.23: Summary of main results and indicators. Rainfed I scenario. Best scenario.

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Fossil energy balance	GJf/GJ road fuel										
Gross			0.23	0.23	0.24	0.23	0.22	0.22	1.57	1.57	1.16
Net of credits											
Press-cake as fertilizer			0.01	0.01	0.01	-0.01	-0.01	-0.01	-0.7	-0.31	
Perss-cake use as co-fuel for power plant			-0.18	-0.18	-0.18	-0.20	-0.20	-0.19	-0.8	-0.50	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			41.39	43.56	40.88	40.95	39.95	40.09	28.28	28.28	89.3
Net of credits											
Press-cake as fertilizer			21.41	23.57	20.90	20.51	19.89	19.95	-28.16	-4.15	
Perss-cake use as co-fuel for power plant			14.43	16.59	13.92	13.52	12.90	12.96	-35.15	-11.13	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			67.93	65.77	68.44	68.83	69.45	69.39	117.50	93.49	
Perss-cake use as co-fuel for power plant			74.91	72.75	75.42	75.82	76.43	76.37	124.48	100.47	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88	
Cost relative to f11			0.96	0.90	0.93	1.00	1.01	1.08	0.99	1.62	
Cost of GHG avoided	GBP/t Ceq		141.33	136.66	135.70	145.23	145.86	155.86	94.17	196.10	
Relative cost of GHG avoided			0.97	0.94	0.93	1.00	1.00	1.07	0.65	1.35	

Table 5.24: Summary of main results and indicators. Rainfed II scenario. Best scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**	**Diesel**
Fossil energy balance	GJf/GJ road fuel										
Gross			0.18	0.18	0.18	0.17	0.16	0.16	0.14	0.14	1.16
Net of credits											
Press-cake as fertilizer			-0.05	-0.05	-0.05	-0.07	-0.07	-0.07	-0.62	-0.27	
Perss-cake use as co-fuel for power plant			-0.24	-0.24	-0.24	-0.26	-0.26	-0.25	-0.81	-0.46	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			32.70	34.87	32.19	32.26	31.26	31.40	30.22	30.22	89.3
Net of credits											
Press-cake as fertilizer			12.72	14.88	12.21	11.82	11.20	11.26	-26.22	-2.21	
Perss-cake use as co-fuel for power plant			5.74	7.90	5.23	4.83	4.22	4.28	-33.20	-9.19	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			76.62	74.45	77.13	77.52	78.14	78.08	115.56	91.54	
Perss-cake use as co-fuel for power plant			83.60	81.44	84.11	84.50	85.12	85.06	122.54	98.53	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88	
Cost relative to f11			0.96	0.9	0.93	1.00	1.01	1.08	0.99	1.62	
Cost of GHG avoided	GBP/t Ceq		135.83	120.77	130.46	139.66	140.31	149.92	91.77	189.79	
Relative cost of GHG avoided			0.97	0.86	0.93	1.00	1.00	1.07	0.66	1.36	

Table 5.25: Summary of main results and indicators. Irrigated I scenario. Low scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT + unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT + unfired HRSG +BPSTG**	**c22 NG GT + co-fired HRSG +BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Fossil energy balance	GJf/GJ road fuel															
Gross			0.48	0.48	0.48	0.53	0.53	0.53	0.80	0.68	0.99	0.82	0.17	0.17	0.17	1.16
Net of credits																
Press-cake as fertilizer			0.26	0.26	0.26	0.19	0.19	0.19	-0.06	0.27	-0.22	0.22	-0.35	-0.43	-0.88	
Perss-cake use as co-fuel for power plant			0.07	0.07	0.07	0.00	0.00	0.00	-0.25	0.09	-0.41	0.03	-0.54	-0.62	-1.06	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			37.03	54.08	32.98	40.59	62.23	35.45	50.47	43.41	60.49	51.25	13.18	13.18	13.18	89.3
Net of credits																
Press-cake as fertilizer			17.30	34.35	13.25	12.66	34.29	7.51	-13.64	11.29	-27.12	5.49	-27.38	-32.79	-63.43	
Press-cake used as co-fuel for power plant			10.37	27.43	6.32	5.73	27.36	0.58	-20.57	4.36	-34.05	-1.44	-34.31	-39.72	-70.36	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			72.04	54.98	76.09	76.68	55.04	81.83	102.98	78.05	116.46	83.84	116.71	122.12	152.77	
Press-cake used as co-fuel for power plant			78.97	61.91	83.02	83.61	61.97	88.75	109.91	84.98	123.39	90.77	123.64	129.05	159.70	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-13.43	-8.56	-9.57	-13.42	-7.33	-8.77	-3.26	-9.19	0.24	-7.49	-8.54	-7.55	-0.99	
Cost relative to b21			1.53	0.98	1.09	1.53	0.84	1.00	0.37	1.05	-0.03	0.85	0.97	0.86	0.11	
Cost of GHG avoided	GBP/t Ceq		248.52	212.00	166.90	232.16	181.33	141.58	41.28	155.99	-2.71	117.94	99.14	83.44	8.59	
Relative cost of GHG avoided			1.76	1.50	1.18	1.64	1.28	1.00	0.29	1.10	-0.02	0.83	0.70	0.59	0.06	

Table 5.26: Summary of main results and indicators. Irrigated II scenario. Low scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Intetgated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Fossil energy balance	GJf/GJ road fuel															
Gross			0.31	0.31	0.31	0.29	0.29	0.29	0.39	0.35	0.39	0.35	0.45	0.45	0.85	1.16
Net of credits																
Press-cake as fertilizer			0.09	0.09	0.09	0.04	0.04	0.04	-0.01	0.09	-0.05	0.05	-0.02	-0.47	-0.43	
Perss-cake use as co-fuel for power plant			-0.10	-0.10	-0.10	-0.15	-0.15	-0.15	-0.20	-0.10	-0.24	-0.14	-0.02	-0.66	-0.62	
GHG emissions	kg CO2eq/GJ road fuel															
Gross			24.83	29.75	23.66	23.14	28.09	21.96	27.34	25.30	27.69	25.58	13.18	13.18	13.18	89.34
Net of credits																
Press-cake as fertilizer			5.11	10.03	3.94	3.37	8.31	2.19	7.29	5.50	7.55	5.70	-7.11	-7.33	-6.55	
Perss-cake use as co-fuel for power plant			-1.82	3.10	-2.99	-3.56	1.39	-4.74	0.36	-1.43	0.62	-1.23	-14.04	-14.26	-13.48	
GHG avoided	kg CO_2eq/GJ road fuel															
Press-cake as fertilizer			84.23	79.31	85.40	85.97	81.02	87.15	82.05	83.84	81.79	83.64	96.45	96.67	95.89	
Perss-cake use as co-fuel for power plant			91.16	86.24	92.33	92.90	87.95	94.08	88.98	90.77	88.72	90.57	103.37	103.60	102.82	
Cost parameters (press-cake as fertilizer)																
Economic margin deficit	p/l		-9.30	-7.93	-8.26	-8.98	-7.72	-8.23	-6.90	-8.65	-6.35	-8.16	-5.83	-4.23	-5.72	
Cost relative to b21			1.13	0.96	1.00	1.09	0.94	1.00	0.84	1.05	0.77	0.99	0.71	0.51	0.69	
Cost of GHG avoided	GBP/t Ceq		145.58	132.39	127.53	134.86	123.34	121.89	96.47	131.60	85.93	120.25	67.68	45.62	63.21	
Relative cost of GHG avoided			1.19	1.09	1.05	1.11	1.01	1.00	0.79	1.08	0.71	0.99	0.56	0.37	0.52	

Table 5.27: Summary of main results and indicators. Rainfed I scenario. Low scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**	**Diesel**
Fossil energy balance	GJf/GJ road fuel										
Gross			0.21	0.21	0.21	0.20	0.20	0.20	1.54	1.54	1.16
Net of credits											
Press-cake as fertilizer			-0.02	-0.02	-0.02	-0.04	-0.03	-0.03	-0.7	-0.34	
Perss-cake use as co-fuel for power plant			-0.21	-0.21	-0.21	-0.22	-0.22	-0.22	-0.9	-0.53	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			31.14	33.30	30.62	30.70	29.69	29.83	18.03	18.03	89.3
Net of credits											
Press-cake as fertilizer			11.16	13.32	10.64	10.25	9.63	9.69	-38.42	-14.40	
Perss-cake use as co-fuel for power plant			4.17	6.34	3.66	3.27	2.65	2.71	-45.40	-21.38	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			78.18	76.02	78.70	79.09	79.71	79.65	127.76	103.74	
Perss-cake use as co-fuel for power plant			85.16	83.00	85.68	86.07	86.69	86.63	134.74	110.72	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-10.40	-9.89	-10.13	-10.74	-10.85	-11.43	-10.66	-16.06	
Cost relative to f11			0.97	0.92	0.94	1.00	1.01	1.06	0.99	1.50	
Cost of GHG avoided	GBP/t Ceq		168.24	164.63	162.75	171.61	171.99	181.44	113.75	215.81	
Relative cost of GHG avoided			0.98	0.96	0.95	1.00	1.00	1.06	0.66	1.26	

Table 5.28: Summary of main results and indicators. Rainfed II scenario. Low scenario.

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**	**Diesel**
Fossil energy balance	GJf/GJ road fuel										
Gross			0.18	0.18	0.18	0.17	0.16	0.16	0.14	0.14	1.16
Net of credits											
Press-cake as fertilizer			-0.05	-0.05	-0.05	-0.07	-0.07	-0.07	-0.62	-0.27	
Perss-cake use as co-fuel for power plant			-0.24	-0.24	-0.24	-0.26	-0.26	-0.25	-0.81	-0.46	
GHG emissions	kg CO2eq/GJ road fuel										
Gross			28.53	30.69	28.01	28.09	27.08	27.22	26.05	26.05	89.3
Net of credits											
Press-cake as fertilizer			8.55	10.71	8.03	7.64	7.02	7.08	-30.40	-6.38	
Perss-cake use as co-fuel for power plant			1.56	3.73	1.05	0.66	0.04	0.10	-37.38	-13.36	
GHG avoided	kg CO_2eq/GJ road fuel										
Press-cake as fertilizer			80.79	78.63	81.31	81.70	82.32	82.26	119.74	95.72	
Perss-cake use as co-fuel for power plant			87.77	85.61	88.29	88.68	89.30	89.24	126.72	102.70	
Cost parameters (press-cake as fertilizer)											
Economic margin deficit	p/l		-8.23	-7.72	-7.96	-8.56	-8.67	-9.26	-8.48	-13.88	
Cost relative to f11			0.96	0.9	0.93	1.00	1.01	1.08	0.99	1.62	
Cost of GHG avoided	GBP/t Ceq		128.71	116.08	123.66	132.41	133.08	142.20	88.56	181.47	
Relative cost of GHG avoided			0.97	0.88	0.93	1.00	1.01	1.07	0.67	1.37	

Chapter 6: Techno-Economic Analysis

Cost-benefit analysis (CBA) is a social economic evaluation method based on welfare economics. In CBA the key issue is to make an inventory of the costs and benefits associated to the direct and indirect effects of a project (de Bruin, *et. al.*: 2008). Generally speaking, CBA will determine is program qualifies on cost-benefit grounds based on the present value of benefits compared to the present value of costs. The CBA serves as an appraisal technique for public investments and public policy. It examines whether a particular use of resources generates net returns. Van der Bergh (2004) states that a drawback of quantative CBA is that a known intergenerational welfare function is assumed. Hanley and Shogren (2005) point that the limits of CBA are its acceptance of the current income distribution, path dependency, aggregation problems, presumptions of rational choice, and its exclusion of all but utilitarian values (Ibid.). Pindyck (2000) points out that "it is always uncertainty over the future costs and benefits, and there are important irreversibilities associated with environemtnal policy which affects the optimal timing and design of environemtnal policy" (Ibid.).

The consensus in the investment literature is that of the objective of a firm is the maximization of profit or wealth of business, then the Net Present Value (NPV) model is an appropriate procedure to evaluate investment decision (Van Horne & Wachowitz cited by Tauer: no date). Real option analysis which aims to evaluate physical rather than financial investments, requires specifying what strategic decisions might exist in the future, and estimating the possible value of those decisions (Ibid.).

Tauer (2000) says that the preferred approach to evaluate investments is to use the Net Present Value (NPV) model. When the timing of the different costs and benefit elements and the discount. The net present value (NPV) is

$$NPV = \sum_{0}^{T} \frac{B_t - C_t}{(1+r)^t} = \sum_{0}^{T} \frac{B_t}{(1+r)^t} - \sum_{0}^{T} \frac{C_t}{(1+r)^t} \tag{6.1}$$

where B_t = the benefits in year t,

C_t = the costs in year t, and

B_t - C_t = net cash flow for period t,

r = the discount rate, and

T = the project period.

In any cases, the cost of investment is included as a cash flow in NPV the year that investment is made (usually the first year). What differs is that the net taxes from writing off the investment as a cost may be different from country to country. The Net Return in any year should simply be the cash inflow and outflow that year resulting from the investment, regardless of what the accountants or tax collectors state is allowed to be deducted as an expense or included as income in any year (Ibid.).

The NPV will either be positive, in which case the investment should be made, or the NPV will be negative and the investment should not be made. A positive NPV indicates that the project delivers a surplus of benefit over cost. This implies that there is no decision for decision-makers to make. Although NPV is calculated from the expectations of net returns, those net returns have an underlying probability distribution, and the analyst can statistically draw from those distributions and illustrate the impact on NPV of various occurrences. This approach done by simulation is typically reffered to as sensitivity analysis (Tauer: 2000, Perman, *et. al*.: 2003 cited by de Bruin, *et. al*.: 2008).

6.1 Discounting

In long-term business projects, time has a complex effect on the value of revenues and costs and, hence, profit (Friday, *et. al*.: 2000). As the net return in any year is not known with certainty, it was found that it would be best to incorporate this uncertainty into evaluation by adjusting the discount rate upward so that it consisted of a risk-free rate plus a risk premium (Tauer: 2000). The value of time is accounted by applying an interest rate reffered to as the discount rate (Friday, *et. al*.: 2000). Discounting is a process to obtain the present value of future money amounts:

$$PV = FV * \left(\frac{1}{(1+r)^t} \right) \tag{6.2}$$

where PV = present value,
FV = future value,
r = discount rate, and
t - the number of periods into the future.

Likewise, it is also possible to convert a future value to a present value by discounting (Friday, *et. al.*: 2000).

In private discounting the Ramsey equation is used to formulate the appropriate (constant) discount rate. The discount rate (r) is determined by:

$$r = \delta + \eta * g \tag{6.3}$$

where δ is the pure rate of time preference, η is the elasticity of marginal utility of consumption, and g is the growth rate of consumption per capita (de Bruin, *et. al.*: 2008, Nordhaus: 2007).

Besides, in the context of climate change, where a long-time horizon is present, several authors (Pindyck: 2007, Weitzman: 2007, de Bruin, *et. al.*: 2008) indicate that a decreasing discount rate should be used, as to give benefits and costs that occur in the future more weight when calculating the Net Present Value. The UK government also applies a declining long-term discount rate for costs and benefits that occur more than 30 years into the future, as stated by the H. M. Treasury.

Basically, this balance presents revenue and costs (such as costs of site preparation, seedlings and organic manure and chemical fertilizers application) against future revenues and costs (such as revenues from oilseed harvesting and oil extraction). For each year of the project, the sum all revenues and costs for that year to come up with annual Net Revenue. Each annual net revenue is then discounted by the appropriate number of years, back to the present. The sum of all the discounted annual net revenues gives us the net present value (NPV) of the project (Friday, *et. al.*: 2000).

About 30 years ago, investment analysts realized the shortcomings of static NPV and its inability to incorporate the value of strategic decisions during the investment period. Decision Tree Analysis (DTA) was developed to model and accommodate those strategic decision points (Tauer: 2000). This, Boehme (no date) demonstrates that the traditional or static NPV approach uses the expected annual cash flow and simply ignored the fact that managers might simply abandon the project next year if the future cash flows are known to be negligible.

Professor Tauer (2000) of Cornel University advocates the use of DTA over the static NPV analysis when strategic decisions are possible throughout the investment period. Even though, DTA is still considered inferior to the use of option theory using contigent claims analysis (CCA). With DTA the same risk adjusted discount rate is used in each period. Yet the accomplishment of DTA is to reduce risk of the investment by shortening the lower tail of any return distribution, i.e. reduce losses. Except doing that, CCA allows a variable risk rate, in the form of so named "risk neutral probabilities". These are the probabilities of specific net returns occurring adjusted for risk. A risk free rate is used for discounting to the present. The risk neutral probabilities are used to adjust for risk (Leunberger: 1998 and Trigeorgis: 1999 cited by Tauer: 2000).

Nevertheless, a static NPV analysis was performed and several scenarios were compared with each other, as the cancellation, scale of operation reduction, or delay of the launched in 2003 action programme of the National Mission on Bio-diesel in India is certainly not an option.

6.2 Assumptions

6.2.1 *Jatropha curcas* oilseed yield and biodiesel production

Rigorous review of the literature and personal communications with government officials, entrepreneurs, researchers and farmers completed during research trip to India in November 2005 - March 2006 highlighted the potential ranges that may exist under both Irrigated and Rainfed conditions. This discussion can be found at the subchapter 2.1.4: "Climate conditions influence on *Jatropha curcas* oilseed yield" and summarized in Table 6.1.

Table 6.1: Annual *Jatropha* oilseed yield and biodiesel production

Year	Jatropha oilseed yield				Biodiesel production	
	Irrigated		Rainfed		Irrigated	Rainfed
	t/ha	%	t/ha	%	tbd/annum	tbd/annum
6-30	5.2	100%	3.45	100%	101,524.4	1015.2
5	4.1	79%	2.75	73%	80,048.1	744.5
4	3.25	63%	2.0	53%	63,452.8	541.4
3	2.5	48%	1.3	35%	48,809.8	351.9
2	1.2	23%	0.5	13%	23,428.7	135.1

The following yields for *Jatropha curcas* oilseeds were used for the Techno-Economic Modeling of feedstock cultivation scenarios: a) Irrigated scenario - 5.2 t/ha for mature trees (6-30 years) (Neelakantan: pers. comm., GOI: 2004, Francis, *et. al.*: 2005, Friends of Earth: 2008); b) Rainfed scenario - 1.0 to 1.5 t/ha in the third and fourth years (NABARD: 2005, ICORE: 2006), and 3.45 t/ha - at mature stage (6-30 years) (Openshaw: 2000).

Biodiesel plant production for all biodiesel production scenarios was used as a proportion to *Jatropha* oilseed yields in both Irrigated and Rainfed scenarios. Full scale plant capacity was calculated based on following assumption: a) 1,000.0 t oilseed per day for Irrigated (large scale) biodiesel production plant, and b) 10.0 t oilseed per day for Rainfed (small-scale) biodiesel plant.

6.2.2 *Jatropha curcas* biomass energy content

The caloric values for biodiesel, *Jatropha* oil, *Jatropha* oilseed, fruit hulls, seed shelves, kernel, pruning material and chemicals used in Techno-Economic Model are the same used for LCA Model and presented at the Table 3.26: "Farming data. Jatropha to biodiesel pathway (Irrigated. 1,111 trees/ha)" for Irrigated scenario, and Table 3.27: "Farming data. Jatropha to biodiesel pathway (Rainfed. 2,500 trees/ha)" for Rainfed scenario.

It also should be notified that the lower heating values (LHV) were used. The conversion factors which should be applied if LHV should be calculated using data on fuels higher heating value (value which includes the condensation heat of moisture in fuel, HHV) presented in subchapter 3.10.1: "Consensus input data. Basic data", Table 3.32: "HHV/LHV conversion factors".

6.3 Financial assumptions

6.3.1 Project lifetimes

Jatropha curcas is a drought-resistant perennial, living up to 30-50 years and can bear fruits for 25 years (AgroForestryTree Database: 2007, Hannan-Jones & Csurhes: 2008). With regards to *Jatropha curcas*, plantations are likely to be productive well beyond 20-25 years and unlikely to be replaced unless there is a valid commercial reason to do.

The expected lifetime of biodiesel plant is likely to be between 25 and 30 years.
Requirements for the general equipment replacement taken from the conversation with Mr. Nick Haughty, Operations Manager for PX Biodiesel Immingham Limited as following:

- Reactor, oil press, vegetable oil tank, methanol tank, catalyst tank, *etc* - 25 years;
- Piping - 25 years;
- Pumps - 5 years;
- Insulation - 10 years.

A lifetime of 30 years was chosen to be consistent with the plantation lifetime, taking also into consideration that typically:

- *Jatropha curcas* begins to produce fruits at 4-5 months of age and reaches maximum seed production from the 2nd or 3rd year (Lele: no date, Beerens: 2007, Hannan-Jones & Csurhes: 2008);

- According to Francis, *et. al*. (2005), *Jatropha* seed yields are estimated to be 1.0 to 5.0 t/ha. These yields assume ~1,300 plants per ha, with each plant typically taking three years to begin bearing fruit and maturity being reached in year five or six;

- Once every 10 years, the entire plant has to be cut low, leaving a stump of 45 cm. The re-growth will be quick and the trees will start yielding again within about 1 year. This intervention will induce new growth and help to stabilize the yield (Gour: 2006 cited by Achten, *et. al*.: 2008).

6.3.2 Opportunity cost

A survey of thirty eight different studies on the economics of reclamation of wastelands by Balooni (2003) concludes that afforestation either with existing natural root stock or using specially adapted crops like *Acacia Nilotica, Prosopis Juliflora, Casuarina Equisetifolia, Sesbania Egyptia, and various Eucalyptus* species are financially viable based on the yield of fuel wood, fodder, timber, and other forest produce. Most of these studies do not even include environmental benefits in the accounting models and still find a positive return on investment. That is to say there exist several competing crops and uses for wastelands. Most recently several authors reveal their disagreement with previous biofuels life cycle and cost-benefit analyses, declare that economic estimates of biofuels (e.g. *Jatropha*) plantations are incorrect in assuming zero opportunity cost for land (e.g. wasteland) (Rajagopal: 2007, Gibbs: 2008; Fargione: 2008; Searchinger: 2008, Porder, *et. al*.: 2009).

A value of 2,500 Rs./ha (34.73-39.51 GBP/ha, using exchange rates Rs./GBP = 63.28 - February 1998. Rs./GBP = 71.99 - October, 1998. www.xe.com/ict) might be considered as 'opportunity cost' of the allotted land for the Irrigated, large scale plantations, which is stated by the Arunachal Pradesh Government. Similar to Orissa, the Arunachal Pradesh Government has also proposed that industry will have the right of surface utilisation for the purpose of raising tree plantation. The Arunachal Pradesh Government proposes that the gross revenues accrued from the plantation activity will be shared with the government in ratio of 75:25. In other words, the government is leasing out the forest lands by charging a rent of 25% only. In any case the MOU never states that only degraded forest lands will be taken up. The rest of the 75% of the expenses will come from banks, which is possible only when plantation is on fertile lands (Saxena, *et. al.*: 1998).

To achieve *Jatropha* oilseed yields at least 3.5-5.0 t/ha, fertile soil, irrigation or high rainfall and inputs of fertiliser and pesticides are required.

Under similar conditions, however, food crops (e.g. wheat and rice) can also be grown in an intensive way. Such food crops achieve higher returns than cultivation of *Jatropha*. Due to these high opportunity costs, not many farmers have made their agricultural land available for *Jatropha* plantations. TBOS-cultivating farmers either integrate the oil-bearing trees into their farming systems (e.g. as intercrops or fences) or grow them for lack of time to engage in more lucrative staples (Shukla, CREDA/CBDA: no date, Altenburg, *et. al.*: 2009).

Bento (2009) noted that the developing countries' comparative advantage in the production of biofuels feedstocks comes from the lower opportunity costs of land. However, it should be also recollected that marginal costs tend to rise over time because the lowest-cost opportunities are adopted first and rates of deforestation decline, while later the opportunity costs of land rise because of rising productivity in agriculture (Kindermann, *et. al.*: 2008). Yields of major crops in India are about 50-67% of the global average (FAOSTAT: 2008 cited by Bekunda, *et. al.*: 2009). Additional land may become available, if yields of main food crops are increased to the global mean levels, while part of this productivity gain is required to keep pace with raised food demand of a growing and more better off population (Bekunda, *et. al.*: 2009). Economies of scale favor small scale production, as it requires family labour in off-season (for harvesting at least), uses land with little opportunity cost, and can be taken up along with agriculture in appropriate agroforestry models. The only disadvantage with small farmers is that of risk, which can be overcome by offering to the farmers proven technology and extension (Saxena, *et. al.*: 1998).

There is definitely another option for the use of the land, and it would be very beneficial to have the growing of trees or crops as another scenario in this overall cost benefit assessment. However, practically speaking, an "opportunity cost" can not be included in current cost-benefit analysis since this makes a dreadful lot of assumptions. It also may be true that afforestation with well-known and cautiously pre-selected tree species is more attractive than *Jatropha* oilseed production, but it is not only the money but the politics that drives this route of energy and rural development, and especially in India. Besides, since the wasteland has not been developed for fuel or food, it may serve as a good indicator that it is not economically attractive for whatever reason, and therefore close to zero opportunity cost might be assumed for the wasteland. Until now, there are no previous CBA analyses of land use (e.g. for fuel wood production or cropping) in India were completed yet, and, therefore, there are no figures reflecting the land opportunity costs available. For the further bioenergy crops economic assessment, a cost benefit analysis of this use of the land should be undertaken, so a comparison could be made.

6.3.3 Exchange rate

Exchange rates available at www.xe.com/ict and www.x-rates.com were used for Indian Rupee, US Dollar, Canadian Dollar and Euro conversion to British Pound.

Costs of biodiesl plants, oilseed procurement centers, drip irrigation systems, commodity prices, average annual wages and salaries, average daily earnings, logistics costs, property, health and vehicles insurance premium rates, and taxation related data were converted from Indian Rupees to British Pounds using exchange rates indicated in Table 6.2.

Table 6.2: Currencies exchange rates

EUR/GBP	0.788108
USD/GBP	0.503315
INR/GBP	0.0126292
GBP/INR	79.2347
INR/USD	0.0251752

Source: www.xe.com/ucc/convert.cgi. Visited 02 April, 2008

At the time when author conducted and finalized his calculations (December 2008 - January 2009), it was difficult to convert CER prices expressed in Euro to the British Pounds due to daily fall of the GBP/EUR exchange rate. As such, daily exchange rates were applied, if required.

6.3.4 Discount rate

Discount rates are a standard economic practice to account for the higher economic value of benefits accrued today rather than tomorrow. In an analysis that accounts explicitly for all of the analytical and psychological factors, the discount rate itself has only one component: the consumer opportunity cost money (Delucchi: 2007).

The lifetime of *Jatropha* cultivation and associated biodiesel production is assumed to be 30 years. Because of the approach in which all Indian Rupies, US Dollars or British Pounds were first normalized to April 2008, only a real discount rate is required to account for the time value of money. The real discount rates defined by OMB Circular No. A-94 (California: USA, revised January 2008) as "a forecast of real interest rates from which the inflation premium has been removed". The real discount rate is primarily used to determine the NPV of monetized costs and benefits. Hence, the monetised impacts of the program may increase or decrease depending on the discount rate applied.

A discount rate of 15% was used in all Agriculture and Production scenarios modeling, as the rate for newly established oilseed crops attracts a market risk premium due to greater instability in the oilseed crops yields and an emerging biodiesel production technology in addition to the typical rate of 10% for the commercially mature technology.

It is recognized that in reality the discount rate may vary. As such, sensitivity analysis was conducted on the discount rate. The discount rate was varied to a lower (5%) and higher (20%) value in both large scale (Irrigated) and small-scale (Rainfed) scenarios for Agriculture scenarios, as well as in both large scale (Irrigated) and small-scale (Rainfed) scenarios for Production scenarios. Sensitivity analysis parameters and results presented at the "Probabilistic sensitivity analysis. Selected sensitivities" and "Results of correlation analysis" - subchapters 8.1.1 and 8.2 respectively.

6.3.5 Interest rate

At the time of this Techno-Economic Model was developed and run (November 2008), the prime lending rate (PLR) of the Indian banks varies between 12.75% and 13.25%. That means no SME can get working capital loan at less than 15.0%. Omkar Goswami, Chairman for CERG Advisory says, "Even if I were to disbelieve the latest WPI inflation numbers and, instead, assume it is nearer 5.0% to 5.5% that would still translate to a crippling real interest rate of 9.5% to 10%". Between 2nd January and mid-October 2008, the rupee has appreciated 12.5% over the US dollar (http://economictimes.indiatimes.com/articleshow/2481902.cms).

According to RBI Governor, Mr. Subarrao, the repo rate, at which RBI infuses cash into banking system, will be cut to 4.75%, and the reverse repo rate, at which it absorbs excess cash from banks, will be reduced to 3.25%, effective immideately. By 25 bps rate cut, the Reserve Bank repeated a call for banks to pass on its rate cuts to customers and said deposit rates should be also cut (www.eastrneye.eu. Visited 29 April, 2009). It is also recognized that in reality the interest rate may vary. As such, sensitivity analysis was conducted on both interest charge (CAPEX) and interest charge (working capital).

Both interest charges were varied to a lower (5%) and higher (20%) value in all Agriculture and Production scenarios. Sensitivity analysis parameters and results presented at the "Probabilistic sensitivity analysis. Selected sensitivities" and "Results of correlation analysis" - subchapters 8.1.1 and 8.2 respectively.

6.3.6 Inflation rate

It was assumed for this TEM that all prices and costs will raise at the same rate, so inflation can be left out of these calculations altogether. Real prices and real interest rates are those not adjusted for inflation. The interest rates offered by banks are nominal rates, which are real rates plus an adjustment to allow for inflation. As real interest rates and prices were consistently used for this TEM, there is no reason to adjust all of them to inflation. However, if in further modeling the nominal interest rates and prices will be used, they should be adjusted for inflation (Friday: 2000). Other related clarifications are presented in subchapter 6.3.4: "Discount rate" earlier.

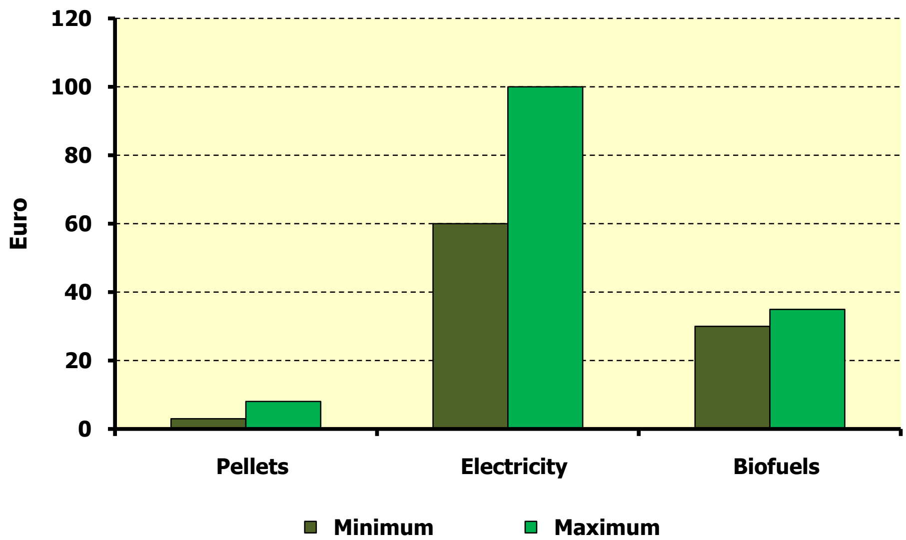
6.3.7 Subsidies and policy incentive assumptions

The Indian biodiesel industry represented by Bio-diesel Association of India (BDAI) in February 2008 demanded additional grants or subsidies for biofuels production, including development of second generation biofuels technologies. BDAI President Sandeep Chaturvedi also says, "India should take the cue from countries like Germany to mandate blending of fuels." Bio-diesel should be categorised as "declared goods" with uniform rate of taxation across the country. Exemption from Value-Added Tax (VAT) and sales tax on bio-diesel component used in blending and income tax exemption under section 80-1B are among other demands made by BDAI in a memorandum to the government (Sharma: 2008 (2); Friends of Earth: 2008).

In addition, BDAI suggested, "30% subsidy of the input cost be given to farmers and for corporates undertaking fuel crop cultivation the subsidy should be extended without upper limit. Corporates having tie-ups with farmers should arrange for carbon credit and part of it should be shared with farmers based on mutual agreement. Government should allow alternative feedstock in case of low availability of *Jatropha* or low oil yields of *Jatropha*" (Sharma: 2008 (2); Friends of Earth: 2008).

Chart 6.1 compares the public subsidies required for the production of 1 MWh of renewable energy for heating from pellets, electricity production or liquid biofuels. The chart represents the subsidy levels in Austria, which are representative for most European countries as well. In Austria, residential pellet boilers receive an investment subsidy of € 1,000-3,000 (788-2,364 GBP, EUR/GBP = 0.788 - April, 2008. www.xe.com/ucc/convert.cgi), renewable electricity from biomass receives feed-in tariffs of € 60-100 (47.3-78.8 GBP) per MWh above market prices, and liquid biofuels receive a tax credit corresponding to about € 35 (27.6 GBP) per MWh (Rakos: 2008).

Chart 6.1: Subsidy requirement per 1 MWh of energy



Source: Rakos: 2008

Sperling (2008) says that biodiesel survives in the United States mostly because of a 0.26 USD per litre federal subsidy, and the substantial tax breaks and production incentives offered in several U.S. states. In Australia, Canada, the EU and Switzerland, its future survival depends on the continuation of subsidies, tax breaks and renewable-fuel mandates.

Detailed description of the multifaceted GOI National Oilseed and Vegetable Oils Development (NOVOD) Board promotional programs, schemes, and pattern of assistance is available at the NOVOD Board website www.novodboard.com.

In a recent paper "Sustainable policy framework for bio-fuels", Surya P. Sethi, GOI energy adviser said, "I with all the humility at my command, must state my fundamental objection to direct input subsidies and interventions by the government in markets through the proposed National Bio-Fuel Board government (Sharma: 2008 (1); Friends of Earth: 2008).

It was also found out that subsidies have both advantages and disadvantages as far as financial, economic and environmental issues are concerned. Some of the advantages are - increased agricultural output and/or incomes, offsetting policy induced market distortions, encourage technology adoption by farmers, e.g. more use of fertilizer at optimal levels and restoration of soil fertility; social protection and environmental protection. The disadvantages were financial burden to governments, inefficient use of inputs and problems in targeting of beneficiaries (ICRISAT: 2008. 1.C.4).

A study on the planting of *Jatropha* as part of the Horticulture Program of the Employment Guarantee Scheme in Maharashtra shows that subsidies are mainly benefiting the large farmers who are the adopters (Rajagopal: 2007). This study also found that the total subsidy that was provided exceeded the cost of cultivation. Small and marginal farmers might at best benefit indirectly if they gain from new employment opportunities in the plantations of adopting farmers or if there is an increase in the price of crops displaced by *Jatropha*.

The World Trade Organization (WTO) identify reduction of import tariffs, import quota restrictions, export subsidies, and, significantly, domestic support (subsidies) as a part of trade liberalization. Subsidies are defined in the WTO Agreement on Subsidies and Countervailing Measures to include not only direct payments to producers, but also reductions in taxes and other charges that reduce government revenues otherwise due (Kojima, *et. al.*: 2007).

If subsidies have to be provided, then they have to be smart - which implies specificity, measurability, achievability of purpose, result oriented and timely delivery of products. The literature also points out that smart subsidies should:

- promote the factor or product as part of a wider strategy;
- favor market based solutions;
- promote competition;
- pay attention to demand;
- promote economic efficiency;
- empower farmers;
- devise an exit strategy;
- pursue regional integration;
- ensure sustainability;
- promote pro poor growth (ICRISAT: 2008. 1.C.4).

Surya P. Sethi believes, the government should not distort markets by mandating blending, restricting rights to direct marketing of bio-fuels, imposing ad-hoc and differential taxes and duties on inputs and restricting import or movement of bio-fuels. Any taxes that should be imposed should be on outputs rather than inputs government (Friends of Earth: 2008).

According to IAG Ltd./Enerquest review "Supply and demand factors relevant to biodiesel production in Alberta", the petroleum producers/retailers questioned the viability of biodiesel. One of the major justification for this is based on requirements to subsidize envirofuels such as biodiesel (IAG Ltd./Enerquest: 2002, Schmidt: 2004). Searchinger (2009 recited OECD: 2008), sais that Canadian and European ethanol and biodiesel would be decline by almost 80%. Only because of high incidence of input subsidies, the predominantly irrigated crops are still profitable, but a majority of the rainfed the crops turned out to be non-remunerative (ICRISAT: 2008. 1.F.1).

The German Development Institute studies (Altenburg, *et. al*.: 2009) says that policy-makers should consider that all subsidies have opportunity costs.

Each rupee spent on subsidising biodiesel cannot be spent for other useful purposes, e.g. other poverty-alleviating programmes or other renewable energies. Policy choices thus need to be based on a comparison of cost-benefit ratios of development alternatives - a task that falls outside of the domain of this study.

6.4 Data review

6.4.1 Feedstock cultivation (agricultural) revenues

6.4.1.1 Jatropha oilseeds

The detailed review and discussion of the *Jatropha curcas* yields in various cultivation conditions was completed in the Chapter 2: "Background to the research", subchapter 2.1.4: "Climate conditions influence on *Jatropha curcas* oilseed yield".

Lack of information caused a high variation in price of *Jatropha* seeds across the states. Various publications indicate price range for *Jatropha* oilseed from 5.0 to 35.0 Rs./kg (0.06 to 0.44 GBP/kg) (Lele: 2003, Rao, *et. al.*: 2004, GOI: 2005). However, this way of reporting *Jatropha* seeds price is not particularly correct. As the biodiesel sector is currently in nascent state, many seeds are sold not for purpose of crushing but rather to establish further nurseries. It rather should separate price of the *Jatropha* oilseeds sold for purpose of oil extraction versus oilseeds sold for seedlings production and new *Jatropha* trees propagation. The price of the first one is ranges from 5.0 to 6.0 Rs./kg (0.06 to 0.08 GBP/kg) in Orissa and Andhra Pradesh to 7.5 Rs./kg (0.095 GBP/kg) in Rajasthan and 11.5 Rs./kg (0.15 GBP/kg) in Gujarat, as the price of the latest one is ranges from 20.25 to 29.0-35.0 Rs./kg (0.26 to 0.37-0.44 GBP/kg) in Chhattisgharh (February 2006) (Chaturvedi: pers. comm., Pegu & Bagla: 2006, Varghese: 2008).

In Karnataka the price of seeds varies between 10.0 Rs./kg (0.13 GBP/kg) and 16.0 Rs./kg (0.20 GBP/kg) (Gowda: no date cited by Altenburg, *et. al.*: 2009), with middlemen charging ~3.0-4.0 Rs./kg (0.04-0.05 GBP/kg) (Swamy: no date cited by Altenburg, *et. al.*: 2009). Tripartite agreements between SHGs, Uttarakhand Biodiesel Board and the Uttarakhand Forest Development Corporation ensure that all seeds will be sold to the company at currently 3.5 Rs./kg (0.04 GBP/kg) at the plantations, with the Forest Development Corporation as an intermediary that will deduct 0.5 Rs./kg (0.006 GBP/kg) for overhead costs. Uttarakhand Biofuels Ltd. calculates that the price "at industry site" is 5.5 Rs./kg (0.07 GBP/kg), reflecting the costs of transportation, drying, cleaning and storage (Singh: no date cited by Altenburg, *et. al.*: 2009). Since the beginning of the 2000s, the level of seed collection in Karnataka has increased from ~30% to 70% (Ramakrishna and GTZ/TERI: 2005 cited by Altenburg, *et. al.*: 2009). Nonetheless, creating market access for farmers and increasing their income by eliminating middlemen is a major challenge in terms of supporting the rural economy in Karnataka (Ibid.).

Chhattisgharh and Andhra Pradesh are two states promoting large-scale plantation of *Jatropha* and due to this the demand for seeds at as high as 29.0 Rs./kg (0.37 GBP/kg) in Andhra Pradesh and 20.0 Rs./kg (0.25 GBP/kg) in Chhattisgharh. Supply in the seed market is tight, so that prices are exceptionally high at the moment. In Chhattisgarh, for example, one kg of *Jatropha* seeds can cost 14.0-35.0 Rs. (0.18-0.44 GBP) on the market (Shiv: no date cited by Altenburg, *et. al*.: 2009). Government of Chhattisgharh has declared the minimum support price of *Jatropha* seed at 6.5 Rs./kg (0.08 GBP/kg) (Altenburg, *et. al*.: 2009), even though it was 4.5 Rs./kg (0.06 GBP/kg) in 2005, and assigned the responsibility of the seed purchase to Chhattisgharh Minor Forest Produce Federation. Andhra Pradesh state extends full National Rural Employment Guarantee Scheme (NREGS) support to all small and marginal farmers under buy-back agreements with the company to procure seeds at the market price, or at least at the minimum support price of *Jatropha* oilseed, currently 6.0 Rs./kg (0.08 GBP/kg) (G.O. Rt. No. 148: 12/2006, Altenburg, *et. al*.: 2009), whereas in Uttarakhand it only 3.0 Rs./kg (0.04 GBP/kg) (Ibid.). By comparison, D1 Mohan Bio Oils Ltd. in Tamil Nadu pays the market price of 7.0 Rs./kg (0.088 GBP/kg) of *Jatropha* seeds (Altenburg, *et. al*.: 2009). Though various states governments have declared their purchasing prices of *Jatropha* seed, they are very less than what are prevailing into the market. But villagers do not have updated information about current oilseed price and selling collected seeds to the middleman and traders accessible in villages and are thus being exploited.

Table 6.3: Commodity prices used for total sales costs calculation. Agricultural scenarios

Oilseeds	0.063	£/kg
Jatropha frut hulls and seed shells (compost)	0.0050	£/kg
Green prune material	0.025	£/kg

Another acute issue in all over the India is that no one particular department can be sure which particular germaplasm is of good variety. Because of this, the germaplasm form Marwahi region, Chhattisgharh (Chaturvedi: pers. comm., Takur: pers. comm., Paramathma: pers. comm., Lele: 2004) and Rajastan (Pegu & Bagla: 2006) are considered best because they were being produced since many yield with oil content up to 30% and 35% respectively and they are being sold as high price as 40.0 Rs./kg in some cases.

6.4.1.2 Co-products. Agricultural scenarios

A number of co-products are produced when *Jatropha* oilseed cultivated as a feedstock for biodiesel production.

Jatropha fruit hulls and seed shells. *Jatropha* oilseeds cleaning results in 2.33 t/ha of hulls (husks and coats) - for Irrigated, large scale scenario and 1.9 t/ha of hulls (husks and coats) - for Rainfed, small-scale scenario. These numbers are consistent with 2.25 t/ha (Openshaw: 2000), as the husk ranges from 31-38% and the rest is the seed yield viz 69-62% (Paramathma: pers. comm., Karanth: pers. comm.). *Jatropha* oilseeds drying and crushing results in 1.1 t/ha of *Jatropha* seed shells - for Irrigated, large scale scenario. This is consistent with 1.8 t/ha (Openshaw: 2000), and 0.5 t/ha of *Jatropha* seed shells - for Rainfed, small-scale scenario, and sell for 400 Rs./t (5.05 GBP/t) (Raina: pers. comm.).

In-field residues. *Jatropha* oilseeds cultivation results in 10.0 t/ha of in-field residues for Irrigated, large scale scenario and 2.0 t/ha of in-field residues for Rainfed, small-scale scenario (Paramathma: pers. comm.). In field residues can be marketed as green prune material, which sells for 2,000 Rs./t (25.24 GBP/t) of Agroresidue (Red Gram Stock delivered to the oiler at Andhra Pradesh. Matrix Power Plant), which is slightly bigger than 1,500 Rs./t (18.94 GBP/t) (CGPL, IISc: 2000) and 1,200-1,800 Rs./t (15.15-22.72 GBP/t) (TIDE/PSG College of Technology: 2005). If dryed, it produced 4.0 air dry t/ha or 3.4 oven dry t/ha (Openshaw: 2000) for Irrigated, large scale scenario, and 0.8 t/ha of in-field residues for Rainfed, small-scale scenario, which sells for 25,000 Rs./t (315.52 GBP/t) (Raina: pers. comm.).

Another economic aspect of the *Jatropha curcas* planting were found and then discussed during visit to the Phytotron Agro Products (India) Pvt. Ltd., Yelahanka, Karnataka. Author had an opportunity to visit this small experimental plantation repeatedly and benefit from inputs provided by its owner, Dr. Ashok K. Raina.

It is 28 months old (February 2006) *Jatropha curcas* plantation with 2x1 m spacing (5,000 trees/ha), "early" and "late" *Jatropha curcas* species with growing time 7 months per annum. With pretty good yield rate, 3.5 tonnes of *Jatropha* seeds were collected over 28 months period. At 6.0 Rs./kg (0.08 GBP/kg) *Jatropha* seeds cost, the total income from oilseed selling comes to 21,000 Rs. (265.04 GBP). If the same plantation would be grown for wood biomass, at 39 kg of *Jatropha* wood biomass per plant (experimentally found value), it could produce 195,000 kg of wet wood over 28 months. At present the price of wet wood is 1 Rs./kg (0.013 GBP/kg), which comes to 195,000 Rs. (2,461.04 GBP) total incomes versus

21,000 Rs. (265.04 GBP) if *Jatropha* were grown for oilseeds. Updated information on *Jatropha* wood biomass production from *Jatropha* presented at the Central Soil Salinity Research Institute report (Sharma, *et. al*. :2008). It claims that in Gujarat more than 10-15 kg fresh biomass becomes available per plant every year as a result of pruning which results in 16.67-24.9 tonnes of fresh (5.0-9.0 tonnes of dry) biomass having 1,666 plants/ha.

Planting *Jatropha curcas* as a short rotation coppice, it is necessarily to keep in mind that trees and shrubs grow continuously, but their growth rate decreases over time. Trees or srubs should be harvested when their growth slows to the point that farmers would be better off harvesting and selling them and planting a new crop. Specifically, farmers should harvest when trees or shrubs reach their maximum NPV. This can be done by calculating NPVs for all years in which harvest could occur, then selecting the year for which the NPV is greatest. This will be the theoretical optimum year of harvest (Friday, *et. al*.: 2000).

6.4.2 Biodiesel production revenues

6.4.2.1 Jatropha oil

Jatropha oil extraction using screw press and hexane solvent results in 1.6-2.5 tonnes of *Jatropha* oil per hectare for Irrigated, large scale scenario, which is consistent with 1.0 t/ha - 3rd year; 1.5 t/ha - 6th year; 2.5 t/ha - 7th-8th year (Paramathma: pers. comm.); 0.75-1.0 t/ha (1.6 t/ha - average, 0.9 t/ha - on poorer soil (GOI: 2004); 2.7 t/ha (D1Oils plc. website. Visited May 2006). For Rainfed, small-scale scenario the SVO yield is 1.0 t/ha, which is consistent with 0.5-1.5 t/ha (Paramathma: pers. comm.), which sells for 16.5 Rs. per liter (0.21 GBP per liter) or 15,156.90 Rs./t (191.28 GBP/t) (Singh & Kalha: WII 2006 conference proceedings). This is consistent with SVO price of 11.0-30.0 Rs/litre (0.14-0.38 GBP/litre) (Varghese: 2008) and the SVO minimum support price of 18.0 Rs./litre (0.23 GBP/litre) in Chattisgarh (Altenburg, *et. al*.: 2009). Though, Mr. Swamy, General Manager for Channabasaveshware Oil Enterprises says that the price of SVO may reach levels of above 50.0 Rs./litre (0.63 GBP/litre) (Ibid.).

6.4.2.2 Biodiesel

The actual biodiesel plant capacity assumed to be 101,524.4 tonnes of biodiesel per annum, which corresponds to processing 1,000.0 tonnes of *Jatropha* oilseeds per day for Irrigated, large-scale scenario, and 1,015.2 tonnes of biodiesel, which corresponds to processing

10.0 tonnes of *Jatropha* oilseeds per day for Rainfed, small-scale scenario respectively. Biodiesel sells for 25,000 Rs./t (315.5 GBP/t) in March 2006. This is consistent with 15.5-40.0 Rs./litre (0.20-0.51 GBP/litre) (Varghese: 2008), 24.8 Rs./kg (0.31 GBP/kg) (GOI: 2003), 26.5 Rs./litre (0.33 GBP/litre) (GOI: June 2007), a cap on biodiesel price of 25.0 Rs./litre (0.32 Rs./litre) in Chattisgarh (Altenburg, *et. al.*: 2009), and higher than 17.62-19.52 Rs./kg (0.22-0.25 GBP/kg) (Subramanian, *et. al.*: 2005), and 14.5 Rs./litre (0.18 GBP/litre) (Paramathma: 2004).

Table 6.4: Commodity prices used for total sales costs calculation. Biodiesel production scenarios

Biodiesels	0.33	£/liter
G-Phase	0.28	£/kg
Press-cake	0.025	£/kg

Since conventional diesel is heavily subsidised by the GOI and negative environmental externalities are not reflected in the prices of conventional diesel, biodiesel is at a disadvantage vis-à-vis conventional diesel. Total oil subsidies are already estimated as hovering around 2-3% of GDP with oil prices at ~80.0 USD/bbl (Chawla. India Energy Conference: 2008).

While India oil companies are oblidged to buy biodiesel at a price of 26.5 Rs./litre (0.33 GBP/litre), entrepreneurs in the biodiesel sector state that presently biodiesel production is only viable at a price of 45.0-50.0 Rs./litre (0.57-0.63 GBP/litre) (Altenburg, *et. al.*: 2009).

6.4.2.3 Co-products. Biodiesel production scenarios

A number of co-products are produced when biodiesel is manufactured.

G-Phase. The production of biodiesel results in 0.112 tonnes of crude glycerine per 1.0 tonne of biodiesel (Sarin: 2004) for Irrigated, large scale scenario, and 0.125 tonnes of crude glycerine per 1.0 tonne of biodiesel (Natter: pers. comm.) for Rainfed, small-scale scenario. These numbers are consistent with 0.115 t crude glycerol (89%) per 1.0 tonne of biodiesel (Shetty: pers. comm.), and 2.094 GJ of glycerol per 1.0 tonne of biodiesel (da Costa, *et. al.*: no date). Glycerine can be marketed as crude glycerine, which sells for 22,000 Rs. per tonne (0.28 GBP per kg or 0.35 GBP per liter) (Bhatt: pers. comm.). After purification (refining) this glycerine can be transformed into pharmaceutical glycerine yelding 0.095 tonne per 1.0 tonne of biodiesel (Subramanian, *et. al.*: 2005; Natter: pers. comm.), which is consistent with 0.097 tonnes of pharma grade glycerin (92-95% concentrated) per 1 tonne of biodiesel (Shetty: pers. comm.) and 0.089 tonnes of pharma grade glycerin (97.7%) per 1.0 tonne of biodiesel (CIMBRIA Group. Denmark: no date), which sells for 65,000 Rs./t (820.31 GBP/t) (Subramanian, *et. al.*: 2005, Varghese: 2008).

Since recently, extensive biodiesel production is flooding the market with glycerine and drive the price down (Brunskill: 2001, Bender: 1999, Boyd, *et. al.*: 2004, ESTMAP: 2007). Thus, glycerine prices have dropped by two-thirds in the last five years, and market analysts anticipate downward pressure on glycerine prices to last for the next few years (Energy Resource: 2006 cited by Kojima, *et. al.*: 2007).

Falling glycerine prices would adversely affect the economics of biodiesel production. As glycerine manufacturers are searching for new applications for glycerine, a significant amount of the glycerine could be combusted in small-scale CHP plant to produce heat and electricity for local consumption or for selling to the National Grid.

Press-cake. *Jatropha* oil extraction using screw press and hexane solvent results in 2.23 tonnes of press-cake (seed-cake) per tonne of biodiesel - for both Irrigated, large scale scenario and Rainfed, small-scale scenario, which sells for 2,000 Rs./t (25.24 GBP/t) (Subramanian, *et. al.*: 2005). This is consistent with low point of 2,000-6,000 Rs./t (25.24-75.72 GBP/t) de-oiled cake price range reported by Varghese (2008) and lower than 8,500 Rs./t (107.95 GBP/t) (Altenburg, *et. al.*: 2009).

6.4.3 Cost of the land

It was assumed that the landowner already owns the land and would be keeping it in agriculture in any case, so land cost (lease or mortgage payments) and property taxes are set to zero. Other options include the assumptions that farmers receive the waste land from the Government or will establish *Jatropha curcas* or any other TBOS plantation on communal land for no additional cost. This assumption leaves the farmer to decide whether to grow trees or another crop, unless land is targeted for TBOS plantation development. In this case, it is easiest to leave land cost out of the calculations, as it will be the same as all other possible alternatives. However, if land have to be purchased or leased as part of an investment in TBOS farming, and farmers are considering other investments, one should include the interest on the mortgage of lease payments in total production costs (Friday, *et. al.*: 2000).

In Chhattisgarh, the lease rate starts at 500 Rs./ha (6.31 GBP/ha) in the first year and is gradually increased to 1,400 Rs./ha (17.57 GBP/ha) from the eighth year on (Shukla: 2008 cited by Altenburg, *et. al.*: 2009). Compared to the expected returns from a plantation, this is a moderate lease rate. 26% of the money is furthermore paid by the state government, since it remains a 26% stakeholder in the joint venture company involved (Ibid.).

6.4.4 Capital expenditures

GOI *Report of the Committee on Development of Bio-fuel* (2003) says that "Experience in Europe has demonstrated that a transesterification plant of an annual capacity of 80,000 tonnes is economical. This much of oil is expected to be produced from a plantation over an area of 50 to 70 thousand hectares depending upon the agro-climatic conditions. This area under plantation in each of the eight States will support one unit of transesterification. These compact areas will be subdivided in to blocks of about 2,000 ha of plantation each to facilitate supply of planting material, procurement of seed and primary processing through expellers.

Table 6.5: Capital costs of biodiesel plant

Biodiesel plant capacity			Lower limit	Upper limit
Liters/day	**Tonnes per year**	**Tonnes per day**	**Million GBP**	**Million GBP**
10,370.0	3,039.0	9.1	0.95	1.55
31,110.0	9,116.5	27.38	1.5	3.0
51,849.0	15,194.0	45.63	2.45	4.1
77,774.0	22,791.0	68.3	3.15	5.25
103,699.0	30,388.0	91.3	3.75	6.3
155,546.0	45,582.0	136.9	4.75	7.9
207,397.0	60,776.0	182.5	5.7	0.5
311,096.0	91,164.0	273.8	7.25	12.25
518,493.0	151,939.0	456.3	9.85	16.4

Note: 100,000 t/yr biodiesel plant at Immingham on Humberside, United Kingdom.
CAPEX 13.5 million GBP (www.greenenergy.com)

Sources:
1) Gonsalves: 2006;
2) Independent Business Feasibility Group: 2002

Capital costs for the biodiesel production plants in India applied for these estimations were discussed and agreed by Dr. Bhatt, Joint Director, Energy Conservation and Development Division, Central Power Research Institute, Bangalore, Karnataka; Mr. Vijay, Manager, Indus Biodiesel Plant, Rajpur, Chhattisgarh; and Mr. Satyanarayna, Maland Extraction Industries, Shimoga, Karnataka, and Mr. Chaturvedi, R. K., Project Officer, Chhattisgarh Bio-fuel

Development Authority (CBDA), Rajpur, Chhattisgarh. The range of 8.0-20.3 MGBP was considered for a large industrial transesterification plant on a production scale of 1,000.0 tonnes of oilseeds per day (101,524.4 tonnes of biodiesel per year), and 0.11-0.30 MGBP - for small transesterification plant on a production scale of 10.0 tonnes of oilseeds per day (1,015.2 tonnes of biodiesel per year).

Table 6.6: Capital costs of integrated, oilseed crushing, and biodiesel plants

Plant size	**Biodiesel**	**Crusher**	**Integrated**
	USD per litre	USD per litre	USD per litre
1.9 million litre[a)]	0.70	0.340	1.040
11.3 million litre[a)]	0.42	0.230	0,650
56.7 million litre[a)]	0.24	0.150	0.390
113 million litre[a)]	0.19	0.140	0.330
Lurgi 60 million litre[b)]	0.32	0.145	0.465
Lurgi 120 million litre[b)]	0.23	0.140	0.370
BIOX 60 million litre[b)]	0.25	0.145	0.395

Notes:
a) All capital costs are presented in Canadian Dollars per litre of biodiesel produced;
b) Any grade of Canola used as a feedstock for all oilseed crushers and integrated biodiesel plants

Sources:
1) $(S\&T)^2$ and Meyers Norris Penny LLP: 2004 cited by Reaney, *et. al.*: 2006;
2) Envirochem Services Inc.: no date cited by Reaney, *et. al.*: 2006

It was calculated that for the 101,524.4 tonnes of biodiesel per annum (1,000.0 tonnes of oilseeds per day) Biodiesel Plant production, required area of *Jatropha* plantation will be ~66,000 ha (660 km^2) considering oilseed yield of 5.2 t/ha yield. According to GOI recommendations it will be divided into 33 blocks 2,000 ha (20 km^2) each. Therefore 33 Main seed procurement and oil expelling centres should be organized.

The hub and spoke concept was designed to maximize rural development in the Canadian oilseed utilization industry while providing the highest quality of biodiesel. Thus, Milligan Bio-Tech Inc. from the Foam Lake, Saskatchewan, Canada, and its partners are launching the first hub and spoke demonstration project for the valorization of distressed oil seeds. MBTI biodiesel plant will be able to process the oil from up to 5 spokes and a local pressing plant. It is also the plan of the hub and spoke model that as supply is assured near the original hub and spoke that the first spokes will potentially become hubs on their own (Reaney, *et. al.*: 2006).

Technologies such as canola meal valorization, augmented crushing and a more efficient biodiesel production technology might be integrated in a system of spokes (crushing systems, feed mills and feeding sites) and hubs (biodiesel plant and meal plant).

Thus, in conventional (mechanical) oilseed crushing technology heating of the input material (*Jatropha* oilseeds) can be applied to increase compressibility of the seed material and thus lower the oil-point pressure (Faborode & Favier: 1996 cited by Beerens: 2007). But the augmented crushing technology is less energy intensive than is the industry method of mechanical seed crushes with subsequent hexane extraction of residual oil. Hexane evaporation is an energy intensve step in the process, but this step will be eliminated with augmented crushing, developed by Agriculture and Agri-Food Canada (AAFC), that results in the recovery of most of the seed oil, without the need for additional solvent extraction (Reaney, *et. al.*: 2006).

Table 6.7: Costs of oilseed procurement centres. Irrigated scenario

Seed procurement centres	**No. of units required**	**Per unit**		**Total**	
		Rs.	GBP	Rs.	GBP
Main centres	33	6,200,000	78,249	204,600,000	2,582,202
Sub-centres	132	1,440,000	18,174	190,080,000	2,398,949

Source: GOI: 2003

The hub and spoke commercial approach currently under way includes the commissioning and optimization of a portable mechanical oil seed crushing system (spoke) having an approximate capacity of 50 t/day (each unit) one in Manitoba and one in Alberta, and a permanent biodiesel (esterification) plant recently commissioned in Foam Lake (hub) which will process seed oil from several satellite crushing plants. Implementation of this design will also have a social and economic impact by adding value to oilseed crops and by creating high quality jobs in rural areas where they are much needed (Ibid.).

The total costs for establishing the drip irrigation are presented in Table 6.8:

Table 6.8: Cost of establishing the drip irrigation

	Rs./ha	GBP/ha	Rs./ha	GBP/ha	Rs./ha	GBP/ha
Cost of drip system	20,000	252.4	25,000	315.1	30,000	378.6
Depriciation	3,400	42.9	4,250	53.6	5,100	64.4
Interest @ 13%	1,200	15.1	1,500	18.9	1,800	22.7
Repair & Maintenance	1,000	12.6	1,250	15.8	1,500	18.9
Total	25,600	323.0	32,000	404.0	38,400	485.0

	Rs./ha	GBP/ha	Rs./ha	GBP/ha	Rs./ha	GBP/ha
Cost of drip system	35,000	441.7	40,000	504.8	45,000	567.9
Depriciation	5,950	75.1	6,800	85.8	7,650	96.5
Interest @ 13%	2,100	26.5	2,400	30.3	2,700	34.1
Repair & Maintenance	1,750	22.1	2,000	25.2	2,250	28.4
Total	44,800	565.0	51,200	646.0	57,600	727.0

Note: Spacing 3x3m (1,111 trees/ha)

Sources:
1) Siddheshwas: pers. comm.;
2) Chaturvedi: pers. comm.

6.5 Production costs (Operational expenditures)

6.5.1 Variable and fixed costs

6.5.1.1 Feedstock cultivation (agricultural) scenarios

The variable costs for feedstock (*Jatropha* oilseeds) cultivation - Irrigated (IRR_Agro I and IRR_Agro II), large scale scenarios - consist of cost of seedlings including transport and gap filling, materials costs such as organic compost, chemical fertilizers (urea, single super phosphate, and muriate of potash), pesticides; energy costs (water and electricity for drip irrigation); labour cost; principle rapayments on working capital; transportation of oilseeds; insurance costs; National Agricultural Insurance Scheme charges, Weather Based Crop Insurance costs; interest charge on CAPEX, interest charges on working capital; and contingency.

The variable costs for feedstock (*Jatropha* oilseeds) cultivation - Rainfed (RAIN_Agro I, RAIN_Agro II and RAIN_Agro III), small-scale scenarios - consist of cost of seedlings including transport and gap filling; materials costs such as organic compost, chemical fertilizers (urea, single super phosphate, and muriate of potash), pesticides; energy costs (water and electricity for drip irrigation); labour cost; principle rapayments on working capital; transportation of oilseeds using draft animals; insurance costs; National Agricultural Insurance Scheme charges; Weather Based Crop Insurance costs; interest charges on working capital; and contingency. Chemical fertilizers and pesticides are not applied in RAIN_Agro III scenario.

The fixed costs for feedstock production, for all Irrigated and Rainfed agricultural scenarios consist of depreciation; and principle rapayments for CAPEX.

The variable and fixed costs for *Jatropha* oilseeds cultivation are presented in Table 6.43: "Cost-benefit analysis. Agriculture. Irrigated scenarios"; and Table 6.44: "Cost-benefit analysis. Agriculture. Rainfed scenarios".

Detailed information about operating costs in agricultural scenarios is presented in: a) Table 6.10: "The establishment costs for Large scale *Jatropha* plantation (Irrigated scenario)"; b) Table 6.11 and Chart 6.3: "Total agrochemicals and energy costs. IRR_Agro_I scenario. Fruit hulls and seed shells used as compost"; c) Table 6.12 and Chart 6.4: "Total agrochemicals and energy costs. IRR_Agro_II scenario. Fruit hulls and seed shells used as combustibles"; d) Table 6.13 and Chart 6.5: "Total labour costs distribution. Agriculture. Large scale (Irrigated) scenarios - for Irrigated, large scale scenarios", and e) Table 6.14: "The establishment costs for small-scale *Jatropha* plantation (Rainfed scenario)"; f) Table 6.15 and Chart 6.6: "Total agrochemicals and energy costs. RAIN_Agro_I scenario. Fruit hulls and seed shells used as compost"; g) Table 6.16 and Chart 6.7: "Total agrochemicals and energy costs. RAIN_Agro_II scenario. Fruit hulls and seed shells used as combustibles"; h) Table 6.17 and Chart 6.8: "Total labour costs distribution. Agriculture. Small-scale (Rainfed) scenarios - for Rainfed, small-scale scenarios".

6.5.1.2 Biodiesel production scenarios

The variable costs for biodiesel manufacture - Irrigated (IRR_Production_No Initial Investment and IRR_Production_Private capital), large scale scenarios, and Rainfed (RAIN_Production_No Initial Investment and RAIN_Production_Private capital), small-scale scenarios - consist of material costs (*Jatropha* oil, methanol, catalyst, sulphuric acid); energy costs (water (in circulation) and electricity); personnel costs (e.g. operational staff (workers), management, administration, personnel costs (purchase/sales) and start-up personnel costs); principle rapayments for working capital; transportaion costs (e.g. costs of transportation of oilseeds, hulls and shells, prune material, methanol, biodiesel and glycerine, drivers' salary, drivers' medical insurance, drivers' workmen's compensation, and vehicles insurance); various costs such as construction expences, Corporate Income tax, Minimum Alternate tax; interest charge on CAPEX, interest charges on working capital; medical and property insurance costs per annum and workmen's compensation; and contingency.

The fixed costs for biodiesel manufacture consist of depreciation; principle rapayments for CAPEX; rent of land and buildings; and permission costs.

The operating and fixed costs for biodiesel manufacture are presented in Table 6.45: Cost-benefit analysis. Production. Large scale scenarios, and Table 6.46: Cost-benefit analysis. Production. Small-scale scenarios.

6.6 Material costs

6.6.1 Feedstock (Jatropha oilseed) cultivation

6.6.1.1 Cost of seedlings

The seedlings cost of 4.0 Rs./seedling (0.005 GBP/seedling) used in this Techno-Economic Model (Raina: pers. comm.).

6.6.1.2 Fertilizers cost

World fertilizer prices rose steadily from 2004 through 2006 - then soared in 2007 (Hargrove: 2008). Farmers in industrialized countries are applying high levels of fertilizers to maximize harvests of grain at the highest prices ever, says Dr. Balu Bumb, Chair of the Policy, Trade, and Markets Program of IFDC - An International Center for Soil Fertility and Agricultural Development. Those forces drive fertilizer prices higher (Hargrove: 2008). The highest price rise in 2007 was for diammonium phosphate (DAP). The U.S. Gulf price for DAP was about 252 USD/t in January 2007 - but had almost tripled a year later, rising to 752 USD/t by January 2008 (Hargrove: 2008).

Similarly, the Arab Gulf price of prilled urea rose from 272 to 415 USD/t in the same period, and the Vancouver price of muriate of potash (MOP) rose from 172 to 352 USD/t (Hargrove: 2008). "The unprecedented rise in fertilizer prices - more than 200% in the past year - is creating a fertilizer crisis for resource-poor farmers in developing countries", Dr. Bumb says (Ibid.).

Prices of phosphate fertilizers rose more steeply than the price of nitrogen-based urea because production sources are more limited, says Dr. Bumb. Most of the world's phosphate fertilizers are produced in the U.S., Morocco, and along the Baltic Sea. Canada produces 70% of the world's muriate of potash. But plants to manufacture urea, for which natural gas is the main raw material resource, are dispersed worldwide. The world is currently short of urea, but global production may increase because at least six large new urea plants were projected to open in 2008: two in Iran and one each in Egypt, Nigeria, Oman, and Russia (Hargrove: 2008).

Table 6.9: Energy, seedlings and fertilizers prices used for all agricultural scenarios

Cost of seedlings including transport and gap filling	0.05	£/seedling
Organic compost	0.005	£/kg
Chemical fertilizers		
Urea (N)	0.133	£/kg
SSP (P_2O_5)	0.276	£/kg
MOP (K_2O)	0.093	£/kg
Pesticides	6.31	£/ha
Water for Irrigation	0.00000021	£/liter
Energy for irrigation	0.041	£/kWh

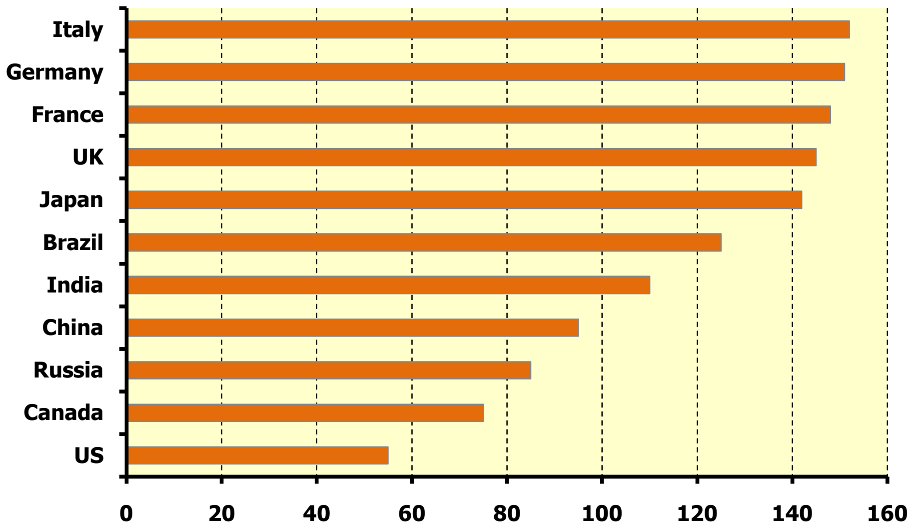
Source: Prices and Profitability of Fertilizers. Chapter 5. Available at: www.fao.org/docrep/009/a0257e/A0257E06.htm

Phil Humphres, IFDC Senior Specialist-Engineering points out that competition for the world's natural gas resources is growing. Production of 1 tonne of ammonia requires ~30 to 33 million Btu (31.65-34.81 GJ) of natural gas - ~90% of the raw material cost, he says. Much of the world's huge reserves of gas is flared or burned off and wasted, but natural gas is also the main raw resource to produce ammonia for nitrogen fertilizer production (Tables 3.35 & 3.36) (Hargrove: 2008).

6.6.1.3 Energy for feedstock cultivation

Diesel fuel prices can vary widely in rural India, depending heavily on transport costs. In Gujarat, the urban (Ahmedabad) price of diesel as observed in January 2003 was 19.0 Rs./litre (0.25 GBP/litre). The price in rural Kachchh (Rapar) was 21.0 Rs./litre (0.28 GBP/litre) and in Khadir it was 22.0 Rs./litre (0.29 GBP/litre) because of transport surcharges (all costs are presents in real 2003 US Dollars, British Pounds or Indian Rupees using Rs./USD = 46.0 and Rs./GBP = 75.5 exchange rate. www.xe.com/ict) (Joshi & Hansen: 2003).

Chart 6.2: Comparative fuel prices. Mid November 2008 (US cents per litre)



Note: At a crude oil price of 48 USD/bbl

Sources:
1) EIA: no date;
2) GTZ International Fuel Price Survey: no date;
3) Financial Times. 20 May, 2009

Also, in recent years, the prices of energy, both thermal and electrical, have been increasing steadily. For example, diesel oil prices have increased to 17.05 Rs./litre (2001) (0.25 GBP/litre, all costs are presents in real 2001 British Pounds or Indian Rupees using Rs./GBP = 69.5 exchange rate. www.xe.com/ict) from 7.95 Rs./litre (January 1997) (0.13 GBP/litre, all costs are presents in real January 1997 British Pounds or Indian Rupees using Rs./GBP = 60.0 exchange rate. www.xe.com/ict) (Malhotra, *et. al.*: 2002).

The price of diesel has been used at 22,000 Rs./kl (277.66 GBP/kl, 18,181.818 Rs./t, 229.47 GBP/t); 2) Calorific Value (HHV): 10,860 kcal/kg (45.469 GJ/t). Weight to Volume Ratio: 1.21. (CEA. Planning Wing. February, 2004); 3) Calculated: 399.873 Rs./GJ (5.05 GBP/GJ, using exchange rate Rs./GBP = 79.23 - April 2008. www.xe.com/ucc/convert.cgi).

The price of water has been used: 1) 0.017 Rs./l (0.000215 GBP/l) - delivered by water truck; 2) 0.005 Rs./l (0.000063 GBP/litre) - supply from pipeline; 3) 3.0 Rs./kWh (0.04 GBP/kWh, using exchange rate Rs./GBP = 79.23 - April 2008. www.xe.com/ucc/convert.cgi) - the price for electricity to run a water pump. Water per se is free if supplied from the owned borewell (Raina: pers. comm.).

6.6.1.4 Feedstock plantation establishment costs

Large Scale. Irrigated scenario

Table 6.10: The establishment costs for Large scale *Jatropha* plantation (Irrigated scenario)

Labour ManHours (1111 trees/ha)

				Year 1	Year 2
Site Preparation	80	hr/ha	hr/ha	80.0	
Conservation Tillage		hr/ha	hr/ha	78.6	
Tractor Ploughing	6	hr/ha	hr/ha	6.0	
Alignment & Stalking	32	hr/ha	hr/ha	32.0	
Digging, Planting & Refilling Pits	500	hr/ha	hr/ha	500.0	
Protective Watering Immediately after Planting	5	hr/ha	hr/ha	5.0	
Re-Planting 1st Year	20%		hr/ha	100.0	
Maintenance & Irrigation		hr/ha	hr/ha	140.5	148.0
Weeding, Soil Working & Fertilizers Application	480	hr/ha	hr/ha	169.0	178.0
Re-Planting 2nd Year	10%		hr/ha		50.0
Harvesting, Pruning and Trimming		hr/ha	hr/ha	0	159.9
Plantation Manager	2	hr/ha	hr/ha	2.0	2.0
Total Labour (Man Hours)				**1,113.1**	**537.9**

Labour Cost

Site Preparation	0.12	£/hour	£/ha	9.6	
Conservation Tillage	0.14	£/hour	£/ha	10.6	
Tractor Ploughing	0.14	£/hour	£/ha	2.1	
Alignment & Stalking	0.12	£/hour	£/ha	3.8	
Digging, Planting & Refilling Pits	0.14	£/hour	£/ha	70.7	
Protective Watering Immediately after Planting	0.12	£/hour	£/ha	0.6	
Re-Planting 1st Year	0.14	£/hour	£/ha	14.1	
Maintenance & Irrigation	0.12	£/hour	£/ha	16.8	17.7
Weeding, Soil Working & Fertilizers Application	0.15	£/hour	£/ha	24.6	25.9
Re-Planting 2nd Year	0.14	£/hour	£/ha		7.1
Harvesting, Pruning and Trimming	0.21	£/hour	£/ha	0	34.2
Plantation Manager	0.27	£/hour	£/ha	0.53	0.53
Total Labour Cost (Salary)				**153.5**	**85.4**

Note: All wages rates were discussed and agreed with Dr. Jens Lerche. Senior Lecturer in Development Studies. SOAS. London: United Kingdom and presented in the Table 6.34: Staff annual salaries. Agriculture.

**Table 6.11: Total agrochemicals and energy costs. IRR_Agro_I scenario.
Fruit hulls and seed shells used as compost**

	Material costs, £	% of Total material and energy costs
Organic compost	303.0	6.73
Chemical fertilizers:		
Urea (N)	421.5	9.36
SSP (P_2O_5)	1,700	37.73
MOP (K_2O)	209.6	4.65
Pesticides	83.3	1.85
Water for irrigation	0.05	0.001
Energy for irrigation	1,787.6	39.68
Total materials and energy costs	4,504.9	100.00

**Chart 6.3: Total agrochemicals and energy costs. IRR_Agro_I scenario.
Fruit hulls and seed shells used as compost**

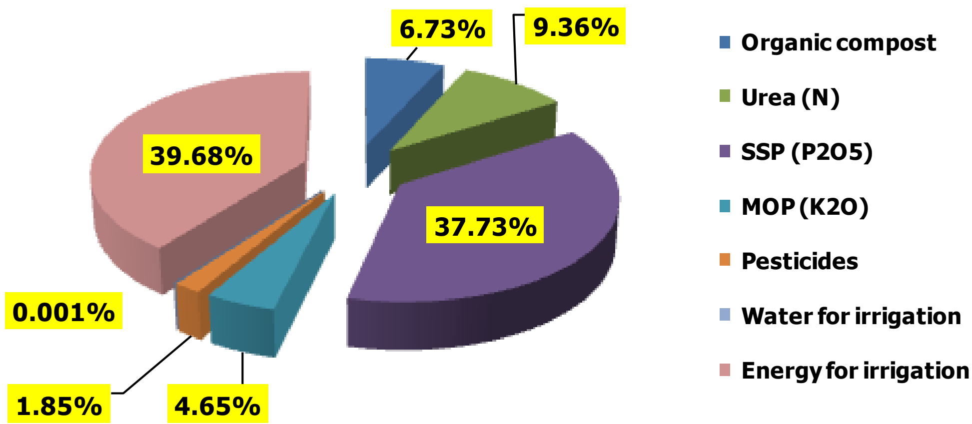


Table 6.12: Total agrochemicals and energy costs. IRR_Agro_II scenario. Fruit hulls and seed shells used as combustibles

	Material costs, £	% of Total material and energy costs
Chemical fertilizers:		
Urea (N)	540.8	11.80
SSP (P_2O_5)	2,066.0	45.10
MOP (K_2O)	349.7	7.63
Pesticides	83.3	1.82
Water for irrigation	0.05	0.001
Energy for irrigation	1,541.5	33.65
Total materials and energy costs	4,581.4	100.00

Chart 6.4: Total agrochemicals and energy costs. IRR_Agro_II scenario. Fruit hulls and seed shells used as combustibles

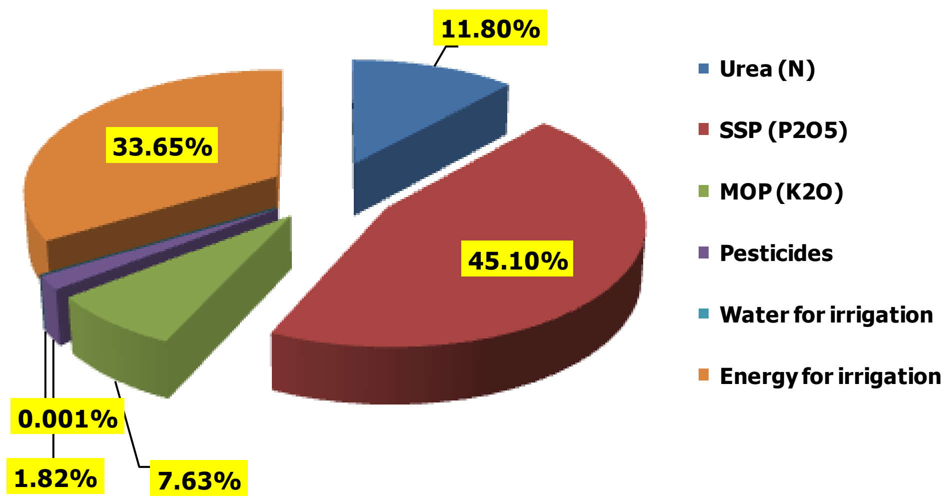
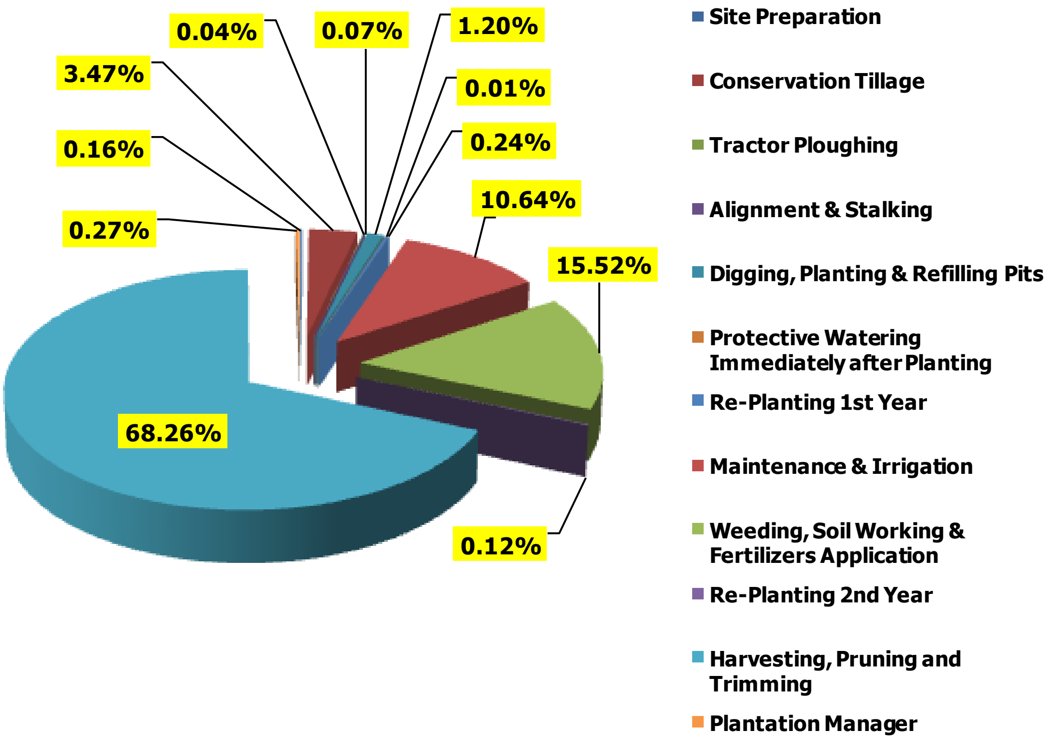


Table 6.13: Total labour costs distribution. Agriculture. Large scale (Irrigated) scenarios

	Labour costs, £/ha	% of Total labour costs
Site Preparation	9.6	0.16
Conservation Tillage	204.3	3.47
Tractor Ploughing	2.1	0.04
Alignment & Stalking	3.8	0.07
Digging, Planting & Refilling Pits	70.7	1.20
Protective Watering Immediately after Planting	0.6	0.01
Re-Planting 1st Year	14.1	0.24
Maintenance & Irrigation	625.8	10.64
Weeding, Soil Working & Fertilizers Application	913.4	15.52
Re-Planting 2nd Year	7.1	0.12
Harvesting, Pruning and Trimming	4,015.9	68.26
Plantation Manager	16.0	0.27
Total Labour Cost (Salary)	5,883.4	100

Chart 6.5: Total labour costs distribution. Agriculture. Large scale (Irrigated) scenarios



Small-scale. Rainfed scenario

Table 6.14: The establishment costs for small-scale *Jatropha* plantation (Rainfed scenario)

Labour ManHours (2500 trees/ha)

				Year 1	Year 2
Site Preparation	80	hr/ha	hr/ha	80.0	
Conservation Tillage		hr/ha	hr/ha	177.0	
Alignment & Stalking	64	hr/ha	hr/ha	64.0	
Digging, Planting & Refilling Pits	222	hr/ha	hr/ha	222.0	
Protective Watering Immediately after Planting	12	hr/ha	hr/ha	12.0	
Re-Planting 1st Year	20%		hr/ha	44.4	
Maintenance & Irrigation		hr/ha	hr/ha	307.1	323.4
Weeding, Soil Working & Fertilizers Application		hr/ha	hr/ha	380.0	400.0
Re-Planting 2nd Year	10%		hr/ha		22.2
Harvesting, Pruning and Trimming		hr/ha	hr/ha	0	72.5
Plantation Manager	2.5	hr/ha	hr/ha	2.5	2.5
Total Labour (Man Hours)				**1289.0**	**820.6**

Labour Cost

Site Preparation	0.12	£/hour	£/ha	9.6	
Conservation Tillage	0.14	£/hour	£/ha	23.9	
Alignment & Stalking	0.12	£/hour	£/ha	7.7	
Digging, Planting & Refilling Pits	0.14	£/hour	£/ha	31.4	
Protective Watering Immediately after Planting	0.12	£/hour	£/ha	1.4	
Re-Planting 1st Year	0.14	£/hour	£/ha	6.3	
Maintenance & Irrigation	0.12	£/hour	£/ha	36.8	38.7
Weeding, Soil Working & Fertilizers Application	0.15	£/hour	£/ha	55.2	58.1
Re-Planting 2nd Year	0.14	£/hour	£/ha		3.1
Harvesting, Pruning and Trimming	0.21	£/hour	£/ha	0	15.5
Plantation Manager	0.27	£/hour	£/ha		
Total Labour Cost (Salary)				**172.2**	**115.5**

Note: All wages rates were discussed and agreed with Dr. Jens Lerche. Senior Lecturer in Development Studies. SOAS. London: United Kingdom and presented in the Table 6.34: Staff annual salaries. Agriculture.

Table 6.15: Total agrochemicals and energy costs. RAIN_Agro_I scenario. Fruit hulls and seed shells used as compost

	Material costs, £	% of Total material and energy costs
Organic compost	212.0	16.58
Chemical fertilizers:		
Urea (N)	188.8	14.76
SSP (P_2O_5)	635	49.66
MOP (K_2O)	53.7	4.20
Pesticides	189.3	14.80
Water for irrigation	0.0	0.0
Energy for irrigation	0.0	0.0
Total materials and energy costs	1,279.0	100.00

Chart 6.6: Total agrochemicals and energy costs. RAIN_Agro_I scenario. Fruit hulls and seed shells used as compost

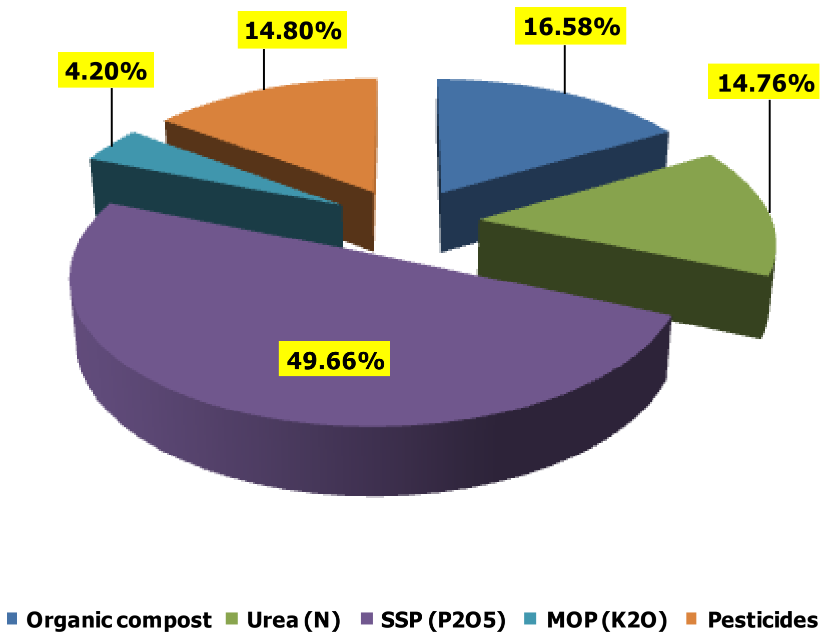


Table 6.16: Total agrochemicals and energy costs. RAIN_Agro_II scenario. Fruit hulls and seed shells used as combustibles

	Material costs, £	% of Total material and energy costs
Chemical fertilizers:		
Urea (N)	275.0	19.61
SSP (P_2O_5)	890.8	63.52
MOP (K_2O)	53.7	3.83
Pesticides	183.0	13.05
Water for irrigation	0.0	0.0
Energy for irrigation	0.0	0.0
Total materials and energy costs	1,402.4	100.00

Chart 6.7: Total agrochemicals and energy costs. RAIN_Agro_II scenario. Fruit hulls and seed shells used as combustibles

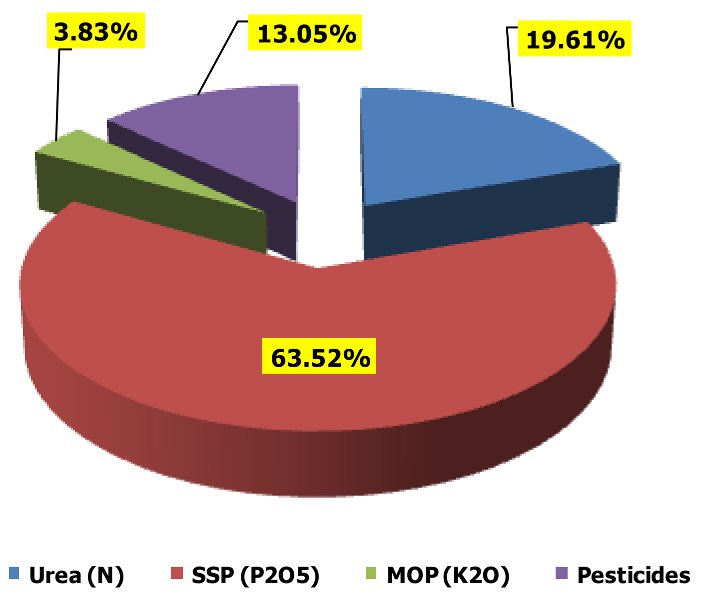
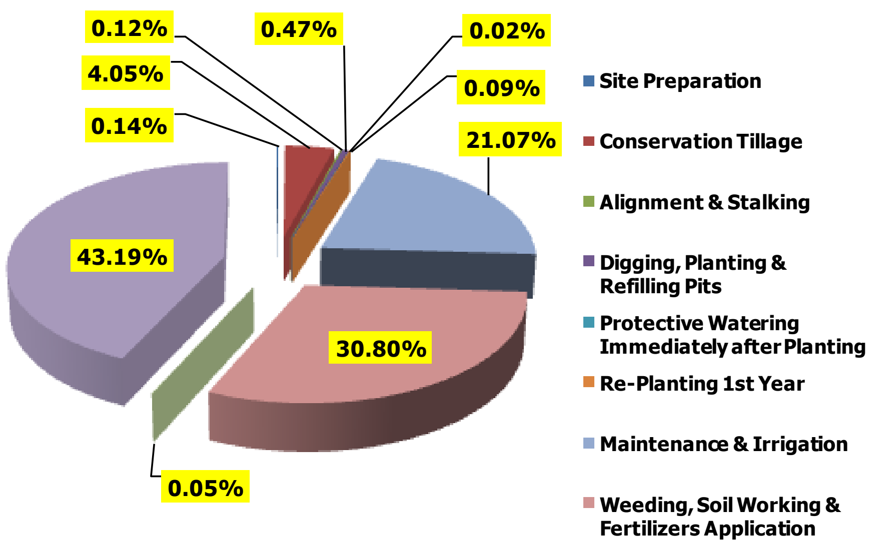


Table 6.17: Total labour costs distribution. Agriculture. Small-scale (Rainfed) scenarios

	Labour costs, £/ha	% of Total labour costs
Site Preparation	9.6	0.14
Conservation Tillage	269.4	4.05
Alignment & Stalking	7.7	0.12
Digging, Planting & Refilling Pits	31.4	0.47
Protective Watering Immediately after Planting	1.4	0.02
Re-Planting 1st Year	6.3	0.09
Maintenance & Irrigation	1,401.8	21.07
Weeding, Soil Working & Fertilizers Application	2,049.1	30.80
Re-Planting 2nd Year	3.1	0.05
Harvesting, Pruning and Trimming	2,873.3	43.19
Plantation Manager	0.0	0.00
Total Labour Cost (Salary)	6,653.0	100.00

Chart 6.8: Total labour costs distribution. Agriculture. Small-scale (Rainfed) scenarios



6.6.2 Biodiesel production

6.6.2.1 Feedstock cost

Biodiesel plant production economics are highly dependent upon the cost associated with feedstock procurement. Feedstock costs represent ~75-80% of the overall costs of biodiesel production (www.green-trust.org/biodiesel1.htm). Looking at the economics of production and distribution, one gallon of biodiesel consumes 7.5 pounds of fat or oil in production, which is 75-80% of the operating costs (www.ybiofuels.org/bio_fuels/benefitsEconNaSec.html).

Table 6.18: Breakdown of production costs

	Input detail	Percentage of production cost
Feedstock	0.992 kg/litre biodiesel	83.67%
Methanol	0.107 kg/litre biodiesel	6.62%
Catalyst (acid or base)	0.001 kg/litre biodiesel	0.34%
Sales and Administration	0.004 GBP/litre biodiesel	5.77%
Maintenance	1.56% (% of capital cost per litre biodiesel)	2.57%
Insurance	0.63% (% of capital cost per litre biodiesel)	1.03%

Note: Feedstock cost attracts 83.67% OPEX

Sources:
1) Government of Western Australia: 2006;
2) Independent Biodiesel Feasibility Group, LLC: no date

When oil prices are high, demand for biofuels can help drive higher grain prices to a point at which producers can no longer make a profit. This phenomenon occurred in the summer of 2008 as extraordinarily high corn prices forced US ethanol producers to cut back (Peer: 2008 cited by Searchinger: 2009).

Commodity prices used in the Techno-Economic Model collected during fieldwork in India in November 2005 - March 2006 and later verified with various secondary sources are summarised in Table 6.19.

Table 6.19: Commodity prices

Jatropha oilseed	GBP/t	63.10	Rs./t	5000.00	Subramanian, et. al.: 2003.
In-field residues (biomass)	GBP/t	25.24	Rs./t	2000.0	Agroresidue delivered to the Matrix Power Plant, AP 1200-1800 Rs./t - TIDE/PSG College of Technology. 2005
Firewood (dry)	GBP/t	315.51	Rs./t	25000.0	Dr. Ashok Raina, pers. comm
Jatropha fruit hulls and seed shells	GBP/t	5.05	Rs./t	400.0	Dr. Ashok Raina, pers. comm
Jatropha oil	Rs./t	15,156.90	GBP/t	191.28	Singh, M.P. and Kalha, Geetika. WII 2006 conference
	Rs./l	16.50	GBP/l	0.21	
Methanol (MeOH)	GBP/t	383.40	Rs./t	30379.75	24.0 Rs./l - Industrial scale. 30.0 Rs./l - 200 litres barrel
Ethanol (EtOH)	GBP/t	303.52	Rs./t	24050.63	17.0-19.0 Rs./l
Sulphuric acid (H_2SO_4)	GBP/l	0.38	Rs./l	30.00	
	GBP/t	206.44	Rs./t	16357.69	30.00 Rs/l - Industrial scale. 31.40 Rs./l - batches
Potassium hydroxide (KOH)	GBP/t	315.51	Rs./t	25000.00	25.0 Rs./kg. Density: 1.0025 kg/l. www.handymath.com
Sodium hydroxide (NaOH)	GBP/t	567.91	Rs./t	45000.00	Density: 2,139 g/m3. www.handymath.com
Sodium Methoxides ($NaOCH_3$, 30% in MeOH)	GBP/t	454.33	Rs./t	36000.00	Mr. Nirav Kothari. Evonik Degussa India Pvt. Ltd. (pers. comm.)
Press-cake	GBP/t	25.24	Rs./t	2000.00	Subramanian, et. al.: 2003.
Unreacted oil for soap making	GBP/t	140.08	Rs./t	11100.00	Mr. Vijay. Manager. Indus Biodiesel Plant. Rajpur (pers. comm.)
Crude glycerine	GBP/t	277.64	Rs./t	22000.00	Dr. M. Siddhartha Bhatt. CPRI. Bangalore
Pharmaceutical glycerine	GBP/t	820.31	Rs./t	65000.00	Subramanian, et. al.: 2003

Table 6.19: Commodity prices (cont)

NG	GBP/GJ	2.78	Rs./GJ	220.26	Rs. 4000 per 1000 m3. CEA. Planning Wing. 02/2004
LPG	GBP/GJ	4.92	Rs./GJ	389.61	23 Rs./kg - Mr. V.P.Tale. WII Conference, 2006
LNG	GBP/GJ	3.17	Rs./GJ	251.45	6480 Rs./t at port. CEA. Planning Wing. 02/2004
Electricity	GBP/MWh	41.02	Rs./MWh	3250.00	3.25 Rs./kWh - Planning Commission. GOI. 2004
	GBP/GJ	11.39	Rs./GJ	902.78	
Fuel oil (LSHD)	GBP/t	378.61	Rs./t	30000.00	March 2006
	GBP/GJ	8.38	Rs./GJ	663.72	
Coal (domestic)	GBP/GJ	1.45	Rs./GJ	114.65	CEA. Planning Wing. 02/2004
Coal (imported)	GBP/GJ	1.50	Rs./GJ	119.05	CEA. Planning Wing. 02/2004
Lignite	GBP/GJ	1.56	Rs./GJ	123.84	CEA. Planning Wing. 02/2004
Naphta	GBP/GJ	17.37	Rs./GJ	1376.15	CEA. Planning Wing. 02/2004
Diesel	GBP/GJ	8.88	Rs./GJ	703.40	CEA. Planning Wing. 02/2004
Gasoline	GBP/GJ	23.38	Rs./GJ	1852.71	
Biodiesel	GBP/t	315.505	Rs./t	25000.00	24.8 Rs./kg. Planning Commission. GOI
	GBP/GJ	8.47	Rs./GJ	670.78	
Water	GBP/l	0.000215	Rs./l	0.017	Dr. Ashok Raina (pers. comm.)
	GBP/t	0.215	Rs./t	17.00	
Phosphoric acid (H3PO4)	GBP/t	244.11	Rs./t	19341.82	485.0 USD/t. The Hindu Business Line. 05/2005

The cost of chemicals, mainly alcohol and catalyst, depends on the process (additional comments related to this issue can be found in subchapter 2.4: "Biodiesel production process"), as well as the unit prices for the chemicals. The continuous flow process requires only the stoichiometric amount of alcohol, while the batch process requires an excess of at least 75% to drive the reaction to completion. With this amount of projected recovery, the increased cost of chemicals in the batch process over the continuous process would be relatively small at the same prices (Bender: 1999, Noordam & Withers: 1996).

The price of in-field residue (biomass): 1) 2,000 Rs./t (25.24 GBP/t) of Agroresidue (Red Gram Stock) delivered to the oiler at Adhra Pradesh. Matrix Power Plant. 4.5 MW, grid connected; 2) 1,500 Rs./t (18.93 GBP/t) (CGPL, IISc: 2000). 3) 1,200-1,800 Rs./t (15.14-22.72 GBP/t) (TIDE/PSG College of Technology: 2005).

The price of Methanol (CH_3OH or MeOH) has been taken as: 1) 24.0 Rs./l (0.3 GBP/l) - supplied in balk on industrial scale; 2) 30.0 Rs./l (0.38 GBP/l) - 200 liters barrel.

The price of Ethanol (C_2H_5OH or EtOH) has been taken as 17.0-19.0 Rs./l (0.21-0.21 GBP/l).

The price of Sulphuric acid (H_2SO_4, 96%): 1) 30.0 Rs./l (0.38 GBP/l) - supplied in balk on industrial scale; 2) 31.4 Rs./l (0.4 GBP/l) - supplied in batches (Northeast Biofuels: no date).

The price of Potassium hydroxide (KOH): 25.0 Rs./kg (0.316 GBP/kg) (2006). Alkaline catalyst concentration in the range of 0.5-1.0% by weight yields 94-99% conversion of vegetable oil to esters (GOI: no date).

The price of Sodium hydroxide (NaOH): 40.0-45.0 Rs./kg (0.50-0.57 GBP/kg) (2006).

Free fatty acids (FFA) can be sold (in Canada (AE)) for 0.01 CAD/kg with a cost of selling at 0.005 CAD/kg (Reaney, *et. al.*: 2006). However, FFA was not included into the current cost-benefit analysis, as no market for this product exists in India yet and, hence, no market price for FFA available up to date.

The price of biodiesel: 1) 24.8 Rs./kg (0.31 GBP/kg) (Planning Commission: 2004). 2) 17.62-19.52 Rs./kg (0.22-0.25 GBP/kg) (Subramanian, *et. al.*: 2005). 3) 14.50 Rs./l (0.18 GBP/l) (Paramathma: 2004).

6.6.2.2 Energy costs for biodiesel production

The price of gas along the HBJ pipeline has been assumed as constant and has been taken as Rs. 4,000/1,000 m^3 (50.48 GBP/1,000 m^3) inclusive of Royalty, Sales tax and transportation charges of gas along gas pipeline, with associated calorific value of 10,000 kcal/m^3 (41.868 MJ/m^3) (CEA. Planning Wing: 2004), 35.0 MJ/m^3 - natural gas (SimaPro 1.1), 40.9 MJ/m^3 - gas from oil production (SimaPro 1.1), 35.1-42.3 MJ/m^3 (PEI: March, 2009). However the price of gas along the HBJ pipeline is location dependant due to varying sales tax in the different Indian States.

The price of LNG at port has been taken as 6,480 Rs./t with associated calorific value of 9,500 kcal/kg (39.77 GJ/t).

Prevailing price of Naphtha has been taken as 17,400 Rs./t (219.6 GBP/t) (including handling charges of 100 Rs./t (1.262 GBP/t) at port) with associated calorific value of 10,500 kcal/kg (43.961 GJ/t) (CEA. Planning Wing: 2004). 2) Calculated: 395.8 Rs./GJ (~5.0 GBP/GJ).

The price of Domestic coal: 1) The total cost of Domestic coal 517 Rs./t. (6.52 GBP/t) Calorific value of coal 3,750 kcal/kg (15.7 GJ/t). Calculated: 32.93 Rs./GJ (0.416 GBP/GJ)-before benification. Cost of beneficiation of domestic coal has been considered as 125 Rs./t, which would improve the calorific value of coal from 3,750 kcal/kg (15.7 GJ/t) to 4,150 kcal/kg (17.4 GJ/t). Calculated: 36.95 Rs./GJ (0.47 GBP/GJ) after benification (CEA. Planning Wing: 2004). 2) The average landed cost of Indian domestic coal mix: 1,522-2,595 Rs./t (19.2-32.95 GBP/t). Calorific value of coal: 3,586-5,216 kcal/kg (15.0-21.8 GJ/t) (CEA. New Delhi. 2001). 3) 2,950 Rs./t (37.23 GBP/t) (TIDE/PSG College of Technology: 2005).

The price of Imported coal: 1) 1,925 Rs./t (24.29 GBP/t) (CEA. Planning Wing: 02/2004). Calorific value of coal: 5,400 kcal/kg (22.6 GJ/t). Calculated: 85.177 Rs./GJ. 2) The average landed cost of imported coal: 3,300-3,800 Rs./t (41.65-47.96 GBP/t). Calorific value of coal: 5,950-6,500 kcal/kg (24.9-27.2 GJ/t) (CEA: 2001), 18.0 GJ/t (SimaPro 1.1).

The price of Lignite: 1) 800 Rs./t (10.1 GBP/t); 2) Calorific value: 11.7 GJ/t (2,800 kcal/kg). (CEA. Planning Wing: 2004), 8.0 GJ/t (SimaPro 1.1); 3) Calculated: 68.376 Rs./GJ (0.863 GBP/GJ).

6.7 Logistics

Regarding the logistics operations such as collection of oilseed, biomass, fruits hulls and seed shells, calculations were based on the assumption that for oilseed, *Jatropha* oil, biomass, fruits hulls and seed shells transportation a medium sized truck will travel an average 35-100 km one way and heavy duty truck will travel an average 200-300 km one way for methanol delivery to the large-scale transesterification plant. For small-scale biodiesel production scenarios, calculations were based on the assumptions that a medium sized truck travelling up to 55 km for oilseed, biomass, fruits hulls and seed shells transportation and 30-55 km for methanol transportation (Balachandra: pers. comm.). Jungbluth (1995) in his report for GTZ GmbH says that the average distance LPG and kerosene are carried (across India) is estimated 960 and 930 km respectively.

Table 6.20: Estimated annual economic operating costs of small operations (Rs.)

Type of Truck	5 tonnes	9 tonnes	16 tonnes	27 tonnes
Cost per Truck*km (Rs.)	6.95	7.15	9.57	15.41
Cost per tonne*km of capacity (Rs.)	1.39	0.79	0.6	0.57

Source: World Bank Report: 2005

The vehicle insurance premium rate (Tables 6.21, 6.22 & 6.23) calculated base on The Insurance Regulatory and Development Authority (IRDA) latest regulations, which reduced third party premium on all categories of vehicles, including goods carriers, from 150% to 70% with retrospective effect from January 1, 2007.

The revised premium for goods vehicles with gross vehicle weight (GVW) not exceedding 7,500 kg has been revised to Rs. 5,580 (70.42 GBP) from Rs. 8,000 (100.96 GBP); for GVW exceeding 7,500 kg but below 12,000 kg premium has been revised to Rs. 5,920 (74.71 GBP) from Rs. 8,000 (100.96 GBP); for GVW exceeding 12,000 kg but below 20,000 kg premium has been revised to Rs. 6,090 (76.86 GBP) from Rs 9,000 (113.59 GBP).

For GVW exceeding 20,000 kg but below 40,000 kg premium has been revised to Rs. 6,260 (79.0 GBP) from Rs 9,000 (113.59 GBP); for GVW exceeding 40,000 kg the premium has been revised to Rs. 6,770 (80.44 GBP) from Rs. 9,000 (113.59 GBP), the press note added (The Tribune. Chandigarh. 29 January, 2007. Available at: www.tribuneindia.com/2007/20070129/biz.htm).

Table 6.21: Heavy vehicle insurance premium rates

Insurance premium	Type of truck			
	5 tonnes	9 tonnes	16 tonnes	27 tonnes
Rs.	5,580	5,920	6,090	6,260
GBP	70.4	74.7	76.9	79.0

Source: The Tribune. Chandigarh. 29 January 2007. Available at: www.tribuneindia.com/2007/ 20070129/ biz.htm

Table 6.22: Calculation of trucks requirement. Irrigated (industrial scale) scenario

	Year 3	Year 4	Year 5	Years 6-30
Oilseeds	30.0	39.1	49.3	62.5
Hulls and shells	19.8	25.8	32.5	41.2
Green prune material	57.8	75.1	94.8	120.2
Methanol	1.1	1.4	1.8	2.2
Biodiesel	5.4	7.1	8.9	11.3
Glycerine	1.8	2.4	3.0	3.8
Total vehicles required per day	116.0	150.8	190.2	241.2
Number of lorry drivers	97	126	159	202
Vehicles insurance (GBP/annum)	7464.0	9682.2	11465.1	15542.9

Table 6.23: Calculation of trucks requirement. Rainfed (small-scale) scenario

	Year 2	Year 3	Year 4	Year 5	Years 6-30
Oilseeds	0.27	0.69	1.07	1.47	2.00
Hulls and shells	0.19	0.48	0.74	1.02	1.39
Green prune material	0.15	0.40	0.62	0.85	1.16
Methanol	0.01	0.02	0.04	0.05	0.07
Biodiesel	0.08	0.21	0.33	0.45	0.61
Glycerine	0.01	0.03	0.04	0.06	0.08
Total vehicles required per day	0.71	1.85	2.83	3.89	5.31
Number of lorry drivers	1	1	2	2	3
Vehicles insurance (GBP/annum)	770.4	70.4	140.8	140.8	211.3

6.7.1 Usage of draft animals (Bullocks)

For the usage of draft animals the following assumptions were adopted:

Cost of pair of bullocks - 10,000 Rs. (126.21 GBP);

- ❒ Cost of the bullocks carts:
  - Steel: 15,000 Rs. (189.31 GBP);

- Wood: 10,000-18,000 Rs. (126.21-227.17 GBP);

- A pair of bullocks can care 1,200-1,500 pounds (544-480 kg) of load and can make 15-20 miles (25-32 km) per day (www.hindu.com/2008/01/27/stories/2008012755491800.htm);
- Bullock labour - 450 Rs. (5.68 GBP) per day (www.icrisat.org/gt-aes/text/India/EcoF-Legumes.html);
- According to research, a farmer in India spends 3,000-4,000 Rs. (37.82-50.48 GBP) per month on maintaining a pair of bullocks;
- This is an incremental expense which must be borne during their life span which is about 5 years (http://thinkchangeindia.wordpress.com/2008/02/25/bullocks-protest-introduction-of-affordable-tractor-into-indian-agriculture/).

Table 6.24: Number of bullock-pairs required for Jatropha fruits delivery to the oilseed procurement sub-centers (per 1 ha). Irrigated scenario

Jatropha fruits yield	kg/ha	7,500
Load per pair of bullocks	kg	450
Requirement	pairs	17
Days		8
Cost of bullocks labour	Rs.	3,750
	GBP	47.3
Cost of peoples labour	Rs.	67
	GBP	0.84
Bullocks maintenance	Rs.	1,042
	GBP	13

Table 6.25: Total cost of draft animal usage. Irrigated (large scale) scenario

Year	Jatropha oilsed yield	Cost of bullock labour		Cost of peoples labour	
	t/ha	Rs.	GBP	Rs.	GBP
6-30	5.2	3,750	47	67	0.84
5	4.1	2,957	37	53	0.66
4	3.25	2,344	30	42	0.53
3	2.5	1,803	23	32	0.42
2	1.2	865	11	15	0.19

Table 6.26: Number of bullock-pairs required for Jatropha fruits delivery to the oilseed procurement sub-centers (per 1 ha). Rainfed scenario

Jatropha fruits yield	kg/ha	5,308
Load per pair of bullocks	kg	450
Requirement	pairs	12
Days		6
Cost of bullocks labour	Rs.	2,654
	GBP	33.5
Cost of peoples labour	Rs.	47
	GBP	0.60
Bullocks maintenance	Rs.	737
	GBP	9

Table 6.27: Total cost of draft animal usage. Rainfed (small-scale) scenario

Year	Jatropha oilsed yield	Cost of bullock labour		Cost of peoples labour	
	t/ha	Rs.	GBP	Rs.	GBP
6-30	3.75	2,654	33	47	0.60
5	2.75	1,946	25	35	0.44
4	2.0	1,415	18	25	0.32
3	1.3	920	12	16	0.21
2	0.5	354	4	6	0.08

6.8 Labour cost

Literature review produced various labour requirements for *Jatropha curcas* plantation establishment, irrigation, maintenance, weeding, harvesting, *etc*. The following assumptions and estimations for labour requirement were collected:

- Weeding of crop: 1 hectare of land attracts 2.468 hp-hrs (6.63 MJ) (Rehman: 2003);
- Tractor 35.0 hp (26.1 kW) consumed 1.5 liters of diesel as a fuel to work for 1 hour. 1.5 liters of diesel attracts 21.99 hp-hrs (59.03 MJ) (Rehman: 2003);
- Productivity harvesting: 2-3 kg seeds/man-hr (Burgos: 2005);
- Average employment of one person per two ha (Francis, *et. al.*: 2005):
  1) An average time of maintenance: 275.0 hrs/ha/annum;
  2) Seeds harvesting: 125.0 hrs/t;
  3) Average daily wage in the agricultural sector: Rs. 65.0 (0.82 GBP);
  4) Average hourly labour rate is 8.0 Rs./hr (0.1 GBP/hr) of manwork ("Economics of Jatropha cultivation". www.jatrophaworld.org/15).

Labour requirements and labour costs used in current TEM summarized in Tables 6.28 and 6.29.

Table 6.28: Harvesting and pruning labour requirements

Density (trees/ha)		Yield (t/ha)	MD	Manhours	
1,600	Irrigated, 5 months during dry season	3.0	50	400	Jorge A. DelaVega (Mexico)
1,111	Irrigated	5.2	87	693	Paramathma: pers. comm.
2,500	Rainfed	3.75	62.5	500	Planning Commission of India (2004)

Table 6.29: Harvesting. Total annual labour cost (GBP/t)

Year	Irigated	Rainfed
6-30	65.6	47.3
5	51.7	34.7
4	41.0	25.2
3	31.6	16.4
2	15.1	6.3

Note: Assumed for harvesting: 1,000 Rs./t (12.62 GBP/t)

Source: www.ikisan.com/Archives

6.8.1 Staff required during construction period

Staff requirements for large scale (Industrial scenario, 100,000.0 t.p.a.) biodiesel plant based on the PX Biodiesel Immingham Limited biodiesel plant in Immingham, United Kingdom. Period of Biodiesel Plant construction for Large scale, Irrigated, scenario assumed to be 2 years. Staff required for this period: regular staff plus 10 support workers. Including 1 director, 5 managers, 1 accountant (Haughty: pers. comm.) (Tables 6.30 & 6.31).

Staff requirements for a small-scale (Rainfed scenario, 1,000.0 t.p.a.) biodiesel plant based on the Indus Biodiesel Plant, Rajpur, Chhattisgarh, India. Period of small scale biodiesel plant construction for Rainfed, small-scale, scenario assumed to be 1 year. Staff required for this period: regular staff plus 2 support workers. Including 1 manager and 1 accountant (Vijay: pers. comm.) (Tables 6.32 & 6.33).

Oilseed procurement and oil expelling centers staff required calculated as 1 manager per Main center durng both construction and operation periods, and 3 workers during construction period. For operation perial staff requirement estimated for the seed procurement and oil expelling centre (Main centre) is: 1 manager and 6 workers - operational staff. Staff requirement for the Sub-centre is 2 workers. Overall 4 Sub-centers required per 1 Main centre. Additional expenditures involve cost of training which assumed to be equal to 250.0 GBP for 20 persons for 5 days (Vijay: pers. comm., Haughty: pers. comm.).

Table 6.30: Staff requirements. Irrigated scenario. Industrial scale biodiesel plant

Position	Operational period		Construction/Training Period	
	Min	Max	Min	Max
Administration				
Director	1		1	
Secretary	1		1	
Accountant	1		1	
Manager	4		5	
Laboratory analyst	2		2	
Operational staff	20		20	
Maintenance	2		2	
Contract support staff	2	10	10	18
Total Administration	3		3	
Total Management	6		7	
Total Workers	24	32	32	40
Procurement centers staff	198		99	
Procurement center manger	33		33	

Source: Haughty: pers. comm.

Table 6.31: Staff annual salaries. Irrigated scenario. Industrial scale biodiesel plant

Position	Average Daily Earnings		Average Annual Salary/Wages	
	Rs.	£	Rs./a	£/a
Administration				
Director	1200.00	15.1	360000.0	4543.5
Secretary	198.46	2.5	59538.0	751.4
Accountant	405.67	5.1	121701.0	1536.0
Manager	787.09	9.9	236127.0	2980.1
Laboratory analyst	405.67	5.1	121701.0	1536.0
Operational staff	271.33	3.4	81399.0	1027.3
Maintenance	328.41	4.1	98523.0	1243.4
Contract support staff	135.84	1.7	40752.0	514.3
Total Administration	1804.13	22.8	541239.0	6830.8
Total Management	3959.7	50.0	1187910.0	14992.3
Total Workers	7441.82	93.9	2232546.0	28176.4
Procurement centers staff	72.28	0.91	21684.0	273.7
Procurement center manger	96.41	1.22	28923.0	365.0

Sources:
1) Labour Bureau. Government of India. Available at: www.labourbureau.nic.in/main2.html;
2) Ibid. Reports. Available at: www.labourbureau.nic.in/reports.htm;
3) Annual Survey of Industries, 2003-04, Vol. I: Statistics on Employment and Labour Cost. Available at: www.labourbureau.nic.in/ASI2K4ELC%20Contents.htm;
4) Annual Survey of Industries 2003-04 (Part I & Part II). Tables 5.6.1 & 5.6.2. Available at: http://www.labourbureau.nic.in/ASI%202k4%20Contents.htm;
5) Pocket Book of Labour Statistics 2006. Available at: www.labourbureau.nic.in/PBS2K6%20Contents.htm;
6) Monthly Economic Review. January 2006. Part XII. Labour and Social Sector. Available at: www.epwrf.res.in/upload/MER/mer10601012.htm.

Table 6.32: Staff requirements. Rainfed scenario. Industrial scale biodiesel plant

Position	Operational period		Construction/Training Period	
	Min	Max	Min	Max
Administration				
Senior manager	1		1	
Accountant	1		1	
Manager	1	2	2	
Laboratory analyst	1		1	
Operational staff	6		6	
Maintenance	1		1	
Contract support staff	1	2	2	
Total Administration	2	3	2	
Total Management	2		3	
Total Workers	8	9	10	

Source: Vijay: pers. comm.

Table 6.33: Staff annual salaries. Rainfed scenario. Small-scale biodiesel plant

Position	Average Daily Earnings		Average Annual Salary/Wages	
	Rs.	£	Rs./a	£/a
Administration				
Senior manager	436.2	5.5	130860	1651.5
Accountant	241.78	3.1	72534	915.4
Manager	333.08	4.2	99924	1261.1
Laboratory analyst	241.78	3.1	72534	915.4
Operational staff	166.96	2.1	50088	632.1
Maintenance	171.58	2.2	51474	649.6
Contract support staff	116.28	1.5	34884	440.3
Total Administration	677.98	8.6	203394	2567.0
Total Management	907.94	11.5	272382	3437.7
Total Workers	1289.62	16.3	386886	4882.8

Sources:
1) Labour Bureau. Government of India. Available at: www.labourbureau.nic.in/main2.html;
2) Ibid. Reports. Available at: www.labourbureau.nic.in/reports.htm;
3) Annual Survey of Industries, 2003-04, Vol. I: Statistics on Employment and Labour Cost. Available at: www.labourbureau.nic.in/ASI2K4ELC%20Contents.htm;
4) Annual Survey of Industries 2003-04 (Part I & Part II). Tables 5.6.1 & 5.6.2. Available at: www.labourbureau.nic.in/ASI%202k4%20Contents.htm;
5) Pocket Book of Labour Statistics 2006. Available at: www.labourbureau.nic.in/PBS2K6%20Contents.htm;
6) Monthly Economic Review. January 2006. Part XII. Labour and Social Sector. Available at: www.epwrf.res.in/upload/MER/mer10601012.htm.

Table 6.34: Staff annual salaries. Agriculture.

Position	Average Daily Earnings		Average Hourly Earnings	
	Rs.	£	Rs.	£
Site Preparation	75.88	0.96	9.49	0.12
Weeding & Soil Working	75.88	0.96	9.49	0.12
Conservation Tillage	85.68	1.08	10.71	0.14
Tractor Ploughing	89.63	1.13	11.20	0.14
Alignment & Stalking	75.88	0.96	9.49	0.12
Digging & Refilling Pits	82.98	1.05	10.37	0.13
Planting & Gap Filling	89.63	1.13	11.20	0.14
Protective Watering upon Planting	75.88	0.96	9.49	0.12
Maintenance & Irrigation	77.9	0.98	9.74	0.12
Fertilizers & Pesticides Application	92.12	1.16	11.52	0.15
Harvesting	135.42	1.71	16.93	0.21
Pruning and Trimming	82.98	1.05	10.37	0.13
Plantation Manager	168.73	2.13	21.09	0.27
Driver	107.98	1.36	13.50	0.17

Sources:
1) Labour Bureau. Government of India. Available at: www.labourbureau.nic.in/main2.html;
2) Ibid. Reports. Available at: www.labourbureau.nic.in/reports.htm;
3) Occupational Wage Survey (Sixth Round 2006): Report on Plantation Industries. Available at: www.labourbureau.nic.in/OWS%20Contents.htm;

4) Pocket Book of Labour Statistics 2006. Available at: www.labourbureau.nic.in/ PBS2K6%20Contents.htm;
5) Monthly Economic Review. January 2006. Part XII. Labour and Social Sector. Available at: www.epwrf.res.in/upload/MER/mer10601012.htm.

6.9 Insurance premium calculation

The premium paid for the property, fire and business interruption insurance, as well as staff medical insurance and workmen's compensations depends on particular contract of insurance between the insured and insurance company signed by the oilseed farming and biodiesel production companies in accordance with the law applying in the country where the farm or biodiesel production facility is located.

Two sets of data for the Insurance Premium calculations valid in April 2008 were analyzed. The first one is based on Insurance Policy provided by the Head Office of the Bajaj Allianz General Insurance, Pune, Maharashtra. Another one based on the Insurance Guidelines from the National Insurance Company Limited, Kolkata, West Bengal.

The first set of data for Insurance Premium calculation obtained from the communication with Mr. Vishnu Sharma, Bajaj Allianz General Insurance, Head Office, Pune, Maharashtra as following:

- The manufacturing activity for the Standard Fire insurance will attract a rate of 3.00 Rs. (0.038 GBP) per 1,000 Rs. (12.62 GBP) of property value. Further discounts can be allowed up to 50% based on risk features viz. fire protection, housekeeping, electrical fittings, previous loss history & construction of main production house building. Discount is decided based on physical inspection of the plant.
- Health Insurance Premium Calculations based on 2,500 Rs. (31.55 GBP) per 1.00 lacs (100,000.0 Rs.; 1,262.07 GBP) of Sum Insured for healthy 25-30 years old man (Table 6.35).

Table 6.35: Annual limit of indemnity

Annual limit of indemnity, Rs.	Premium	
	Rs.	£
100,000	2,500	31.55
200,000	5,000	63.10

Notes:
a) Based on 2,500 Rs. (31.55 GBP) per 1.00 lacs (1,262.07 GBP) Sum Insured for healthy man aged 25-30;
b) Exchange rate GBR/ INR = 79.23 - April 02, 2008. www.xe.com/ucc/convert.cgi

Source: Sharma: pers. comm.

The following assumptions applied to the Insurance Premium calculations based on personal communication with Mr. Subir Bhattacharyya, National Insurance Company Limited, Kolkata, West Bengal:

- Property Insurance Premium attracts Rs. 1.10 (0.014 GBP) to Rs. 1.25 (0.016 GBP) per Rs. 1,000 (12.62 GBP) on the value of the property.
- Business Interruption: Rate depends on the Indemnity Period and may vary from 90% to 125% of the property rate for Indemnity Period varying from 6 months to 1 year. This rate is applied on the Indemnity Limit which is the gross profit plus insured standing charges.
- Medical Insurance: Premium depends on age and Sum Insured (Table 6.36).

Table 6.36: Medical insurance premium rates

Age (years)	Sum Insured, Rs.	Premium, Rs.p.a.
35	100,000	1500
35	500,000	5000
50	100,000	3000
50	500,000	13500

Source: Bhattacharyya: pers. comm.

- Workmen's Compensation: The Premium chargeable starts from 15.00 Rs. (0.19 GBP) per 1,000 Rs. (12.62 GBP) on the annual wages up to 48,000 Rs. (605.8 GBP) and 2.00 Rs. (0.025 GBP) per 1,000 Rs. (12.62 GBP) on the balance wages.

The preliminary estimations demonstrate insignificant difference in the Total Insurance Premium between both options. As such, the National Insurance Company Limited insurance policy was applied for the Property and Fire Insurance for industrial and small-scale biodiesel plants, seed procurement and oil expelling centres (main centres and sub-centres), drip irrigation, as well as for Medical Insurance and Workmen’s Compensation. Business Interruption insurance was not included to these calculations.

6.10 Taxes calculation

In India, Income tax, Corporation tax, Wealth tax are examples of direct taxes whereas, Customs, Excise and Sales taxes are examples of indirect taxes.

6.10.1 Corporate Income Tax calculations

In India the income of a Company is taxed under Income Tax Act. Income tax in India has three components:

a. Base Income tax;
b. Surcharge applicable for companies with taxable income above 1 crore Rs. (10 million Rs., 126,207.3 GBP, GBR/INR = 79.23 - 02 April, 2008. www.xe.com/ ucc/convert.cgi).
c. Education and Secondary Higher Education cess aggregating to 3% of the total tax payable;
d. A separate tax called Wealth Tax is levied on certain assets of the company at 1% if the Net Asset exceeds 1.5 million Rs. (18,931.1 GBP). (This is a very minor levy and hence not very material for most companies) (V. Krishnan & Co: pers. comm., Seth Associates: pers. comm.).

For companies, income is taxed at a flat rate of 30% for Indian companies, with a 10% surcharge applied on the tax paid by companies with gross turnover over 1 crore Rs. (10.0 million Rs., 126,207.3 GBP). Foreign companies pay 40%. An education cess of 3% (on both the tax and the surcharge) is payable. It is yielding effective tax rates of 33.99% for domestic companies and 41.2% for foreign companies (Ibid.).

A 10% surcharge (tax on tax) is applicable if the taxable income (taking into consideration all the deductions) is above 10 lakh Rs. (1.0 million Rs., 12,620.7 GBP). The limit of 10 lakh Rs. (1.0 million Rs., 12,620.7 GBP) was increased to 1 crore Rs. (10 million Rs., 126,207.3 GBP) with effect from 1st June 2007 for corporate assesses (Ibid.).

Table 6.37: The effective Corporate Income Tax (IT) rates

Particulars	**If the Book Profits does not exceed Rs. 1 crore**	**If the Book Profits exceed Rs. 1 crore**
Indian companies	33.99%	30.90%
Foreign companies	42.23%	41.20%

Note:
Income Tax Rates (including base tax, surcharge for companies with income above 10 million Rs. (126,207.3 GBP) of 10% of Indian companies and 2.50% for foreign companies and Education and higher & secondary education cess of 3%)

Source: Haran. PKF Sridhar & Santhanam. Chennai: pers. comm.

Companies are liable to pay Dividend Distribution Tax on the dividends distributed by them. The present rate of Dividend Distribution tax is 16.995% (inclusive of surcharge (10%) and cess (3%) (Haran: pers. comm.).

Minimum Alternate tax is payable by the companies if their tax payable on the income as per the Income tax Act (computed as per the scheme of computation given therein) is less than 10% of their book profits (generally profits as per audited accounts before appropriations and tax) (Ibid.).

Table 6.38: The effective Minimum Alternate Tax (MAT) rates

Particulars	If the Book Profits does not exceed Rs. 1 crore	If the Book Profits exceed Rs. 1 crore
Indian companies	10.30%	11.33%
Foreign companies	10.30%	10.56%

Source: Haran. PKF Sridhar & Santhanam. Chennai: pers. comm.

Under the provisions of Section 10 (1) of the Income Tax Act, agricultural income is fully exempt from income tax. However, for individuals or HUFs when agricultural income is in excess of 5,000 Rs. (63.1 GBP), it is aggregated with the total income for the purposes of computing tax on the total income in a manner which results into no tax on agricultural income but an increased income tax on the other income.

Agricultural income which fulfils the above conditions is completely exempt from tax. The manner of calculating tax on total income and agricultural income is explained in following illustration:

For the assessment year 2008-2009 an individual has a total income from trading in cloth amounting to 111,000 Rs. (1,400.9 GBP) besides, he has earned 40,000 Rs. (504.83 GBP) as income from agriculture.

The income tax payable by him will be computed as under:

On the first 110,000 Rs. (1,388.28 GBP) of taxable non-agricultural income: NIL;

On the next 40,000 Rs. (504.83 GBP) of agricultural income (failing under 10% slab): NIL;

On the next 1,000 Rs. (12.62 GBP) of taxable non-agricultural income @ 20%: 200 Rs. (2.52 GBP);

Total on aggregated income of 110,000 Rs. (1,388.28 GBP) + 40,000 Rs. (504.83 GBP) = 151,000 Rs. (1,905.73 GBP): 200 Rs. (2.52 GBP).

Adopted from: http://sify.com/finance/tax/fullstory.php?id=14428247

No Individual Income Tax, Dividend Distribution Tax and Wealth Tax were applied for this Cost-Benefit Analysis.

6.10.2 Service Tax

Service Tax is a form of indirect tax imposed on specified services called "taxable services". The provisions relating to Service Tax were brought into force with effect from 1st July 1994. Service tax cannot be levied on any service which is not included in the list of taxable services. The services, brought under the tax net in the year 1994-1995, are telephone, stockbroker, and general insurance. Over the past years, service tax been expanded to cover new services, which might also influence total cost of biofuels production, marketing and distribution in India. The intention of the government is to gradually increase the list of taxable services until most services fall within the scope of service tax. Thus, The Finance Acts of 1997 and 1998 further extended the scope of service tax to cover a larger number of services rendered by a variety of service providers including consulting engineers and manpower recruitment agency. In 1998-1999 union Budget Government of India notified imposition of service tax on twelve new services, including market research agencies. In the Budget 2002-2003, ten more services have been added to the tax net, including cargo handling and storage and warehousing services. In the Budget 2003-2004 seven more services along with extension to three existing services have been added to the tax net, including technical testing and analysis (excluding health & diagnostic testing), technical inspection and certification service, maintenance & repair services, and commission and installation services. In the Budget 2004-2005, ten more services have been introduced in the service tax net along with reintroduction of three existing services, including transport of goods by road (earlier goods transport operators service re-introduced). At the same time, the rate of service tax has been enhanced to 10% from 8%. Besides this 2% Education Cess on the amount of service tax has also been introduced. Thereafter Service Tax is increased up to 12.24% and now currently the effective service tax rate is 12.36% including Education Cess (CBEC: no date). For 2007-2008 financial year, the service tax remains the same as in 2006-2007 financial year at 12% (plus an Education Cess of 3%) (Rajaram & Baxi: 2007).

Neither Service Tax nor Capital Gains Tax were applied for this Cost-Benefit Analysis. However, in future, for more comprehensive Techno-Economic Analysis influence of Service Tax on total cost of biodiesel production, marketing and distribution in India should be considered. Additional taxation that will influence and should be added to the total cost of biodiesel at the gas stations are following: 1) plant design (e.g. engineering consulting services), 2) technical inspection and certification of equipment and piping (if independent company hired); 3) technical testing and analysis (if independent company hired); 4) equipment installation, maintenance and service (if contractor company hired), 5) market research service (if contractor company hired); 6) manpower recruitment agency (if contractor company hired).

6.10.3 Central Sales Tax and Value Added Tax

Sales Tax is one of the most important Indirect Tax for purpose of taxation by State Governments. Sales tax is levied on the sale of a commodity, which is produced or imported and sold for the first time. If the product is sold subsequently without being processed further, it is exempt from sales tax. Sales Tax is a levy on purchase and sale of goods in India and is levied under the authority of both Central Legislation (Central Sales Tax) and State Governments Legislations (Sales Tax). The government levies Sales Tax principally on intra-state sale of goods. States also levy tax on transactions which are "deemed sales" like works contracts and leases. Revenue from the Central Sales Tax (CST) goes to the state from which movement of goods commences. Section 3 of Central Sales Tax Act (1956) defines inter-state sale or purchase as follows: A sale or purchase of goods shall be deemed to take place in the course of inter-state trade or commerce if the sale or purchase

a) occasions the movement of goods from one state to another or b) is effected by a transfer of documents of title to the goods during their movement from one state to another. Inter-state sale can be as per section 3 (a) or section 3 (b). Entry 92A of List I - Union List reads: "Taxes on the sale and purchase of goods other than newspapers, where such sale or purchase takes place in the course of inter-state trade or commerce". Entry 54 of list II - State List - reads: "Tax on sale or purchase of goods other than newspapers except tax on inter-state sale or purchase".

Thus, sale within the state (intra-state sale) is within the authority of State Government, while sale outside state (inter-state sale) is within the authority of Central Government. Location of buyer and seller is immaterial. Thus, even if buyer and seller are within the same state, sale will be inter-state, if sale occasions movement of goods from one state to another, e.g. the buyer may have construction site in another state and may ask seller to dispatch goods directly to the site. Inter-state sale by transfer of documents is also possible even when buyer and seller are in same state. Mode of transport is immaterial. It may be aircraft, rail, post, motor transport, angadia, ship or hand cart (Meera Business Services website. Visited 09 April, 2008).

As CST is proving to be a hindrance in introducing Value Added tax (VAT), CST has been reduced to 3% (from 4%) effective on 01 April, 2007. It is announced that it will be reduced by 1% every year and made Nil by 01 April, 2010 (Meera Business Services: Online). From April 01, 2005, most of the states in India have supplemented sales tax with a new Value Added Tax (VAT). There will be only two basic rates of VAT. The practice of VAT executed by State Governments is applied on each stage of sale, with a particular apparatus of credit for the input VAT paid. VAT in India can be classified under the following tax slabs: a) 0.0% for essential commodities; b) 1.0% on gold ingots and expensive stones; c) 4.0% on industrial and agricultural inputs, capital merchandise and commodities of mass consumption, declared goods, capital goods, drugs and medicines; d) 12.5% on other items; e) variable rates (state-dependent) are applicable for petroleum products, tobacco, liquor etc (Trade Chakra (Ed.): no date, Chandra: no date). Value Added Tax is a multi point sales tax with set off for tax paid on purchases. It is basically a tax on the value addition on the product. The burden of tax is ultimately born by the consumer of goods. In many aspects it is equivalent to last point sales tax. It can also be called as a multi point sales tax levied as a proportion of valued added (Trade Chakra (Ed.): no date, Khatik: no date). The New Biofuels Policy (September 2008) confers "declared goods status" on biodiesel and ethanol.

This implies that both will attract a uniform CST or VAT rate rather than the varied sales tax rates prevalent in the states, and movement of biofuels within and outside the states will not be restricted (Altenburg, *et. al*.: 2009).

Neither Cental Sales Tax nor Value Added Tax were applied for this Cost-Benefit Analysis. However, in future, for more comprehensive Techno-Economic Analysis influence of VAT on total cost of biodiesel production, marketing and distribution in India should be considered.

The following assumptions should be considered as well: 1) *Jatropha* hulls and shells, prune material, *Jatropha* press-cake, and wood charcoal will be transported and utilized locally; 2) *Jatropha* plantations and biodiesel plant will operate on intra-state water and, energy resources supply (e.g. electricity, fuel for technological steam production, gasoline or petrodiesel for transportation) and will not be a subject for the CST.

6.11 Results of the cost-benefit analysis

A summary of the Techno-Economic Model results for 5 agricultural (2 Irrigated and 3 Rainfed) and 10 biodiesel production (5 large scale and 5 small-scale) scenarios are presented in Tables from 6.43 to 6.50 and Chatrs from 6.8 to 6.11.

6.11.1 Agricultural scenarios

The NPV results for the agricultural (TBOS cultivation) models are listed in Table 6.39 (large scale) and Table 6.40 (small-scale).

Table 6.39: Net Present Value (GBP/ha). Agriculture. Small-scale scenarios (IRR_Agro I and IRR_Agro II) per life cycle

IRR_Agro I Loan	IRR_Agro I Private capital	IRR_Agro II Loan	IRR_Agro II Private capital
NPV per life cycle (GBP/ha)			
(1,481.67)	(1,269.57)	(1,464.96)	(1,252.86)

Table 6.40: Net Present Value (GBP/ha). Agriculture. Small-scale scenarios (RAIN_Agro I, RAIN_Agro II and RAIN_Agro III) per life cycle

RAIN_Agro I	RAIN_Agro II	RAIN_Agro III
NPV per life cycle (GBP/ha)		
(1,285.58)	(1,299.08)	(869.18)

As cost-benefit analysis for all Irrigated and Rainfed agricultural scenarios have produced the negative NPV values, a number of sensitivity tests were carried out to show how changes in certain parameters would affect those NPV values. The results of these sensitivity tests and their discussion can be found further in the Chapter 8: "Sensitivity analysis".

In large scale agricultural scenarios (Table 6.43) the production costs distribution has almost no fluctuations and vary as little as 45.95% (IRR_Agro II) to 46.23% (IRR_Agro I) - the total labour costs. Of the remainder, materials and energy costs represent 34.4% (IRR_Agro I) to 35.8% (IRR_Agro II); and cost of oilseed transportation represents 13.18% (IRR_Agro II) to 13.26% (IRR_Agro I). Total various costs are negligible at 4.52% (IRR_Agro I) to 4.54% (IRR_Agro II); and costs of seedlings including transport and gap filling at 0.57% (IRR_Agro I and IRR_Agro II).

Similar picture for the production costs distribution in agricultural small-scale scenarios (Table 6.44) which vary as little as 67.72% (RAIN_Agro I) and 66.92% (RAIN_Agro II) to 76.47% (RAIN_Agro III) - the total labour costs. Of the remainder, materials and energy costs represent 2.36% (RAIN_Agro III) to 13.52% (RAIN_Agro_I) and 14.55% (RAIN_Agro II); and cost of oilseed transportation represents 11.75% (RAIN_Agro II) and 11.89% (RAIN_Agro I) to 13.43% (RAIN_Agro III). Total various costs are negligible at 4.78% (RAIN_Agro II) and 4.84% (RAIN_Agro I) to 5.46% (RAIN_Agro III); and cost of seedlings including transport and gap filling at 2.00% (RAIN_Agro II) and 2.02% (RAIN_Agro I) to 2.28% (RAIN_Agro III). The low materials and energy costs in RAIN_Agro III model can be initially expected as no fertilizers and agro-chemicals applied in this scenario.

6.11.2 Biodiesel production scenarios

The NPV results for the biodiesel production models are listed in Table 6.41 (large scale) and Table 6.42 (small-scale).

Table 6.41: Net Present Value (GBP). Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production) per life cycle

8.0 MGBP		11.5 MGBP	
IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
NPV per life cycle (GBP)			
22,912,789.87	21,556,264.47	19,210,871.35	17,548,559.32

15.0 MGBP		18.5 MGBP	
IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
NPV per life cycle (GBP)			
14,737,171.36	13,055,531.53	6,838,784.76	8,805,165.06

20.3 MGBP	
IRR_Prod Loan	IRR_Prod Private capital
NPV per life cycle (GBP)	
3,972,313.81	6,619,262.31

Table 6.42: Net Present Value (GBP). Biodiesel production. Small-scale scenarios (RAIN I_Production and RAIN II_Production) per life cycle

0.11 MGBP		0.16 MGBP	
RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod II Loan	RAIN_Prod Private capital
NPV per life cycle (GBP)			
265,775.14	281,250.71	188,644.47	219,166.92

0.21 MGBP		0.26 MGBP	
RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod Loan	RAIN_Prod Private capital
NPV per life cycle (GBP)			
107,149.27	157,318.65	22,569.50	95,352.62

0.3 MGBP	
RAIN_Prod Loan	RAIN_Prod Private capital
NPV per life cycle (GBP)	
(46,748.63)	46,029.93

In the Biodiesel Production large scale scenarios (Table 6.45) the total production costs distribution have almost no fluctuations and vary as little as 90.63% (TEM_Large, CAPEX 20.3 MGBP) to 90.83% (TEM_Large, CAPEX 8.0 MGBP) for the material costs. Of the remainder, costs of transportation represent 8.47% (TEM_Large, CAPEX 18.5 and 20.3 MGBP) to 8.49% (TEM_Large, CAPEX 8.0 and 11.5 MGBP). Labour costs are negligible at 0.45% (TEM_Large, all CAPEX); and total various costs at 0.24% (TEM_Large, CAPEX 8.0 MGBP) to 0.45% (TEM_Large, CAPEX 20.3 MGBP).

Similar picture for the Biodiesel Production small-scale scenarios (Table 6.46) the total production costs distribution material costs vary as little as 96.16% (TEM_Small, CAPEX 0.30 MGBP) to 96.46% (TEM_Small, CAPEX 0.11 MGBP). Of the reminder, costs of transportation represent 1.59% (TEM_Small, CAPEX 0.21, 0.26 and 0.30 MGBP) to 1.60% (TEM_Small, CAPEX 0.11 and 0.16 MGBP). Labour costs are negligible at 1.30% (TEM_Small, all CAPEX); and total various costs at 0.64% (TEM_Small, CAPEX 0.11 MGBP) to 0.95% (TEM_Small, CAPEX 0.30 MGBP).

In biodiesel production scenarios the Jatropha SVO costs are equal to 66.7% (large scale) and 71.2% (small-scale) of total production (variable) costs per life cycle. The range in the percentage of feedstock to variable cost calculated in other studies is from 70% to 90% (Reaney, *et. al.*: 2006, Van Gerpen: 2007), which is consistent with 65% to 78% (Pruszko: 2006 cited by Tomomatsu & Swallow: 2007). Within the margins of error, although different results between large- and small-scale, the final material costs no difference in scale inputs/outputs between this and any other models.

A summary of the total life cycle sales and the life cycle material costs for both large scale and small-scale biodiesel production models are presented in Charts 6.9-6.12.

The results of sensitivity tests for all biodiesel production scenarios and their discussion can be found further in the Chapter 8: "Sensitivity analysis".

Table 6.43: Cost-benefit analysis. Agriculture. Irrigated scenarios

	Fruit hulls and seed shells used as compost (IRR_Agro I)				Fruit hulls and seed shells used as combustibles (IRR_Agro II)			
	No initial investment		Private capital		No initial investment		Private capital	
	Total, £/ha	%	Total, £/ha	%	Total, £/ha	%	Total, £/ha	%
CAPEX (Drip irrigation centres and seed procurement sub-centres)	682.53		682.53		682.53		682.53	
Sales Total	16,075.9		16,075.9		16,075.9		16,075.9	
Cost of seedlings including transport and gap filling	72.91	0.57	72.91	0.57	72.91	0.57	72.91	0.57
Materials and Energy Costs	4504.90	35.40	4504.90	35.40	4581.37	35.78	4581.37	35.78
Total Labour (Man Hours)	33906.03		33906.03		33906.03		33906.03	
Total Labour Cost (Salary)	5883.36	46.23	5883.36	46.23	5883.36	45.95	5883.36	45.95
Total Transportation of Oilseeds	1687.89	13.26	1687.89	13.26	1687.89	13.18	1687.89	13.18
Various costs:								
Land Rent	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
National Agricultural Insurance Scheme charge (3.5%)	311.5	2.45	311.5	2.45	311.5	2.43	311.5	2.43
Insurance costs	74.6	0.59	74.6	0.59	74.6	0.58	74.6	0.58
Weather Based Crop Insurance costs	192.2	1.51	192.2	1.51	192.2	1.50	192.2	1.50
Total Various Cost	578.3	4.5	578.3	4.5	578.3	4.5	578.3	4.5
Total Production Cost	12,727.4	100.0	12,727.4	100.0	12,803.8	100.0	12,803.8	100.0
EBITDA	3,348.6		3,348.6		3,272.1		3,272.1	
Depreciation	682.5		682.5		682.5		682.5	
Earnings Before Interests & Taxes (EBIT)	2,666.0		2,666.0		2,589.6		2,589.6	
Interest charge (CAPEX) (15%)	1,373		0.0		1,373		0.0	
Interest charge (working capital charge) (15%)	1,909.1		1,909.1		1,920.6		1,920.6	
Pre Tax Income	**-615.9**		756.9		**-703.8**		669.0	
Income Tax (IT) (0%)	0.0		0.0		0.0		0.0	
After Tax Income	**-615.9**		756.9		**-703.8**		669.0	
Contingency (5%)	205.4		136.8		196.3		127.7	
Net Income	**-821.3**		620.1		**-900.1**		541.3	
NPV	**-1,481.7**		**-1,269.6**		**-1,465.0**		**-1,252.9**	

Table 6.44: Cost-benefit analysis. Agriculture. Rainfed scenarios

	RAIN_Agro_I		RAIN_Agro_II		RAIN_Agro_III	
	Fruit hulls and seed shells used as compost		Fruit hulls and seed shells used as combustibles		Fruit hulls and seed shells used as compost	
	No initial investment		No initial investment		No initial investment	
	Total, £/ha	%	Total, £/ha	%	Total, £/ha	%
Sales Total	6058.51		6058.45		6058.51	
Cost of seedlings including transport and gap filling	164.07	2.02	164.06	2.00	164.07	2.28
Materials and Energy Costs	1096.69	13.52	1194.15	14.55	169.62	2.36
Total Labour (Man Hours)	35703.07		35703.07		35703.07	
Total Labour Cost (Salary)	5492.65	67.72	5492.65	66.92	5492.65	76.47
Total Transportation of Oilseeds	964.64	11.89	964.64	11.75	964.64	13.43
Various costs:						
Land Rent	0.0		0.0		0.0	
National Agricultural Insurance Scheme charge (3.5%)	166.9	2.1	166.9	2.0	166.9	2.3
Insurance costs	66.3	0.8	66.3	0.8	66.3	0.9
Weather Based Crop Insurance costs	159.0	2.0	159.0	1.9	159.0	2.2
Total Various Cost	392.2	4.8	392.2	4.8	392.2	5.5
Total Production Cost	8,110.2	100.0	8,207.7	100.0	7,183.2	100.0
EBITDA	**-2051.74**		**-2149.24**		**-1124.67**	
Depreciation	0.0		0.0		0.0	
Earnings Before Interests & Taxes (EBIT)	**-2051.74**		**-2149.24**		**-1124.67**	
Interest charge (CAPEX) (15%)	0.0		0.0		0.0	
Interest charge (working capital charge) (15%)	1216.5		1231.2		1077.5	
Pre Tax Income	**-3268.3**		**-3380.4**		**-2202.1**	
Income Tax (IT) (0%)	0.0		0.0		0.0	
After Tax Income	**-3268.3**		**-3380.4**		**-2202.1**	
Contigencies (5%)	163.4		169.0		110.1	
Net Income	**-3431.69**		**-3549.42**		**-2312.25**	
NPV	**-1285.58**		**-1299.08**		**-869.18**	

Table 6.45: Cost-benefit analysis. Production. Large scale scenarios

	Scenario TEM_Large_8.0 MGBP				Scenario TEM_Large_11.5 MGBP				Scenario TEM_Large_15.0 MGBP			
	No initial investment		Private capital		No initial investment		Private capital		No initial investment		Private capital	
	Total (£)	%	Total	%	Total (£)	%	Total	%	Total (£)	%	Total	%
CAPEX Total (Biodiesel plant and main seeds procurement centres)	10,582,202.0		10,582,202.0		14,082,202.0		14,082,202.0		17,582,202.0		17,582,202.0	
Sales Total	1,241,308,177.5		1,241,308,177.5		1,241,308,177.5		1,241,308,177.5		1,241,308,177.5		1,241,308,177.5	
Material Costs	708,134,509.4	90.83	708,134,509.4	90.83	708,134,509.4	90.77	708,134,509.4	90.77	708,134,509.4	90.72	708,134,509.4	90.72
Cost of Labour	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45
Costs of Transportation	66,196,233.6	8.49	66,196,233.6	8.49	66,196,233.6	8.49	66,196,233.6	8.49	66,196,233.6	8.48	66,196,233.6	8.48
Various costs:												
Construction expenses (10% of CAPEX)	1,058,220.2	0.14	1,058,220.2	0.14	1,408,220.2	0.18	1,408,220.2	0.18	1,758,220.2	0.23	1,758,220.2	0.23
Insurance costs:												
Property insurance	383,604.8	0.05	383,604.8	0.05	510,479.8	0.07	510,479.8	0.07	637,354.8	0.08	637,354.8	0.08
Medical insurance	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03
Workmen's compensation	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01
Personnel Costs (Purchase/Sales)	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01
Start up personnel costs	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003
Total Various Cost	1,836,567.4	0.24	1,836,567.4	0.24	2,313,442.4	0.30	2,313,442.4	0.30	2,790,317.4	0.36	2,790,317.4	0.36
Total Production Cost	779,654,029.6	100.0	779,654,029.6	100.0	780,130,904.6	100.0	780,130,904.6	100.0	780,607,779.6	100.0	780,607,779.6	100.0
EBITDA	461,654,147.9		461,654,147.9		461,177,272.9		461,177,272.9		460,700,397.9		460,700,397.9	
Depreciation	10,582,202.0		10,582,202.0		14,082,202.0		14,082,202.0		17,582,202.0		17,582,202.0	
Earnings Before Interests & Taxes (EBIT)	451,071,945.9		451,071,945.9		447,095,070.9		447,095,070.9		443,118,195.9		443,118,195.9	
Interest charge (15%)	29,744,879.6		0.0		39,753,204.4		0.0		49,761,529.2		0.0	
Interest charge (working capital charges)	116,948,104.4		116,948,104.4		117,019,635.7		117,019,635.7		117,091,166.9		117,091,166.9	
Pre-Tax Income	304,378,961.8		334,123,841.4		290,322,230.7		330,075,435.2		276,265,499.7		326,027,028.9	
Corporate Income Tax (IT) (33.99%)	103,933,155.8		114,043,440.4		99,645,453.4		112,805,907.0		95,940,600.3		111,568,373.5	
Minimum Alternate Tax (11.33%)	0.0		0.0		0.0		0.0		0.0		0.0	
After-tax income	200,445,806.0		220,080,401.1		190,676,777.4		2,127,269,528.2		180,324,899.4		214,458,655.4	
Contigency (5%)	10,161,962.8		11,143,692.5		9,817,724.5		10,674,844.4		9,237,423.7		10,944,111.5	
Net income	190,283,843.3		208,936,708.5		180,859,052.9		206,594,683.8		170,709,079.0		203,514,543.9	
NPV	22,912,789.9		21,556,264.5		19,210,871.4		17,548,559.3		14,737,171.4		13,055,531.5	

Table 6.45: Cost-benefit analysis. Production. Large scale scenarios (cont.)

	Scenario TEM_Large_18.5 MGBP				Scenario TEM_Large_20.3 MGBP			
	No initial investment		Private capital		No initial investment		Private capital	
	Total (£)	%	Total	%	Total (£)	%	Total	%
CAPEX Total (Biodiesel plant and main seeds procurement centres)	21,082,202.0		21,082,202.0		22,882,202.0		22,882,202.0	
Sales Total	1,241,308,177.5		1,241,308,177.5		1,241,308,177.5		1,241,308,177.5	
Material Costs	708,134,509.4	90.66	708,134,509.4	90.66	708,134,509.4	90.63	708,134,509.4	90.63
Cost of Labour	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45	3,486,719.2	0.45
Costs of Transportation	66,196,233.6	8.47	66,196,233.6	8.47	66,196,233.6	8.47	66,196,233.6	8.47
Various costs:								
Construction expenses (10% of CAPEX)	2,108,220.2	0.27	2,108,220.2	0.27	2,288,220.2	0.29	2,288,220.2	0.29
Insurance costs:								
Property insurance	764,229.8	0.10	764,229.8	0.10	829,479.8	0.11	829,479.8	0.11
Medical insurance	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03	268,196.9	0.03
Workmen's compensation	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01	60,471.8	0.01
Personnel Costs (Purchase/Sales)	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01	44,623.7	0.01
Start up personnel costs	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003	21,450.0	0.003
Total Various Cost	3,267,192.4	0.42	3,267,192.4	0.42	3,512,442.4	0.45	3,512,442.4	0.45
Total Production Cost	781,084,654.6	100.0	781,084,654.6	100.0	781,329,904.6	100.0	781,329,904.6	100.0
EBITDA	460,223,522.9		460,223,522.9		459,978,272.9		459,978,272.9	
Depreciation	21,082,202.0		21,082,202.0		22,882,202.0		22,882,202.0	
Earnings Before Interests & Taxes (EBIT)	439,141,320.9		439,141,320.9		437,096,070.9		437,096,070.9	
Interest charge (15%)	79,045,632.0		0.0		85,852,722.6		0.0	
Interest charge (working capital charges)	117,162,698.2		117,162,698.2		117,199,485.7		117,199,485.7	
Pre-Tax Income	242,932,990.7		321,978,622.7		234,043,862.6		319,896,585.2	
Corporate Income Tax (IT) (33.99%)	86,101,544.0		110,330,840.1		84,087,207.6		109,694,394.4	
Minimum Alternate Tax (11.33%)	0.0		0.0		0.0		0.0	
After-tax income	156,831,446.7		211,647,782.5		149,956,655.0		210,202,190.8	
Contigency (5%)	7,841,572.3		10,582,389.1		7,497,832.8		10,510,109.5	
Net income	147,951,739.5		200,803,461.6		141,124,400.8		199,409,190.7	
NPV	6,838,784.8		8,805,165.1		3,972,313.8		6,619,262.3	

Table 6.46: Cost-benefit analysis. Production. Small-scale scenarios

	Scenario TEM_Small_0.11 MGBP				Scenario TEM_Small_0.16 MGBP				Scenario TEM_Small_0.21 MGBP			
	No initial investment		Private capital		No initial investment		Private capital		No initial investment		Private capital	
	Total (£)	%	Total	%	Total (£)	%	Total	%	Total (£)	%	Total	%
CAPEX (Biodiesle plant)	110,000.0		110,000.0		160,000.0		160,000.0		210,000.0		210,000.0	
Sales total	12,461,940.9		12,461,940.9		12,461,940.9		12,461,940.9		12,461,940.9		12,461,940.9	
Material Costs	7,021,181.2	96.46	7,021,181.2	96.46	7,021,181.2	96.38	7,021,181.2	96.38	7,021,181.2	96.28	7,021,181.2	96.28
Costs of Labour	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30
Costs of Transportation	116,229.1	1.60	116,229.1	1.60	116,229.1	1.60	116,229.1	1.60	116,229.1	1.59	116,229.1	1.59
Various costs:												
Construction expenses (10% of CAPEX)	11,000.0	0.15	11,000.0	0.15	16,000.0	0.22	16,000.0	0.22	21,000.0	0.29	21,000.0	0.29
Insurance costs:												
Property insurance	3,987.5	0.05	3,987.5	0.05	5,800.0	0.08	5,800.0	0.08	7,612.5	0.10	7,612.5	0.10
Medical insurance	14,974.5	0.21	14,974.5	0.21	14,526.1	0.20	14,526.1	0.20	14,974.5	0.21	14,974.5	0.21
Workmen's compensation	3,382.9	0.05	3,382.9	0.05	3,382.9	0.05	3,382.9	0.05	3,382.9	0.05	3,382.9	0.05
Personnel Costs (Purchase/Sales)	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14
Start up personnel costs	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04
Total Various Cost	46,559.9	0.64	46,559.9	0.64	52,924.1	0.73	52,924.1	0.73	60,184.9	0.83	60,184.9	0.83
Total Production Cost	7,278,731.0	100.00	7,278,731.0	100.00	7,285,095.1	100.00	7,285,095.1	100.00	7,292,356.0	100.00	7,292,356.0	100.00
EBITDA	5,183,209.9		5,183,209.9		5,176,845.7		5,176,845.7		5,169,584.9		5,169,584.9	
Depreciation	110,000.0		110,000.0		160,000.0		160,000.0		210,000.0		210,000.0	
Earnings Before Interests & Taxes (EBIT)	5,073,209.9		5,073,209.9		5,016,845.7		5,016,845.7		4,959,584.9		4,959,584.9	
Interest charge (15%)	336,492.5		0.0		489,443.7		0.0		642,394.8		0.0	
Interest charge (working capital charges) (15%)	1,091,809.6		1,091,809.6		1,092,764.3		1,092,764.3		1,093,853.4		1,093,853.4	
Pre-Tax Income	3,644,907.7		3,981,400.2		3,434,637.8		3,924,081.5		3,223,336.7		3,865,731.5	
Corporate Income Tax (IT) (30.90%)	1,143,094.6		1,235,250.5		1,094,511.2		1,219,315.7		1,051,926.3		1,203,062.3	
Minimum Alternative Tax (MAT) (10.30%)	0.0		0.0		0.0		0.0		0.0		0.0	
After Tax Income	2,501,813.1		2,746,149.8		2,340,126.6		2,704,765.8		2,171,410.4		2,662,669.2	
Contigency (5%)	125,090.7		137,307.5		117,006.3		135,238.3		108,570.5		133,133.5	
Net income	2,371,279.7		2,607,224.9		2,212,373.2		2,567,335.1		2,044,744.3		2,526,768.3	
NPV	265,775.1		281,250.7		188,644.5		219,166.9		107,149.3		157,318.6	

Table 6.46: Cost-benefit analysis. Production. Small-scale scenarios (cont.)

	Scenario TEM_Small_0.26 MGBP				Scenario TEM_Small_0.30 MGBP			
	No initial investment		Private capital		No initial investment		Private capital	
	Total (£)	%	Total	%	Total (£)	%	Total	%
CAPEX (Biodiesle plant)	260,000.0		260,000.0		300,000.0		300,000.0	
Sales total	12,461,940.9		12,461,940.9		12,461,940.9		12,461,940.9	
Material Costs	7,021,181.2	96.19	7,021,181.2	96.19	7,021,181.2	96.16	7,021,181.2	96.16
Costs of Labour	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30	94,760.7	1.30
Costs of Transportation	116,229.1	1.59	116,229.1	1.59	116,229.1	1.59	116,229.1	1.59
Various costs:								
Construction expenses (10% of CAPEX)	26,000.0	0.36	26,000.0	0.36	30,000.0	0.41	30,000.0	0.41
Insurance costs:								
Property insurance	9,425.0	0.13	9,425.0	0.13	10,875.0	0.15	10,875.0	0.15
Medical insurance	14,974.5	0.21	14,974.5	0.21	14,974.5	0.21	14,974.5	0.21
Workmen's compensation	3,382.9	0.05	3,382.9	0.05	524.0	0.01	524.0	0.01
Personnel Costs (Purchase/Sales)	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14	10,140.0	0.14
Start up personnel costs	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04	3,075.0	0.04
Total Various Cost	66,997.4	0.9	66,997.4	0.9	69,588.5	0.95	69,588.5	0.95
Total Production Cost	7,299,168.5	100.0	7,299,168.5	100.0	7,301,759.5	100.00	7,301,759.5	100.00
EBITDA	5,162,772.4		5,162,772.4		5,160,181.3		5,160,181.3	
Depreciation	260,000.0		260,000.0		300,000.0		300,000.0	
Earnings Before Interests & Taxes (EBIT)	4,902,772.4		4,902,772.4		4,860,181.3		4,860,181.3	
Interest charge (15%)	795,345.9		0.0		917,706.9		0.0	
Interest charge (working capital charges) (15%)	1,094,875.4		1,094,875.3		1,095,263.9		1,095,263.9	
Pre-Tax Income	3,012,551.2		3,807,897.1		2,847,210.5		3,764,917.4	
Corporate Income Tax (IT) (30.90%)	1,014,037.5		1,186,968.2		987,750.0		1,175,108.9	
Minimum Alternative Tax (MAT) (10.30%)	0.0		0.0		0.0		0.0	
After Tax Income	1,998,513.6		2,620,928.9		1,859,460.5		2,589,808.5	
Contigency (5%)	99,925.7		131,046.4		92,973.0		129,490.4	
Net income	1,871,675.0		2,486,540.0		1,731,548.3		2,456,515.7	
NPV	22,569.5		95,352.6		-46,748.6		46,029.9	

Chart 6.9: Material costs per life cycle. Production. Large scale scenarios

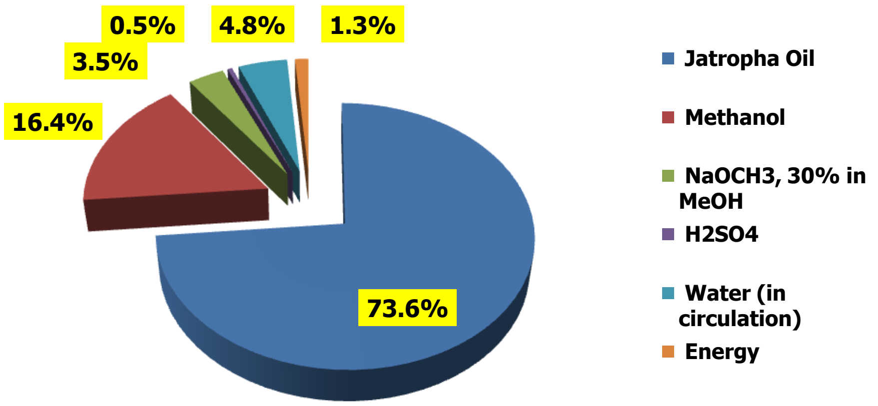


Table 6.47: Material costs per life cycle. Production. Large scale scenarios

Materials	**Total (£)**	**%**
Jatropha oil	520,968,761.7	73.6
Methanol	116,354,197.7	16.4
$NaOCH_3$, 30% in MeOH	24,747,640.2	3.5
H_2SO_4	3,212,811.0	0.5
Water (in circulation)	33,667,920.6	4.8
Energy	9,183,178.1	1.3
Total material costs	**708,134,509.4**	**100.0**

Chart 6.10: Sales per life cycle. Production. Large scale scenarios

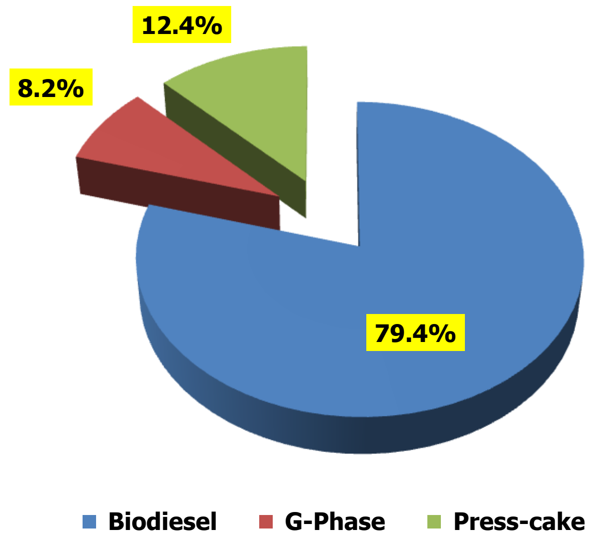


Table 6.48: Sales per life cycle. Production. Large scale scenarios

Sales (£)		**%**
Biodiesel	985,827,543.0	79.4
G-Phase	101,795,927.0	8.2
Press-cake	153,684,707.5	12.4
Sales Total (£)	**1,241,308,177.5**	**100.0**

Chart 6.11: Material costs per life cycle. Production. Small-scale scenarios

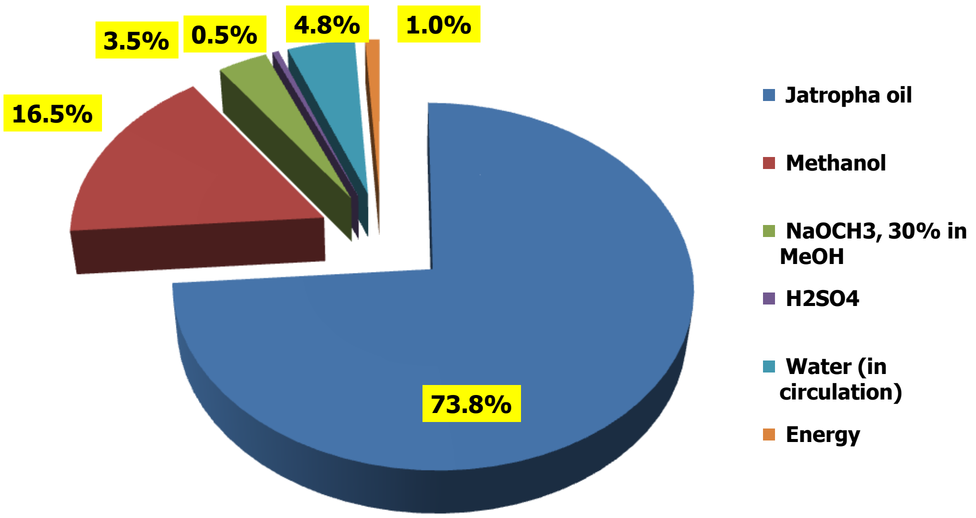


Table 6.49: Material costs per life cycle. Production. Small-scale scenarios

Materials	**Total (£)**	**%**
Jatropha oil	5,180,878.4	73.8
Methanol	1,157,107.7	16.5
$NaOCH_3$, 30% in MeOH	246,107.9	3.5
H_2SO_4	31,950.4	0.5
Water (in circulation)	334,817.4	4.8
Energy	70,319.4	1.0
Total material costs	**7,021,181.2**	**100.0**

Chart 6.12: Sales per life cycle. Production. Small-scale scenarios

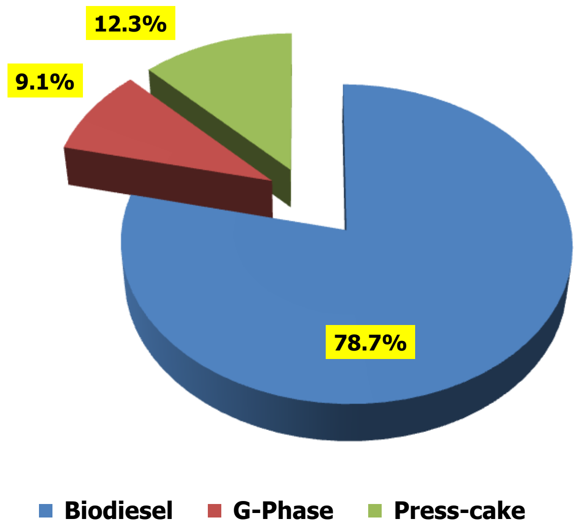


Table 6.50: Sales per life cycle. Production. Small-scale scenarios

Sales (£)		**%**
Biodiesel	9,803,759.8	78.7
G-Phase	1,129,832.6	9.1
Press-cake	1,528,348.4	12.3
Sales total (£)	**12,461,940.9**	**100.0**

Chapter 7: Cost-effectiveness analysis

Cost-effectiveness analysis (CEA) is aimed at determining the cost of achieving a specific physical target. It measures the benefits in physical units rather than in monetary terms. CEA is generally the preferred method when markets of prices do not adequately reflect all the costs and benefits of a proposal. It offers a priority ranking of programmes or activities on the basis of a comparative cost per unit of effectiveness, or comparative units of effectiveness per unit of currency. The cost-effectiveness of a proposal can be measured by calculating cost-effectiveness ratios. The smaller the ratio, the higher is the cost-effectiveness. A cost-effectiveness ratio can be determined for each alternative or option. Once this is done, each alternative can be ranked from the most cost-effective (lowest ratio) to the least cost-effective (highest ratio).

7.1 Costs of GHG avoided

Life cycle cost of GHG avoided calculated based on assumption that price of 1 tonne of of CO_2eq or CO_2eq avoided is equal to the price of 1 Certified Emissions Reduction (CER). This assumption is based on CERs definition in 3.CMP.1, Annex, paragraph 1(b) of the Kyoto Protocol as a "certified emission reduction" or "CER" is a unit representing one tonne of carbon dioxide-equivalent (CO_2eq) sequestered or abated, using global warming potentials defined by 2/CP.3".

CER price of 8.0-18.0 EUR/tCO_2eq (~6.3-14.2 GBP/tCO_2eq) following consultation with Mrs. Sharan Meili, Anandi of the CER India Pvt. Ltd. (pers. comm.: April 2008) were adopted for calculation of the price of GHG emissions avoided. There also social costs, transaction cost and other externalities which are not included into a market price of GHG. Also, a market sometimes fails to anticipate a true cost over time. The price of GHG is highly volatile, exposes to political risks and not necessarily set in terms of overall social costs. Until now, is it no agreement has been reached between scientists of the life cycle costs of global warming to society (e.g. raising of sea level, agricultural impacts, diseases, population migration, *etc*). This cost is also not reflected in GHG cost. Exchange rate considered as EUR/GBP = 0.788; GBP/EUR = 1.269 (April 2008. www.xe.com/ict). Current CER prices presented by European Climate Exchange fluctuate in a range of 12.0-23.0 EUR/tCO_2eq (~8.15-15.62 (~11.15-21.37) GBP/tCO_2eq - depending on EUR/GBP exchange rate from March 2007 to December 2008) (ECX Monthly Report: September 2008, December 2008).

Exchange rate considered as EUR/GBP = 0.851; GBP/EUR = 1.175 (20 March 2007), EUR/GBP = 0.929; GBP/EUR = 1.077 (20 December 2008. www.xe.com/ict).

The NPV1 represents "No Initial Investment (Loan)" scenarios, in which money for the biodiesel plant construction, oilseed procurement centres establishment and working capital are borrowed in bank. The NPV2 represents "Private Capital (Equity Issuance)" scenarios, in which new equity or "stocks" has been sold by a firm to investors to attract capital required for the biodiesel plant and related infrastructure construction and operation.

7.2 Agriculture. Large scale - IRR I, IRR II, and small-scale - RAIN I, RAIN II and RAIN III scenarios

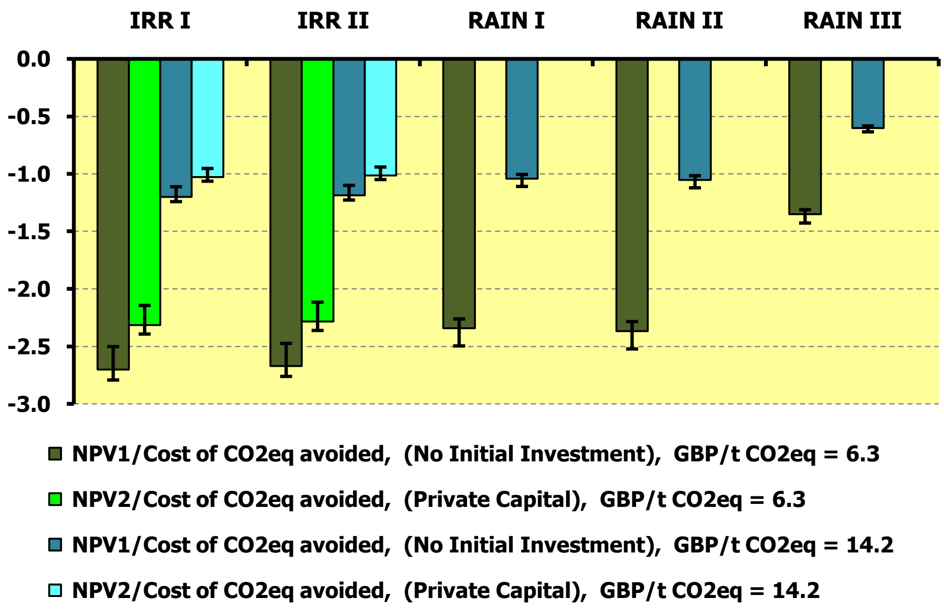
The results for the life cycle GHG avoided have a range 90.0 ktCO_2eq (Low), 87.0 ktCO_2eq (Best), 81.0 ktCO_2eq (High) for IRR I and IRR II scenarios, 93.0 ktCO_2eq (Low), 87.0 ktCO_2eq (Best), 84.0 ktCO_2eq (High) for RAIN I and RAIN II scenarios, and 108.0 ktCO_2eq (Low), 102.0 ktCO_2eq (Best), 99.0 ktCO_2eq (High) for RAIN III scenario. In both large scale and small-scale scenarios there is no difference in GHG avoided between scenarios where hulls and seed shells fruit utilized as compost (IRR I and RAIN I), or as combustibles (IRR II and RAIN II) respectively. Small-scale (RAIN III - chemical fertilizers are not applied) scenario has 15% better performance than RAIN I and RAIN II, as in this scenario emissions from the chemical fertilizers usage and electricity usage for irrigation are equal to zero.

The results for the NPV1 (No Initial Investment) to the life cycle GHG avoided ratios have a range -18.3 GBP/tCO_2eq (High), -17.0 GBP/tCO_2eq (Best), -16.5 GBP/tCO_2eq (Low) for IRR I scenario, -18.1 GBP/tCO_2eq (High), -16.8 GBP/tCO_2eq (Best), -16.3 GBP/tCO_2eq (Low) for IRR II scenario, -15.3 GBP/tCO_2eq (High), -14.8 GBP/tCO_2eq (Best), -13.8 GBP/tCO_2eq (Low) for RAIN I scenario, -15.5 GBP/tCO_2eq (High), -14.9 GBP/tCO_2eq (Best), -14.0 GBP/tCO_2eq (Low) for RAIN II scenario, and -8.8 GBP/tCO_2eq (High), -8.5 GBP/tCO_2eq (Best), -8.0 GBP/tCO_2eq (Low) for the RAIN III scenario.

The results for the NPV2 (Private Capital) to the life cycle GHG avoided ratios have a range -15.7 GBP/tCO_2eq (High), -14.6 GBP/tCO_2eq (Best), -14.1 GBP/tCO_2eq (Low) for IRR I scenario, -15.5 GBP/tCO_2eq (High), -14.4 GBP/tCO_2eq (Best), -13.9 GBP/tCO_2eq (Low) for IRR II scenario.

In terms of a) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 6.3; b) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 14.2; c) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 6.3; and d) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 14.2 ratios results are presented in Chart 7.1.

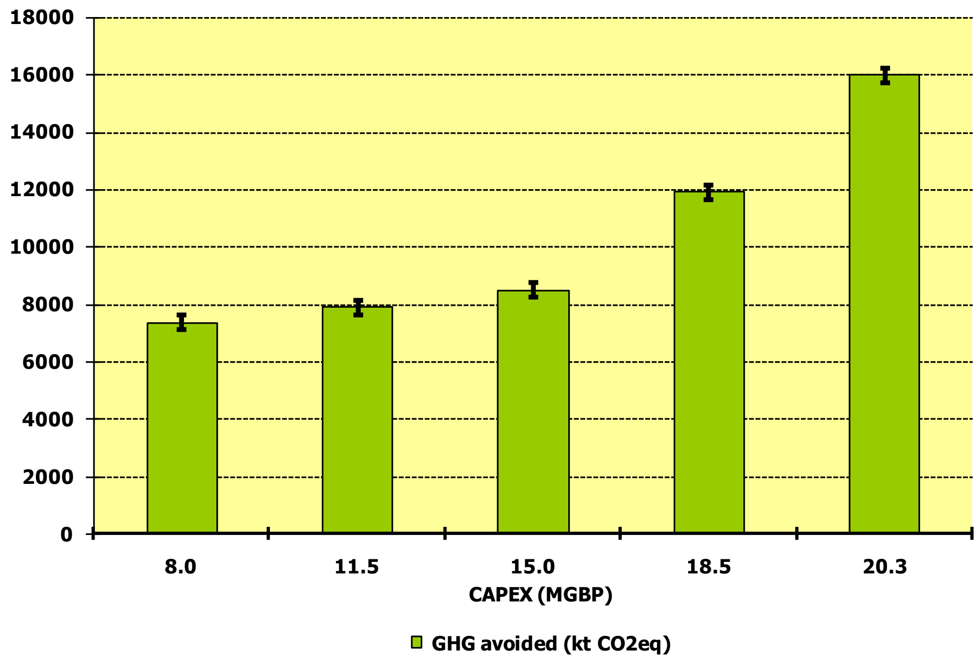
Chart 7.1: NPV/Life cycle cost of CO_2eq avoided. Agro scenarios



7.3 Production. Large scale. IRR I scenario

The results for the life cycle GHG avoided used are the same as calculated for the Life Cycle Assessment, scenario Irrigated I, and presented at the Chapter 5: "WTT results with applicable by-products credits". Significant growth of GHG avoided (2.17 ratio from 8.0 MGBP to 20.3 MGBP scenarios) correspondingly with the growth of CAPEX (2.54 ratio from 8.0 MGBP to 20.3 MGBP scenarios) (Chart 7.2) might be explained that both LCA and CBA reflect growth in CAPEX simultaneously with advancement of energy conversion technologies applied from: a) basic configuration (oil, coal or NG boiler and electricity from grid), through b) optimized fossil-fuelled plant (CHP) (e.g. oil, coal or NG boiler with BPSTG), c) NG gas turbine or NG gas turbine with BPSTG combined with unfired or co-fired HRSG, and, finally, to d) CHP plant fuelled by biomass (e.g. Integrated biomass gasifier with gas turbine) - for large scale (Irrigated) scenarios, as described in details in Chapter 3: "Well-to-Tank (WTT) Life Cycle Assessment for production of biodiesel from *Jatropha curcas* in Southern India".

Chart 7.2: GHG avoided (ktCO$_2$eq). IRR I scenarios



The results for NPV to GHG avoided ratio (MGBP/tCO$_2$eq.) is summarized in Table 7.1:

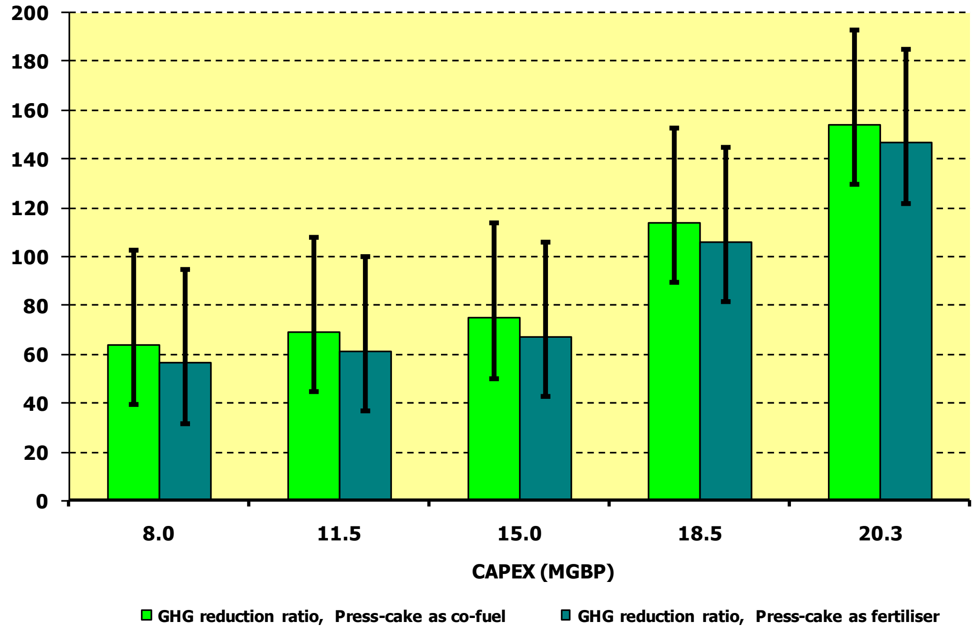
Table 7.1: NPV/GHG avoided, (MGBP/tCO$_2$eq.). IRR I_Production scenarios

CAPEX (MGBP)	8.0	11.5	15.0	18.5	20.3
NPV1/GHG avoided, (No Initial Investment), High	3.213	2.508	1.788	0.586	0.252
NPV1/GHG avoided, (No Initial Investment), Best	3.102	2.427	1.734	0.574	0.248
NPV1/GHG avoided, (No Initial Investment), Low	2.999	2.352	1.683	0.562	0.244
NPV2/GHG avoided, (Private Capital), High	3.023	2.291	1.584	0.755	0.420
NPV2/GHG avoided, (Private Capital), Best	2.919	2.218	1.536	0.739	0.413
NPV2/GHG avoided, (Private Capital), Low	2.821	2.148	1.491	0.723	0.407

For CAPEX 8.0 MGBP, 15.0 MGBP scenarios the NPV/GHG avoided ratio (Best) is bigger in No Initial Investment (Loan) scenario than in Private Capital (Equities) scenario by 5.92% and 11.41% correspondingly. However, for CAPEX 11.5 MGBP, 18.5 MGBP and 20.3 MGBP scenarios the NPV/GHG avoided ratio (Best) is bigger in Private Capital (Equities) scenario than in No Initial Investment (Loan) scenario by 4.76%, 22.33% and 39.98% correspondingly.

GHG reduction ratio (%) calculated using Formula (5.1), the same as in Chapter 5: "WTT results with applicable by-products credits", subchapter 5.3: "*Jatropha* press-cake use as fertilizer (green manure)" and subchapter 5.4: "*Jatropha* press-cake use as co-fuel for power plant".

Chart 7.3: GHG reduction ratio. IRR I scenarios



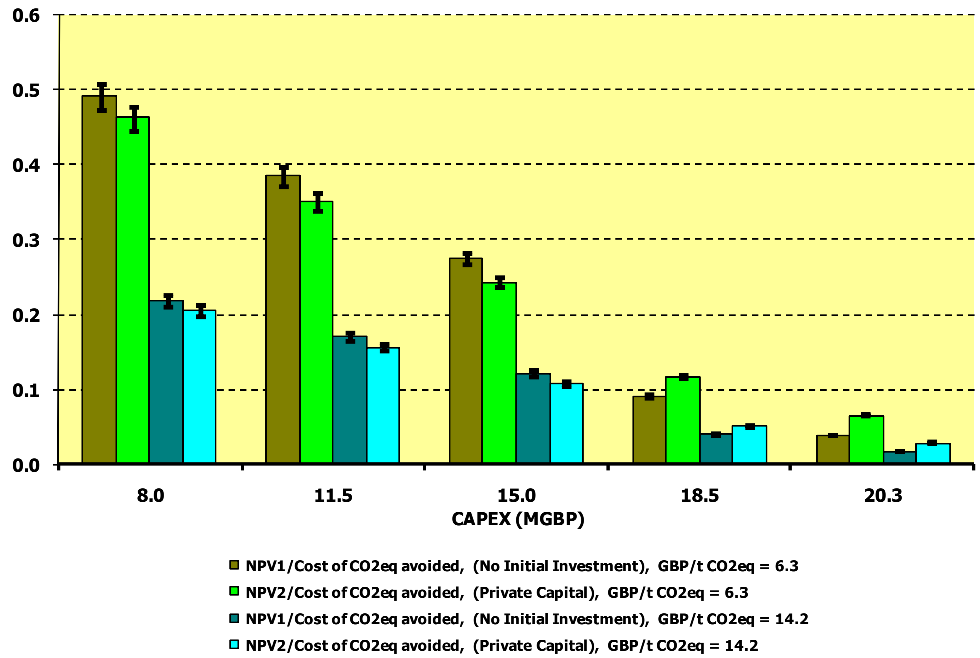
For all IRR I scenarios 8.0 MGBP, 11.5 MGBP. 15.0 MGBP, 18.5 MGBP and 20.3 MGBP - High, Best and Low, in case of press-cake used as co-fuel scenarios the GHG reduction ratio is bigger than in press-cake used as fertilizer scenarios as presented in Table 7.2.

Table 7.2: GHG reduction ratio. Scenario IRR I. Press-cake used as co-fuel/ Scenario IRR I. Press-cake used as fertilizer

CAPEX (MGBP)	**8.0**	**11.5**	**15.0**	**18.5**	**20.3**
High	30.99%	25.66%	21.55%	10.33%	6.72%
Best	12.12%	11.20%	10.35%	6.80%	5.02%
Low	8.78%	8.29%	7.81%	5.60%	4.34%

In terms of a) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 6.3; b) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 14.2; c) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 6.3; and d) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 14.2 ratios results are presented in Chart 7.4.

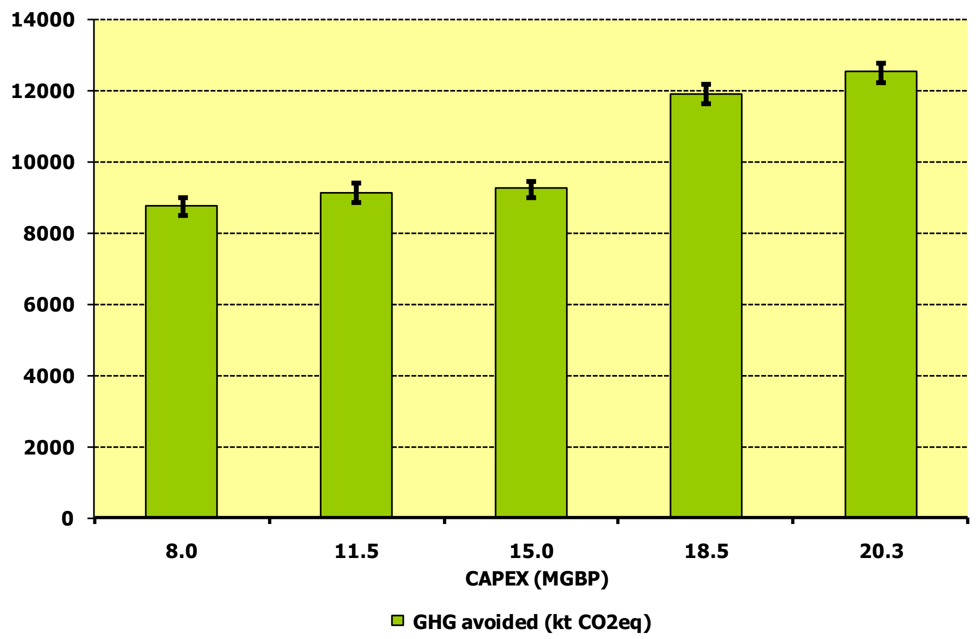
Chart 7.4: NPV/Life cycle cost of CO_2eq avoided. IRR I scenarios



7.4 Production. Large scale. IRR II scenario

The results for the life cycle GHG avoided used are the same as calculated in Life Cycle Assessment Model, scenario Irrigated II, and presented at the Chapter 5: "WTT results with applicable by-products credits". Growth of GHG avoided (1.43 ratio from 8.0 MGBP to 20.3 MGBP scenarios) correspondingly with the growth of CAPEX (2.54 ratio from 8.0 MGBP to 20.3 MGBP scenarios) (Chart 7.5) is less than in Irrigated I scenario by 51.7% due to less GHG savings in two stage - fat splitting (60 bar, 260^{o}C) and esterification (10 bar, 240^{o}C) biodiesel production process compare to one stage Henkel transesterification (90 bar, 240^{o}C) biodiesel production technology.

Chart 7.5: GHG avoided (ktCO_2eq). IRR II scenarios



The results for NPV to GHG avoided ratio (MGBP/tCO_2eq.) is summarized in Table 7.3:

Table 7.3: NPV/GHG avoided (MGBP/tCO_2eq.). IRR II_Production scenarios

CAPEX (MGBP)	8.0	11.5	15.0	18.5	20.3
NPV1/GHG avoided, (No Initial Investment), High	2.691	2.158	1.621	0.586	0.324
NPV1/GHG avoided, (No Initial Investment), Best	2.612	2.098	1.587	0.573	0.317
NPV1/GHG avoided, (No Initial Investment), Low	2.538	2.041	1.544	0.561	0.311
NPV2/GHG avoided, (Private Capital), High	2.532	1.972	1.436	0.755	0.539
NPV2/GHG avoided, (Private Capital), Best	2.457	1.917	1.406	0.738	0.528
NPV2/GHG avoided, (Private Capital), Low	2.388	1.865	1.368	0.723	0.518

For CAPEX 8.0 MGBP and 15.0 MGBP scenarios the NPV/GHG avoided ratio (Best) is bigger in the No Initial Investment (Loan) than in Private Capital (Equities) scenario by 5.92% and 11.41% correspondingly. However, for CAPEX 11.5 MGBP, 18.5 MGBP scenario and 20.3 MGBP scenarios the NPV/GHG avoided ratio (Best) is lesser in the No Initial Investment (Loan) than in Private Capital (Equities) scenario by 4.77%, 22.33%, and 39.99% correspondingly.

For all IRR II scenarios (8.0 MGBP, 11.5 MGBP. 15.0 MGBP, 18.5 MGBP and 20.3 MGBP - High, Best and Low) in case of press-cake used as co-fuel scenarios the GHG reduction ratio is bigger than in press-cake used as fertilizer scenarios as presented in Table 7.4.

Table 7.4: GHG reduction ratio. Scenario IRR II. Press-cake used as co-fuel/ Scenario IRR II. Press-cake used as fertilizer

CAPEX (MGBP)	**8.0**	**11.5**	**15.0**	**18.5**	**20.3**
High	20.05%	19.09%	18.50%	14.80%	14.99%
Best	9.98%	9.74%	9.58%	8.50%	8.55%
Low	7.60%	7.46%	7.37%	6.70%	6.47%

For IRR II in scenarios 8.0 MGBP, 11.5 MGBP and 15.0 MGBP - High, Best and Low, in both cases - press-cake used as co-fuel and press-cake used as fertilizer, GHG reduction ratio is bigger than in corresponding cases in IRR I scenarios as presented in Tables 7.5 and 7.6. However, in IRR II scenarios 18.5 MGBP and 20.3 MGBP - High, Best and Low, in both cases - press-cake used as co-fuel and press-cake used as fertilizer, GHG reduction ratio is lesser than in corresponding IRR I scenarios as presented in Tables 7.5 and 7.6.

Table 7.5: GHG reduction ratio. Press-cake used as co-fuel. Scenario IRR II/Scenario IRR I

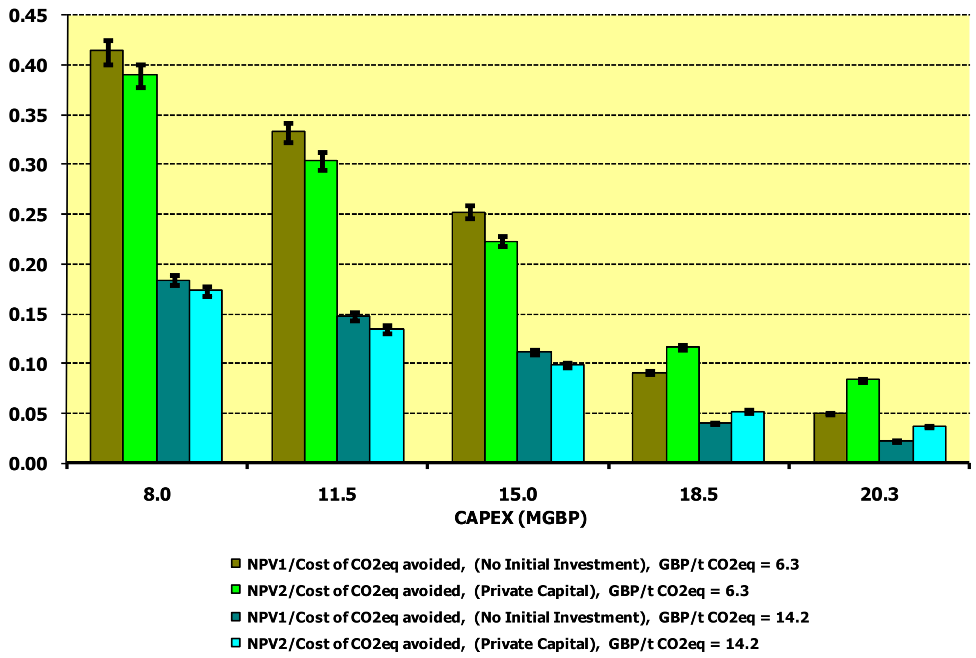
CAPEX (MGBP)	**8.0**	**11.5**	**15.0**	**18.5**	**20.3**
High	35.29%	25.6%	14.21%	-30.23%	-55.17%
Best	17.58%	13.06%	7.27%	-19.90%	-41.23%
Low	13.38%	10.00%	5.66%	-16.40%	-35.62%

Table 7.6: GHG reduction ratio. Press-cake used as fertilizer. Scenario IRR II/Scenario IRR I

CAPEX (MGBP)	**8.0**	**11.5**	**15.0**	**18.5**	**20.3**
High	44.14%	31.63%	17.43%	-33.72%	-59.15%
Best	19.53%	14.47%	8.15%	-21.35%	-43.42%
Low	14.48%	10.81%	6.11%	-17.37%	-37.24%

In terms of a) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 6.3; b) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 14.2; c) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 6.3; and d) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 14.2 ratios results are presented in Chart 7.6.

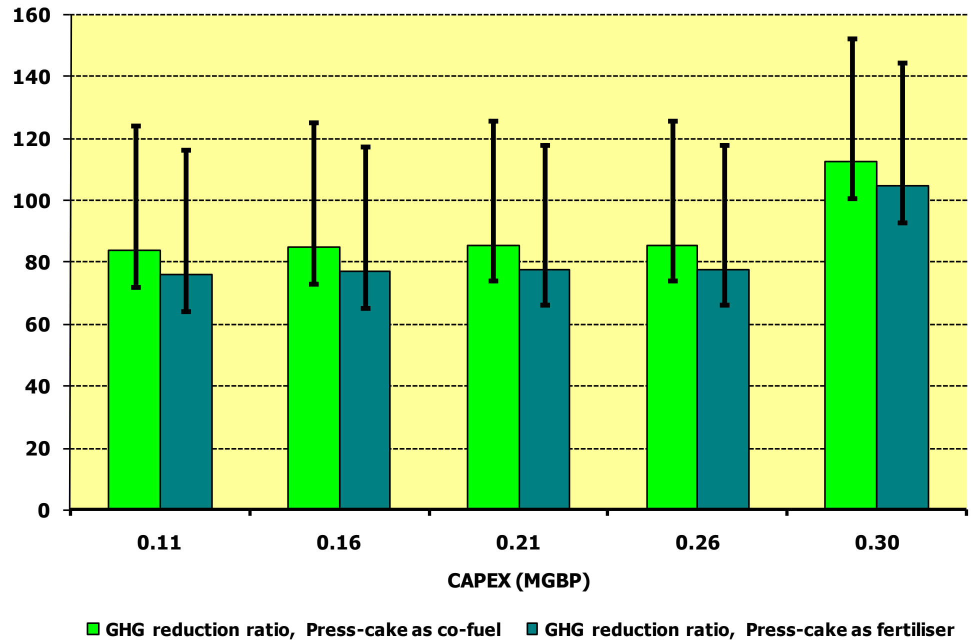
Chart 7.6: NPV/Life cycle cost of CO_2eq avoided. IRR II scenarios



7.5 Production. Small-scale. RAIN I scenario

The results for the life cycle GHG avoided used are the same as calculated for the Life Cycle Assessment, scenarios RAIN I, and presented at the Chapter 5: "WTT results with applicable by-products credits". Growth of GHG avoided (1.22 ratio from 0.11 MGBP to 0.30 MGBP scenarios) correspondingly with the growth of CAPEX (2.73 ratio from 0.11 MGBP to 0.30 MGBP scenarios) might be explained that both LCA and CBA reflect growth in CAPEX simultaneously with advancement of energy conversion technologies applied from: a) basic configuration to b) optimized fossil fueled plant (CHP) (e.g. NG CHP Microturbine), and c) CHP fuelled by biomass (e.g. anaerobic digester and CHP externally fired micro gas turbine with HUB, and Integtated biomass gasifier and Gas engine genset with HUB) - for small-scale (Rainfed) scenarios, as described in details in Chapter 3: "Well-to-Tank (WTT) Life Cycle Assessment for production of biodiesel from *Jatropha curcas* in Southern India".

Chart 7.7: GHG reduction ratio. RAIN I scenarios



For CAPEX 0.11 MGBP, 0.16 MGBP, 0.21 MGBP and 0.26 MGBP scenarios the NPV/GHG avoided ratio (Best) is bigger in Private Capital (Equities) scenario than in No Initial Investment (Loan) scenario by 5.5%, 13.93%, 31.89% and 35.49% correspondingly. For 0.30 MGBP scenario the No Initial Investment (Loan) scenario has a negative NPV/GHG avoided ratio as NPV in this scenario is negative.

In terms of GHG reduction ratio, for all RAIN I scenarios (0.11 MGBP, 0.16 MGBP. 0.21 MGBP, 0.26 MGBP and 0.30 MGBP - High, Best and Low) in case of press-cake used as co-fuel scenarios, the GHG reduction ratio is bigger than in press-cake used as fertilizer scenarios as presented in Table 7.7.

Table 7.7: GHG reduction ratio. Scenario RAIN I. Press-cake used as co-fuel/ Scenario RAIN I. Press-cake used as fertilizer

CAPEX (MGBP)	**0.11**	**0.16**	**0.21**	**0.26**	**0.30**
High	18.01%	17.60%	17.33%	17.35%	10.78%
Best	9.33%	9.21%	9.14%	9.15%	6.95%
Low	8.20%	8.12%	8.06%	8.06%	6.31%

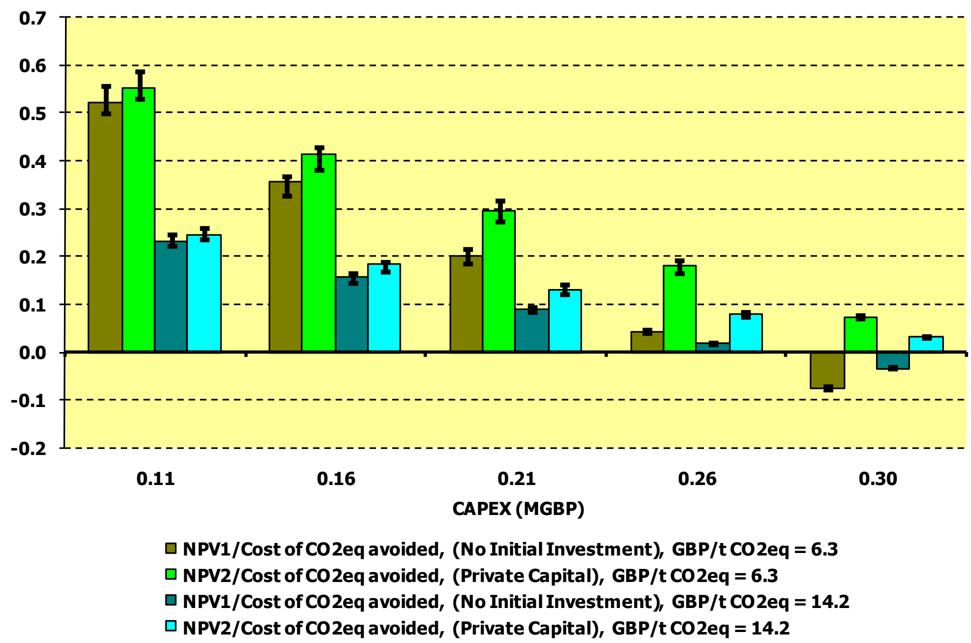
The results for NPV to GHG avoided ratio (MGBP/tCO_2eq.) is summarized in Table 7.8:

Table 7.8: NPV/GHG avoided, (MGBP/tCO_2eq.). RAIN I_Production scenarios

CAPEX (MGBP)	0.11	0.16	0.21	0.26	0.30
NPV1/GHG avoided, (No Initial Investment), High	0.00341	0.00242	0.00137	0.00029	-0.000487
NPV1/GHG avoided, (No Initial Investment), Best	0.00328	0.00225	0.00128	0.00027	-0.000472
NPV1/GHG avoided, (No Initial Investment), Low	0.00305	0.00217	0.00119	0.00025	-0.000445
NPV2/GHG avoided, (Private Capital), High	0.00361	0.00281	0.00202	0.00122	0.00048
NPV2/GHG avoided, (Private Capital), Best	0.00347	0.00261	0.00187	0.00114	0.00046
NPV2/GHG avoided, (Private Capital), Low	0.00323	0.00252	0.00175	0.00106	0.00044

In terms of a) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 6.3; b) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 14.2; c) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 6.3; and d) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 14.2 ratios results are presented in Chart 7.8.

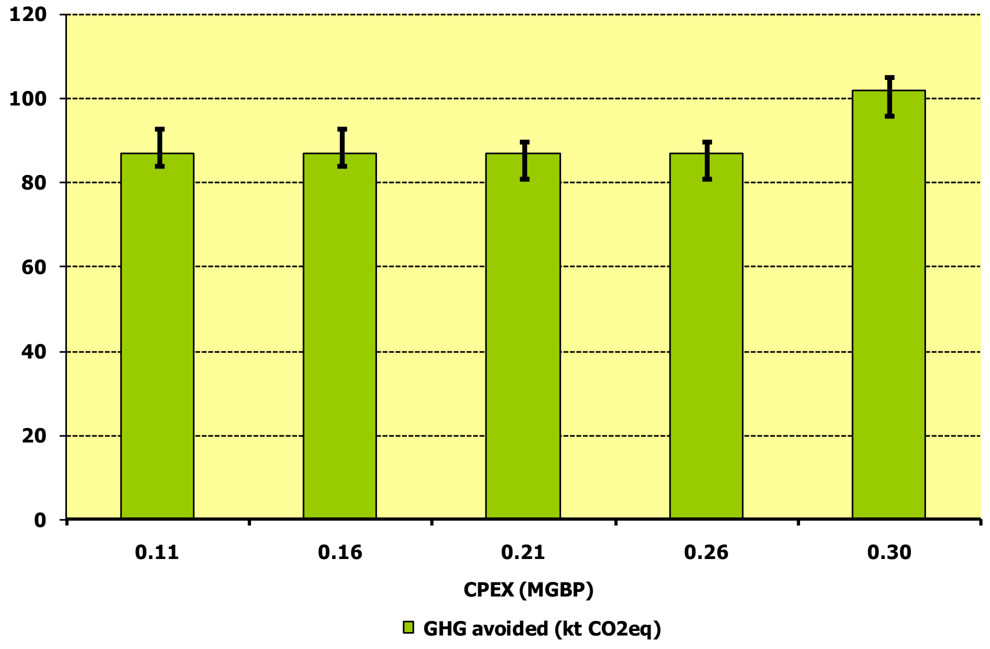
Chart 7.8: NPV/Life cycle cost of CO_2eq avoided. RAIN I scenarios



7.6 Production. Small-scale. RAIN II scenario

The results for the life cycle GHG avoided used are the same as calculated for the Life Cycle Assessment, scenarios RAIN II, and presented at the Chapter 5: "WTT results with applicable by-products credits". Small growth of GHG avoided (1.17 ratio from 0.11 MGBP to 0.30 MGBP scenarios) correspondingly with the growth of CAPEX (2.73 ratio from 0.11 MGBP to 0.30 MGBP scenarios) (Chart 7.9) is less than in RAIN I scenario by only 4.3% due to insignificant influence of emissions from chemical fertilizers to total GHG emissions and, therefore GHG savings.

Chart 7.9: GHG avoided (ktCO_2eq). RAIN II scenarios



For CAPEX 0.11 MGBP, 0.16 MGBP, 0.21 MGBP and 0.26 MGBP scenarios the NPV/GHG avoided ratio (Best) is bigger in Private Capital (Equities) scenario than in No Initial Investment (Loan) scenario by 5.5%, 13.93%, 31.89% and 35.49% correspondingly. For 0.30 MGBP scenario the No Initial Investment (Loan) scenario has a negative NPV/GHG avoided ratio as NPV in this scenario is negative.

In terms of GHG reduction ratio, for all RAIN II scenarios (0.11 MGBP, 0.16 MGBP. 0.21 MGBP, 0.26 MGBP and 0.30 MGBP - High, Best and Low) in case of press-cake used as co-fuel scenarios, the GHG reduction ratio is bigger than in corresponding press-cake used as fertilizer scenarios as presented in Table 7.9.

Chart 7.10: GHG reduction ratio. RAIN II scenarios

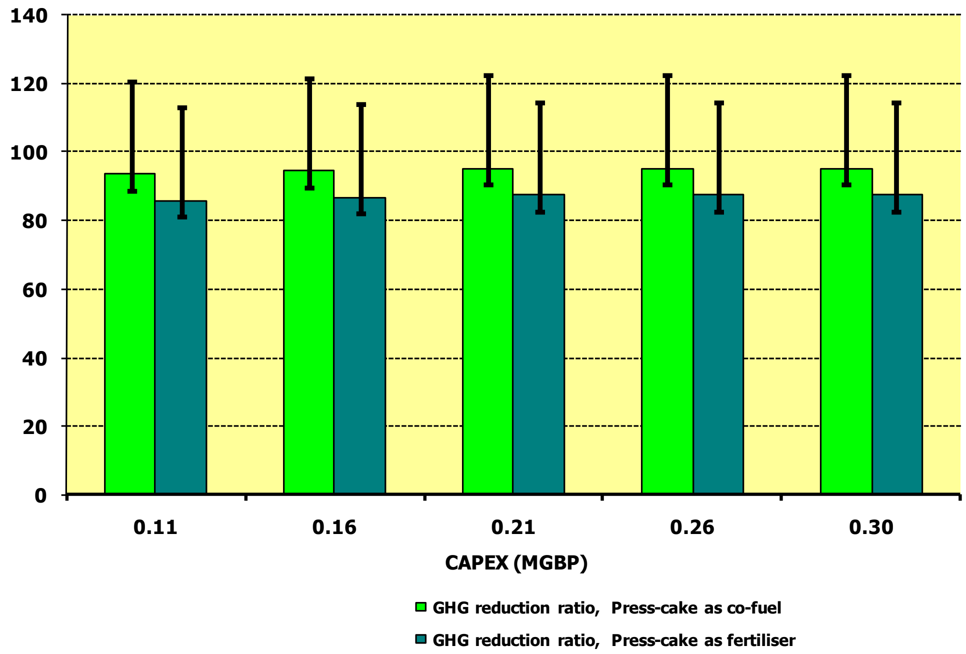


Table 7.9: GHG reduction ratio. Scenario RAIN II. Press-cake used as co-fuel/ Scenario RAIN II. Press-cake used as fertilizer

CAPEX (MGBP)	**0.11**	**0.16**	**0.21**	**0.26**	**0.30**
High	11.79%	11.61%	11.50%	11.51%	11.51%
Best	8.36%	8.27%	8.21%	8.21%	8.21%
Low	7.96%	7.88%	7.82%	7.83%	7.83%

For RAIN I scenarios 0.11 MGBP, 0.16 MGBP. 0.21 MGBP and 0.26 - High, Best and Low, in both cases - press-cake used as co-fuel and press-cake used as fertilizer, GHG reduction ratio is bigger than in corresponding cases in RAIN II scenarios as presented in Tables 7.10 and 7.11. However, in RAIN I scenario 0.30 MGBP - High, Best and Low, in both cases - press-cake used as co-fuel and press-cake used as fertilizer, GHG reduction ratio is lesser than in corresponding RAIN II scenarios as presented in Tables 7.10 and 7.11.

Table 7.10: GHG reduction ratio. Press-cake used as co-fuel. Scenario RAIN II/Scenario RAIN I

CAPEX (MGBP)	**0.11**	**0.16**	**0.21**	**0.26**	**0.30**
High	34.52%	34.00%	33.65%	33.69%	-6.28%
Best	10.40%	10.29%	10.21%	10.22%	-15.34%
Low	2.97%	2.94%	2.92%	2.93%	-19.41%

Table 7.11: GHG reduction ratio. Press-cake used as fertilizer. Scenario RAIN II/Scenario RAIN I

CAPEX (MGBP)	**0.11**	**0.16**	**0.21**	**0.26**	**0.30**
High	39.14%	38.47%	38.03%	38.07%	-7.03%
Best	11.35%	11.21%	11.12%	11.13%	-16.49%
Low	3.23%	3.20%	3.17%	3.17%	-20.72%

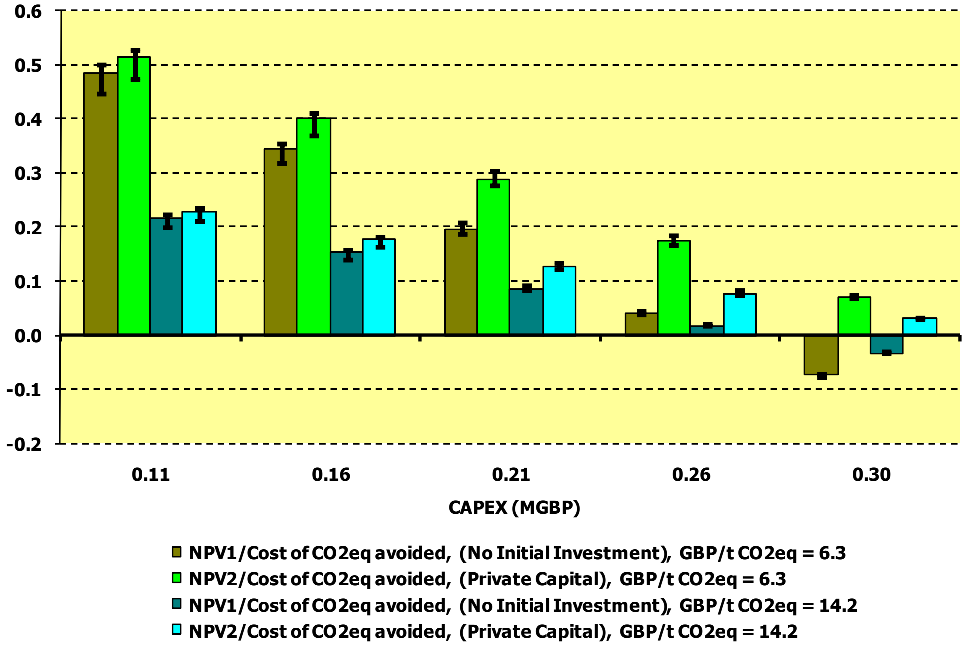
The results for NPV to GHG avoided ratio (MGBP/tCO_2eq.) is summarized in Table 7.12:

Table 7.12: NPV/GHG avoided, (MGBP/tCO_2eq.). RAIN II_Production scenarios

CAPEX (MGBP)	**0.11**	**0.16**	**0.21**	**0.26**	**0.30**
NPV1/GHG avoided, (No Initial Investment), High	0.00328	0.00233	0.00128	0.00027	-0.000472
NPV1/GHG avoided, (No Initial Investment), Best	0.00305	0.00217	0.00123	0.00026	-0.000458
NPV1/GHG avoided, (No Initial Investment), Low	0.00295	0.00210	0.00115	0.00024	-0.000433
NPV2/GHG avoided, (Private Capital), High	0.00347	0.00271	0.00187	0.00114	0.00046
NPV2/GHG avoided, (Private Capital), Best	0.00323	0.00252	0.00181	0.00110	0.00045
NPV2/GHG avoided, (Private Capital), Low	0.00313	0.00244	0.00169	0.00103	0.00043

In terms of a) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 6.3; b) NPV1/Cost of CO_2eq avoided, No Initial Investment, GBP/tCO_2eq = 14.2; c) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 6.3; and d) NPV2/Cost of CO_2eq avoided, Private Capital, GBP/tCO_2eq = 14.2 ratios results are presented in Chart 7.11.

Chart 7.11: NPV/Life cycle cost of CO_2eq avoided. RAIN II scenarios



Chapter 8: Sensitivity analysis

Sensitivity analysis is an efficient tool that can semi-quantitatively demonstrate the uncertainties in the outputs from the Techno-Economic Model. It measures the impact on the project outcomes of changing one or more key input values about which there is uncertainty. Thus, uncertainties in the TEM and CBA for *Jatropha curcas* oilseeds cultivation and biodiesel production could result from the uncertainties associated with the *Jatropha* oilseed yields, price of oilseeds, price of *Jatropha* oil and crude glycerine, annual biodiesel production, labour cost coefficient, discount rate, interest charges on CAPEX and working capital, and subsidies on CAPEX and working capital, *etc*.

Piegorsch and Bailer (2005) distinguish between uncertainty and variability. They define *variability* as "a description of the natural, underlying variation contained in the environmental process or phenomenon". In this case, the source of variation is intrinsic to the process and, therefore, cannot be decreased or changed by any additional knowledge the researcher may attain. Oppose to variability, authors identify *uncertainty* as "those sources of variation in the process that can be affected by investigator's knowledge base".

Uncertainties can be broadly grouped under two major classes. The first class of uncertainty is model-associated, which includes the model formulation itself and coefficients-parameters involved in the model. This uncertainty is the result of the abstraction (oversimplification) of natural processes. The second class of uncertainty is associated with the state of input data, which itself can be classified in two main types. Type I (variability, aleatory) uncertainty arises as a result of natural heterogeneity or stochasticity which cannot be reduced. Type II (epistemic) uncertainty is due to partial ignorance that results from measurement and systematic errors or subjective uncertainty (incomplete knowledge and/or lack of data) dominates the decision analysis of the problem in hand. Contrary to aleatory uncertainty, the epistemic uncertainty can be reduced by collecting more information and data. It pays an important role when the evidence base is small, i.e. sparse data situation (Tesfamariam, *et. al.*: 2006).

Sources of uncertainty include:

- ❒ limited scientific knowledge of the environmental mechanism or process under investigation;
- ❒ lack of sufficient data to provide the desired sensitivity to detect environmental effect (Piegorsch & Bailer: 2005), e.g. small sample size (Cullen & Frey: 1999), or
- ❒ to properly differentiate between competing models that represent the phenomenon, trend or observable fact,

- inadequate background information on the values of a model input parameters (Piegorsch & Bailer: 2005), and
- different views among experts about the interpretation of data or the theoretical bases underlying models (Cullen & Frey: 1999).

Professor Tauer (2000) points that the existence of uncertainty does not mean that a firm would never make an investment or that the uncertainty would have to first be resolved before an investment will be made. The existence of uncertainty only means that the expected net returns would have to be greater than without uncertainty before the investment would be made. These results apply without any appeal to risk aversion for the decision maker.

Sensitivity analysis involves systematically examining the influence of uncertainties in the variables and assumptions employed in an evaluation on the estimated results. Briggs (1995), Briggs & Gray (1999) and Limwattananon (2008) classified techniques of uncertainty management due to parameters in the economic evaluation model into three types.

- The first approach is called a deterministic sensitivity analysis (DSA). This DSA is conducted by varying the value of each parameter, given that the remaining parameters are unvarying. One-way sensitivity analysis, which is the most common type of DSA, systematically examines the impact of each variable in the study by varying it across a plausible range of values while holding all other variables in the analysis constant at their baseline or "best" value.

- The second approach is an extreme scenario analysis, in which several important parameters are set under two extreme scenarios (the best case vs. the worst case) for the intervention of interest. Extreme scenario analysis involves setting each variable to simultaneously take the most optimistic (pessimistic) value from the point of view of the intervention under evaluation in order to generate a best (worst) case scenario.

  Briggs and Gray (1999) draw attention that in real life the components of an evaluation do not vary in isolation nor are they perfectly correlated; therefore, it is likely that one-way sensitivity analysis will underestimate, and extreme scenario analysis overestimate the uncertainty associated with the results of economic evaluation.

- The last approach is a probabilistic sensitivity analysis (PSA) which assumes that a variation in each of the parameters follows a defined pattern of data distribution. It based on a large number of Monte Carlo simulations, examines the effect on the results of an evaluation when the underlying variables are allowed to vary simultaneously across a plausible range according to predefined distributions. These probabilistic analyses are likely to produce results that lie between the ranges implied by one way sensitivity analysis and extreme scenario analysis, and therefore may produce a more realistic estimate of uncertainty (Briggs & Gray: 1999; Limwattananon: 2008).

8.1 Probabilistic sensitivity analysis

The introduction of such a novel bioenergy crop as *Jatropha curcas* and adaptation of biodiesel production technologies to this feedstock involves a lot of uncertainties. Therefore, it is of great importance to determine the most influencing parameters by performing a thorough sensitivity analysis. Such an analysis also provides a good indintification of the chance to have a positive business case. Finally, it will make possible to assess the capability to foresee on fluctuating market circumstances. De Bruin, *et. al*. (2008) highlights several uncertainties which can be distinguished, i.e. unknown probabilities, uncertainty about the discount rate, uncertain costs and benefits (known unknowns and unknown unknowns). Uncertainty implies that (future) costs and benefits are not certain, and probability distribution is not known. Some uncertainties might be resolved through furtier research (Ibid.).

The uncertainty analysis was performed to understand and quantify contributions of the input variables to statistical variations in the output variable when performing the Techno-Economic Analysis. Even though, this thesis is evaluated an existing program, there is lack of reliable data available, and hence there is no much opportunity to narrow uncertainties and risk (i.e. probabilistic outcomes) in the evaluation of TBOS/*Jatropha* cultivation and biodiesel production programs.

Following Saltelli, *et. al*. (2000), a *model uncertainty audit* has been performed, in which the total variance in NPV/GHG avoided ratio has been partitioned into two components, between scenarios and within scenarios, the second of which represents the component of uncertainty arising from lack of perfect knowledge of the scenario-specific parameters. Sensitivity analysis was conducted to demonstrate effect of variability in key modeling parmeters. This type of analysis provides an indication of the impacts of various assumptions and calibration parameters.

Probabilistic (stochastic) sensitivity analysis methodology was chosen to assess the outcome of variations in any of the input data parameters (Cullen & Frey: 1999, Piegorsch & Bailer: 2005, Tesfamariam, *et. al*.: 2006). This type of analysis is used to identify the important parameters that can be de-emphasised or even eliminated altogether without having a major impact on responses predicted by the model. Cullen and Frey (1999) describe several methods to conduct sensitivity analysis, each with advantages and disadvantages. Commonly carried out sensitivity analysis is using random sampling (Monte Carlo type simulations) where the probability distributions for input data can be either assumed or derived from observations (Ang & Tang: 1984 cited by Cullen & Frey: 1999). Statistical simulation (*stochastic simulation, Monte Carlo simulation*), as a "process of replicating the real world based upon a set of assumptions and conceived models of reality", is a conceptualization of a trial-and-error procedure in terms of probability (Piegorsch & Bailer: 2005, Saltelli, *et. al*.: 2000).

Thereafter, the rank correlation method was applied to the results of Monte Carlo simulations to identify input data parameters that dominate the output. The rank correlation method involves the determination of correlation coefficients, which measures the strength of the linear relationship between two variables. In statistics, procedures can be either parametric, which in variably requires that variables have normal distributions, or nonparametric, where assumptions about the distribution of variables are not essential (Tesfamariam, *et. al*.: 2006).

In an industry as agriculture, the prices of commodities are always uncertain (Tauer: 2000). Hence, a sensitivity analysis was performed in which the respective parameters were let to fluctuate around initial value at the range shown in Tables 8.1, 8.3, 8.5 and 8.7 according to the normal distribution. The sensitivity analyses was completed based on the Pearson product moment correlation (parametric) method were applied in the context of input data generated by a Monte Carlo type random sampling using the Visual Basic Code for Stochastic Sensitivity Analysis (Appendix VII). For each scenario (IRR_Agro, RAIN_Agro, IRR_Production and RAIN_Production) and associated sub-scenarios, 2000 trials/iterations for each varying parameter were performed to get a realistic view of the uncertain outcome. The results are compared to each other for each scenario separately on the ground of the life cycle NPV and NPV/GHG avoided ratio.

8.1.1 Selected sensitivities

8.1.1.1 Jatropha oilseed cultivation

Tables 8.1 and 8.2 (IRR_Agro scenarios), and Tables 8.3 and 8.4 (RAIN_Agro scenarios) indicates the sensitivities included in this analysis. All other assumptions remain the same as in the original study, here called the base case. The *Jatropha* oilseed yields, price of oilseeds, labour cost coefficient, discount rate, interest charges on CAPEX and working capital, and subsidies on CAPEX and working capital, were varied to both a higher and lower value in both large scale (Irrigated) and small-scale (Rainfed) scenarios for Agriculture. The parameters related with the market forecast are definitely the most uncertain ones in the business model.

8.1.1.1.1 Irrigated (industrial scale) *Jatropha* oilseeds cultivation

Table 8.1: Sensitivity analysis parameters. Agriculture. Irrigated scenario

Parameter	Unit	Initial value	Low	High
Jatropha oilseed yields	t/ha/a	5.2	2.5	7.5
Price of oilseeds	Rs./t	5,000	4,000	30,000
Labour cost coefficient		1	1	12
Discount rate	%	15	5	20
Interest charge (CAPEX)	%	15	5	20
Interest charge (working capital charge)	%	15	5	20
Subsidies (CAPEX)	%	0	0	75
Subsidies (working capital charge)	%	0	0	75

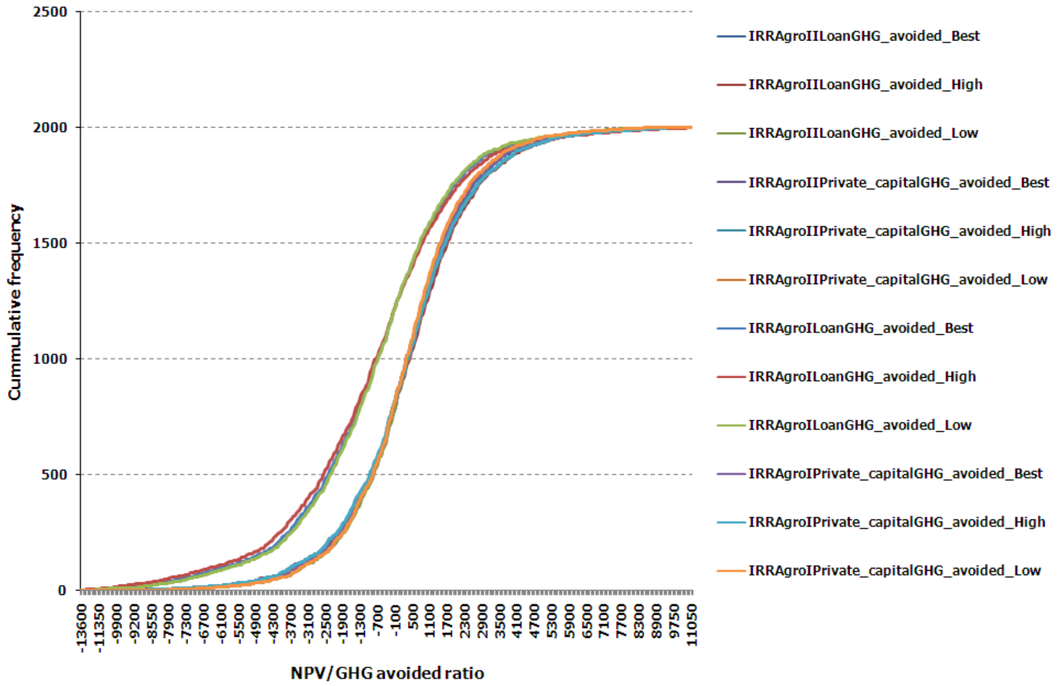
Table 8.2: Sensitivity analysis parameters. Agriculture. Irrigated scenario. Initial values (per life cycle)

Parameter	Unit	IRR_Agro I Loan	IRR_Agro I Private capital	IRR_Agro II Loan	IRR_Agro II Private capital
NPV	GBP	(1,481.67)	(1,269.57)	(1,464.96)	(1,252.86)
Jatropha oilseed yields	kg/ha/a	5,000	5,000	5,000	5,000
GHG avoided. High	$ktCO_2eq$	2.7	2.7	2.7	2.7
GHG avoided. Best	$ktCO_2eq$	2.9	2.9	2.9	2.9
GHG avoided. Low	$ktCO_2eq$	3.0	3.0	3.0	3.0

Notes:
a) Scenario IRR I_Agro: Irrigated large scale *Jatropha* plantation. 1,111 trees/ha. Organic, chemical fertilizers and agro-chemicals applied. Fruit hulls and seed shells used as compost;
b) Scenario IRR II_Agro: Irrigated large scale *Jatropha* plantation. 1,111 trees/ha. Organic, chemical fertilizers and agro-chemicals applied. Fruit hulls and seed shells used as combustibles

The results of probabilistic sensitivity analysis can be found at the Charts 8.1 and 8.2, and Table 8.9 for all agricultural scenarios.

Chart 8.1: Sensitivity analysis results. IRR_Agro scenario



8.1.1.1.2 Rainfed (small-scale) *Jatropha* oilseeds cultivation

Table 8.3: Sensitivity analysis parameters. Agriculture. Rainfed scenario

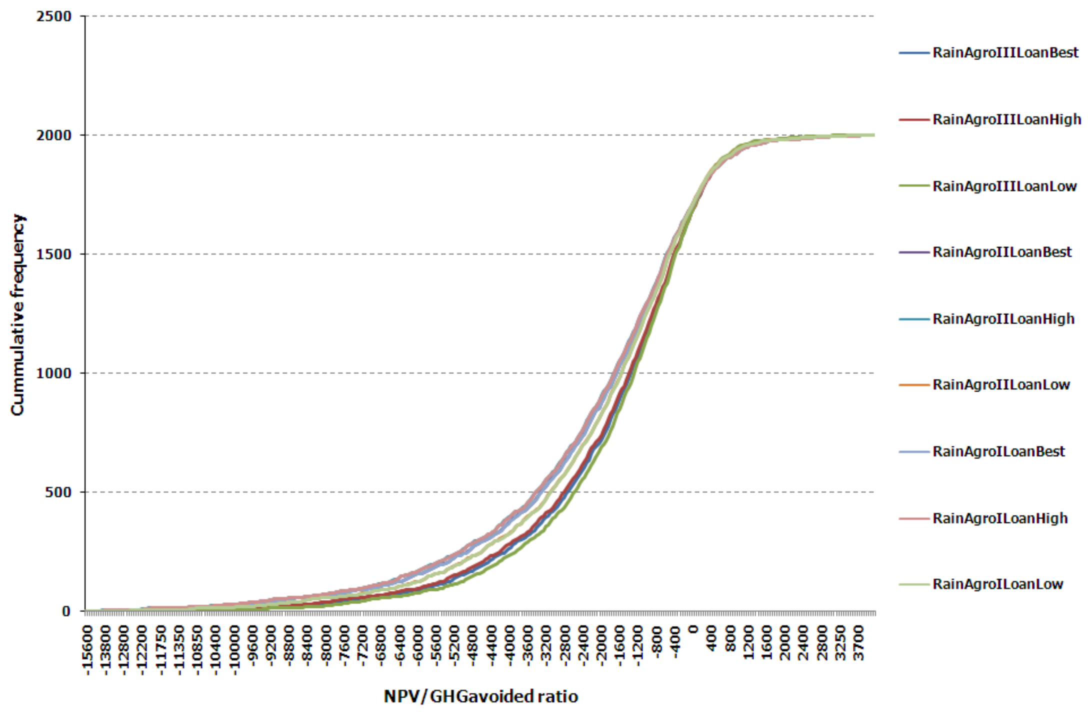
Parameter	Unit	Initial value	Low	High
Jatropha oilseed yields	t/ha/a	3.45	0.5	4.0
Price of oilseeds	Rs./t	5,000	4,000	30,000
Labour cost coefficient		1	1	12
Discount rate	%	15	5	20
Interest charge (CAPEX)	%	15	5	20
Interest charge (working capital charge)	%	15	5	20
Subsidies (CAPEX)	%	0	0	75
Subsidies (working capital charge)	%	0	0	75

Table 8.4: Sensitivity Analysis Parameters. Agriculture. Rainfed scenario. Initial values (per life cycle)

Parameter	Unit	Rain_Agro I	Rain_Agro II	Rain_Agro III
NPV	GBP	(1,271.82)	(1,285.32)	(855.41)
Jatropha oilseed yields	kg/ha/a	3,450	3,450	3,450
GHG avoided. High	ktCO_2eq	2.8	2.8	3.3
GHG avoided. Best	ktCO_2eq	2.9	2.9	3.4
GHG avoided. Low	ktCO_2eq	3.1	3.1	3.6

Notes:
a) Scenario RAIN I_Agro: Rainfed small-scale *Jatropha* plantation. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied. Fruit hulls and seed shells used as compost;
b) Scenario RAIN II_Agro: Rainfed small-scale *Jatropha* plantation. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied. Fruit hulls and seed shells used as combustibles;
c) Scenario RAIN III_Agro: Rainfed small-scale *Jatropha* plantation. 2,500 trees/ha. No fertilizers and agro-chemicals used. Fruit hulls and seed shells used as compost.

Chart 8.2: Sensitivity analysis results. RAIN_Agro scenario



8.1.1.2 Biodiesel production

The annual biodiesel production, price of *Jatropha* oil and crude glycerine, discount rate, interest charges on CAPEX and working capital, subsidies on working capital, transportation distance for *Jatropha* oilseed, hulls and biomass, and transportation distance for methanol, biodiesel and glycerine, were varied to both a higher and lower value in both large scale

(Irrigated) and small-scale (Rainfed) scenarios for Production scenarios (Tables 8.5 & 8.6 (IRR_Production), and Tables 8.7 & 8.8 (RAIN_Production scenarios)).

The results of probabilistic sensitivity analysis can be found at the Charts 8.3 and 8.4, and Table 8.10 - for IRR_Production and Charts 8.5 and 8.6, and Table 8.11 - for RAIN_Production scenarios.

8.1.1.2.1 Large scale biodiesel production

Table 8.5: Sensitivity analysis parameters. Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production).

Parameter	Unit	Initial value	Low	High
Biodiesel production	t bd/a	101,524.2	90,000	115,000
Price of Jatropha oil	Rs./l	16.5	12.0	35.0
Price of crude glycerine	Rs./t	22,000	8,000	25,000
Discount rate	%	15	5	20
Interest charge (CAPEX)	%	15	5	20
Interest charge (working capital charge)	%	15	5	20
Subsidies (working capital charge)	%	0	0	75
Transportation of Jatropha oilseed, hulls and biomass	km	100	30	120
Transportation of methanol, biodiesel and glycerine	km	300	150	450

Table 8.6: Sensitivity analysis parameters. Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production). Initial values (per life cycle)

Scenario/CAPEX		8.0 MGBP		11.5 MGBP	
Parameter	**Unit**	**IRR_Prod Loan**	**IRR_Prod Private capital**	**IRR_Prod Loan**	**IRR_Prod Private capital**
NPV	GBP	22,912,789.9	21,556,264.5	19,210,871.4	17,548,559.3
Scenario IRR I					
GHG avoided. High	$ktCO_2eq$	7,131.0	7,131.0	7,659.0	7,659.0
GHG avoided. Best	$ktCO_2eq$	7,386.0	7,386.0	7,914.0	7,914.0
GHG avoided. Low	$ktCO_2eq$	7,641.0	7,641.0	8,169.0	8,169.0
Scenario IRR II					
GHG avoided. High	$ktCO_2eq$	8,514.0	8,514.0	8,901.0	8,901.0
GHG avoided. Best	$ktCO_2eq$	8,772.0	8,772.0	9,156.0	9,156.0
GHG avoided. Low	$ktCO_2eq$	9,027.0	9,027.0	9,411.0	9,411.0

Table 8.6: Sensitivity analysis parameters. Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production). Initial values (per life cycle) (cont.)

Scenario/CAPEX		15.0 MGBP		18.5 MGBP	
Parameter	Unit	IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
NPV	GBP	14,737,171.4	13,055,531.6	6,838,784.8	8,805,165.1
Scenario IRR I					
GHG avoided. High	$ktCO_2eq$	8,241.0	8,241.0	11,661.0	11,661.0
GHG avoided. Best	$ktCO_2eq$	8,499.0	8,499.0	11,916.0	11,916.0
GHG avoided. Low	$ktCO_2eq$	8,754.0	8,754.0	12,171.0	12,171.0
Scenario IRR II					
GHG avoided. High	$ktCO_2eq$	9,093.0	9,093.0	11,670.0	11,670.0
GHG avoided. Best	$ktCO_2eq$	9,288.0	9,288.0	11,928.0	11,928.0
GHG avoided. Low	$ktCO_2eq$	9,546.0	9,546.0	12,183.0	12,183.0

Scenario/CAPEX		20.3 MGBP	
Parameter	Unit	IRR_Prod Loan	IRR_Prod Private capital
NPV	GBP	3,972,313.8	6,619,262.3
Scenario IRR I			
GHG avoided. High	$ktCO_2eq$	15,753.0	15,753.0
GHG avoided. Best	$ktCO_2eq$	16,008.0	16,008.0
GHG avoided. Low	$ktCO_2eq$	16,263.0	16,263.0
Scenario IRR II			
GHG avoided. High	$ktCO_2eq$	12,276.0	12,276.0
GHG avoided. Best	$ktCO_2eq$	12,531.0	12,531.0
GHG avoided. Low	$ktCO_2eq$	12,786.0	12,786.0

Notes:

a) Scenario IRR I_Production: Irrigated large scale *Jatropha* plantation. 1,111 trees/ha). One-stage large scale Henkel transesterification process (90 bar, 240^oC).

b) Scenario: IRR II_Production: Irrigated large scale *Jatropha* plantation. 1,111 trees/ha). Two-stage large scale biodiesel production process. Fat-splitting (60 bar, 260^oC) and Esterification (10 bar, 240^oC).

Chart 8.3: Sensitivity analysis results. IRR_Production scenario. CAPEX 11.5 MGBP

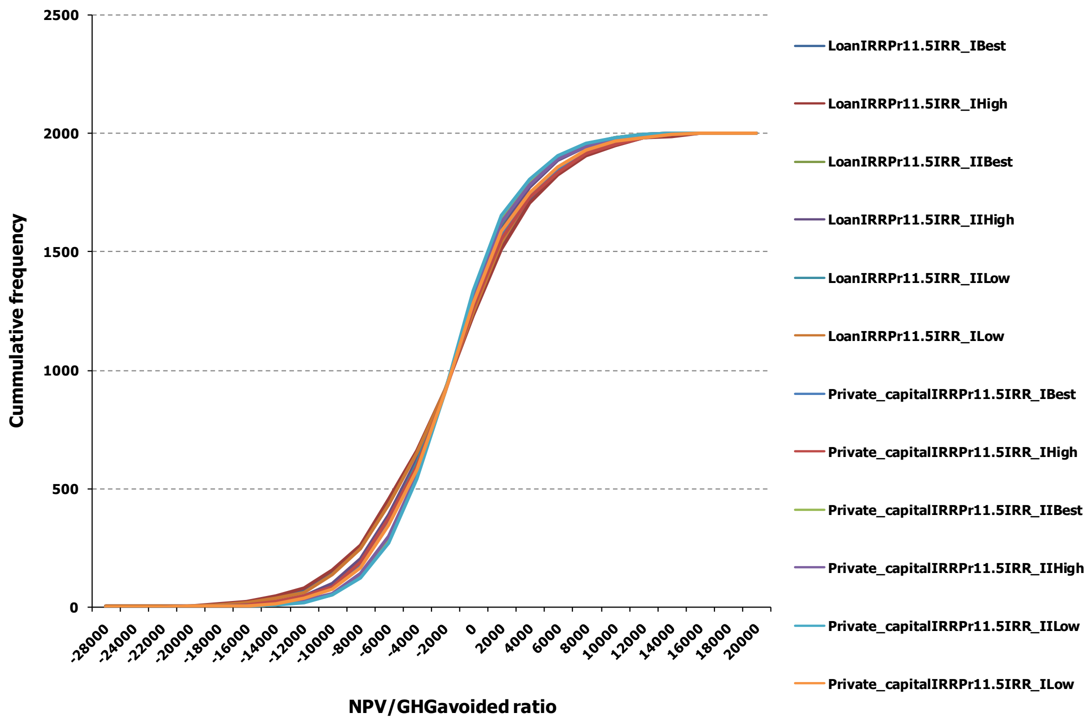
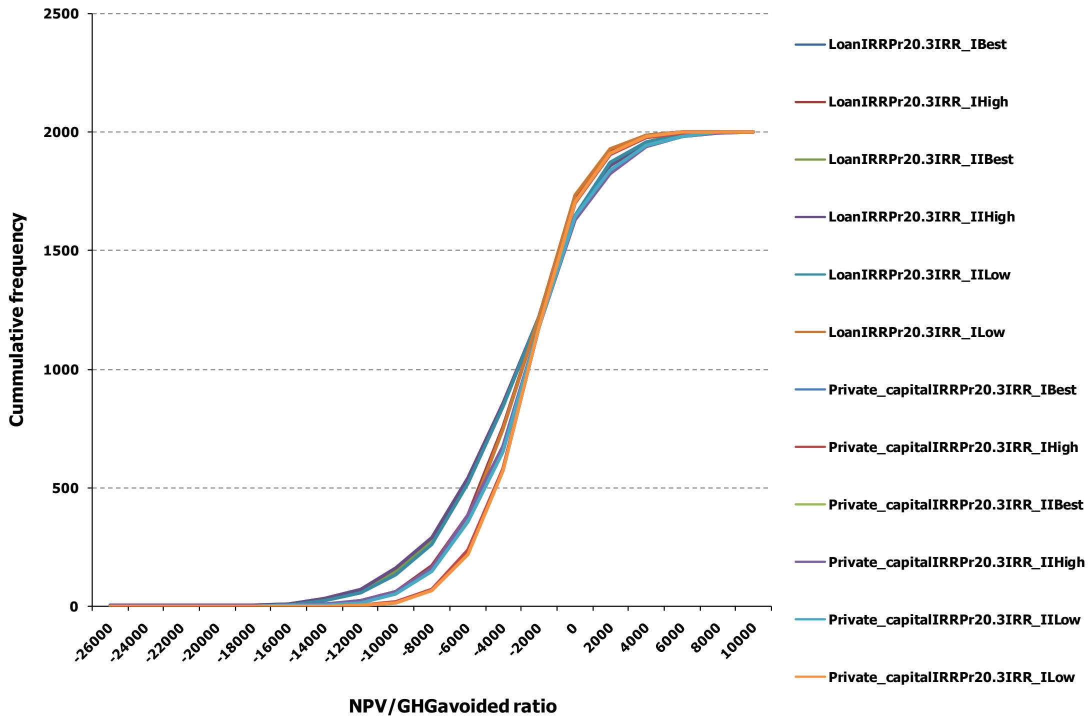


Chart 8.4: Sensitivity analysis results. IRR_Production scenario. CAPEX 20.3 MGBP



8.1.1.2.2 Small-scale biodiesel production

Table 8.7: Sensitivity analysis parameters. Biodiesel production. Small-scale scenarios (RAIN I_Production and RAIN II_Production)

Parameter	Unit	Initial value	Low	High
Biodiesel production	t bd/a	1,015.2	850	1,150
Price of Jatropha oil	Rs./l	16.5	12.0	35.0
Price of crude glycerine	Rs./t	22,000	8,000	25,000
Discount rate	%	15	5	20
Interest charge (CAPEX)	%	15	5	20
Interest charge (working capital charge)	%	15	5	20
Subsidies (working capital charge)	%	0	0	75
Transportation of Jatropha oilseed, hulls and biomass	km	55	5	55
Transportation of methanol, biodiesel and glycerine	km	55	5	55

Table 8.8: Sensitivity Analysis parameters. Biodiesel Production. Small-scale scenarios (RAIN I_Production and RAIN II_Production). Initial values (per life cycle)

Parameter	Unit	0.11 MGBP		0.16 MGBP	
		RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod Loan	RAIN_Prod Private capital
NPV	GBP	265,775.1	281,250.7	188,644.5	219,166.9
Scenario RAIN I					
GHG avoided. High	$ktCO_2eq$	78.0	78.0	78.0	78.0
GHG avoided. Best	$ktCO_2eq$	81.0	81.0	84.0	84.0
GHG avoided. Low	$ktCO_2eq$	87.0	87.0	87.0	87.0
Scenario RAIN II					
GHG avoided. High	$ktCO_2eq$	78.0	78.0	78.0	78.0
GHG avoided. Best	$ktCO_2eq$	81.0	81.0	84.0	84.0
GHG avoided. Low	$ktCO_2eq$	87.0	87.0	87.0	87.0

Parameter	Unit	0.21 MGBP		0.26 MGBP	
		RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod Loan	RAIN_Prod Private capital
NPV	GBP	107,149.3	157,318.7	22,569.5	95,352.6
Scenario RAIN I					
GHG avoided. High	$ktCO_2eq$	78.0	78.0	78.0	78.0
GHG avoided. Best	$ktCO_2eq$	84.0	84.0	84.0	84.0
GHG avoided. Low	$ktCO_2eq$	90.0	90.0	90.0	90.0
Scenario RAIN II					
GHG avoided. High	$ktCO_2eq$	78.0	78.0	78.0	78.0
GHG avoided. Best	$ktCO_2eq$	84.0	84.0	84.0	84.0
GHG avoided. Low	$ktCO_2eq$	90.0	90.0	90.0	90.0

Table 8.8: Sensitivity Analysis parameters. Biodiesel Production. Small-scale scenarios (RAIN I_Production and RAIN II_Production). Initial values (per life cycle) (cont.)

Parameter	Unit	0.3 MGBP	
		RAIN_Prod Loan	RAIN_Prod Private capital
NPV	GBP	(46,748.6)	46,029.9
Scenario RAIN I			
GHG avoided. High	ktCO_2eq	96.0	96.0
GHG avoided. Best	ktCO_2eq	99.0	99.0
GHG avoided. Low	ktCO_2eq	105.0	105.0
Scenario RAIN II			
GHG avoided. High	ktCO_2eq	96.0	96.0
GHG avoided. Best	ktCO_2eq	99.0	99.0
GHG avoided. Low	ktCO_2eq	105.0	105.0

Notes:
a) Scenario RAIN I_Production: Rainfed small-scale *Jatropha* plantation. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied. Small-scale transesterification process (1.4 bar, 60°C).
b) Scenario RAIN II_Production: Rainfed small-scale *Jatropha* plantation. 2,500 trees/ha. No fertilizers and agro-chemicals used. Small-scale transesterification process (1.4 bar, 60°C).

Chart 8.5: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.16 MGBP

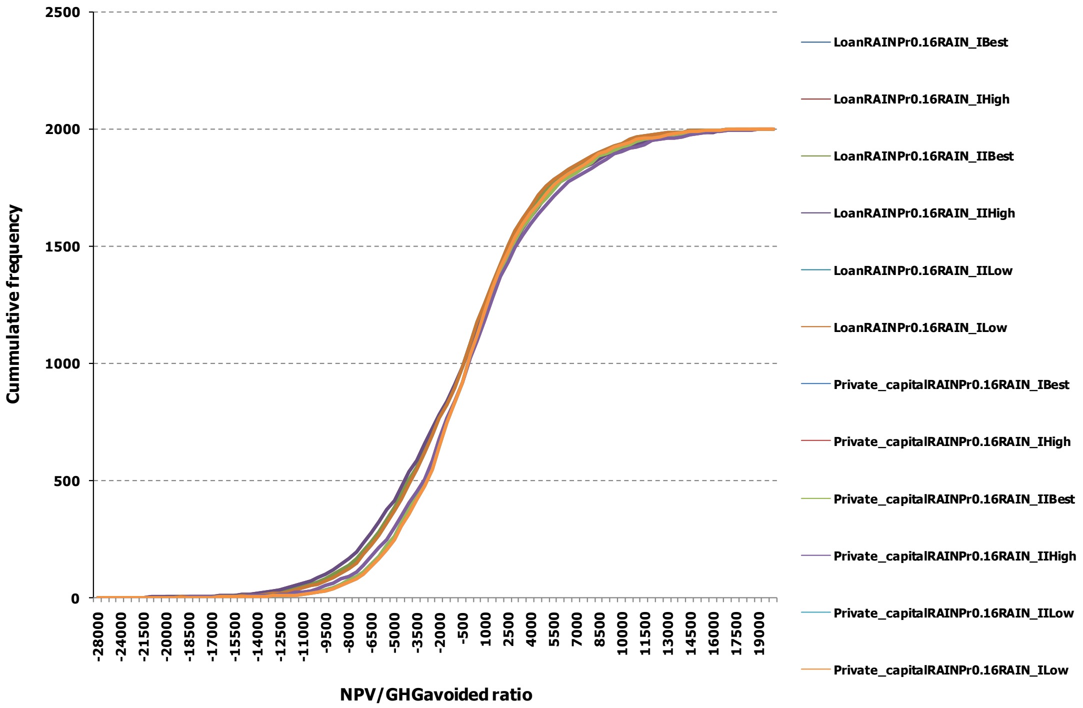


Chart 8.6: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.30 MGBP

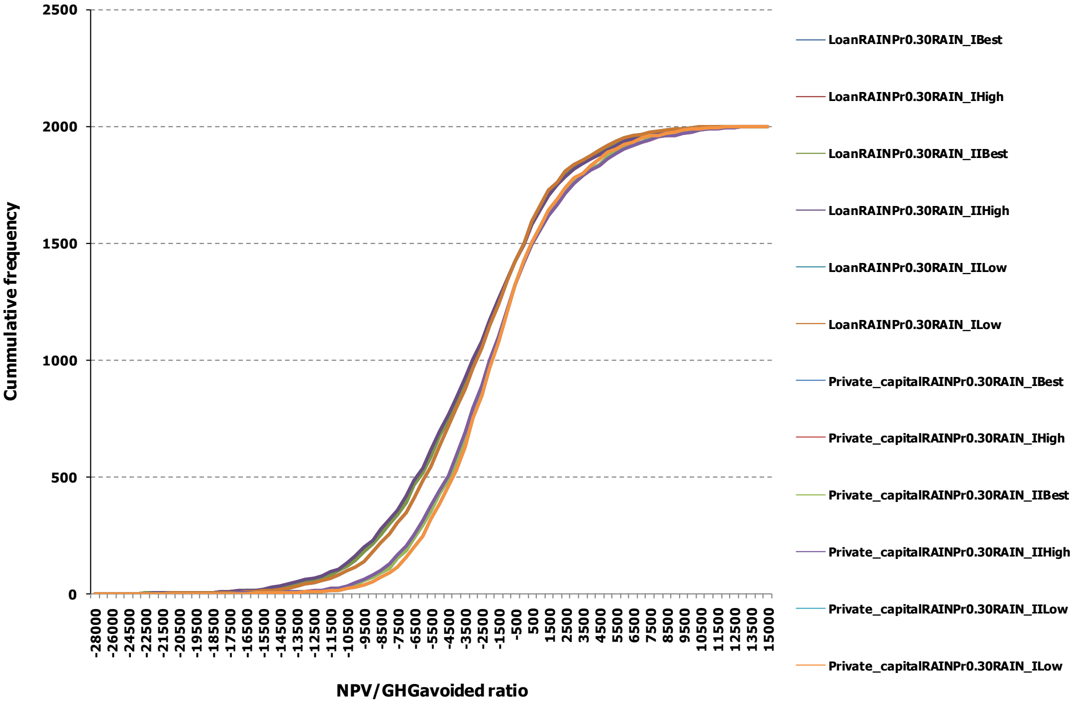


Table 8.9: Proportion of cases which makes positive NPV (NPV/GHG avoided ratio). Jatropha oilseeds cultivation (Agricultural scenarios. Low, Best and High)

Scenarios	IRR I _Agro		IRR II _Agro		RAIN I _Agro	RAIN II _Agro	RAIN III _Agro
	Loan	Private capital	Loan	Private capital	Loan	Loan	Loan
Ratio (%)	37.15 - 37.30	56.65 - 56.80	58.15 - 58.30	56.75 - 56.85	15.2-15.3	15.2	16.3-16.4

Table 8.10: Proportion of cases which makes positive NPV (NPV/GHG avoided ratio). Large scale biodiesel production (IRR I_Production and IRR II_Production scenarios. Low, Best and High)

Scenario/ CAPEX	8.0 MGBP		11.5 MGBP	
	IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
Ratio (%)	40.1-43.8	38.9-42.6	35.0-38.7	33.2-36.9

Scenario/ CAPEX	15.0 MGBP		18.5 MGBP	
	IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
Ratio (%)	30.7-32.9	28.4-30.3	19.9-21.1	20.2-21.1

Table 8.10: Proportion of cases which makes positive NPV (NPV/GHG avoided ratio). Large scale biodiesel production (IRR I_Production and IRR II_Production scenarios. Low, Best and High) (cont.)

Scenario/ CAPEX	20.3 MGBP	
	IRR_Prod Loan	IRR_Prod Private capital
Ratio (%)	13.4-18.2	14.7-18.6

Table 8.11: Proportion of cases which makes positive NPV (NPV/GHG avoided ratio). Small-scale biodiesel production (RAIN I_Production and RAIN II_Production scenarios. Low, Best and High)

Scenario/ CAPEX	0.11 MGBP		0.16 MGBP	
	RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod Loan	RAIN_Prod Private capital
Ratio (%)	54.8-55.3	55.9-56.5	45.7-46.2	48.2-48.9

Scenario/ CAPEX	0.21 MGBP		0.26 MGBP	
	IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
Ratio (%)	37.9-38.3	41.5-42.3	23.3-23.9	34.4-35.0

Scenario/ CAPEX	0.3 MGBP	
	RAIN_Prod Loan	RAIN_Prod Private capital
Ratio (%)	24.9-25.3	28.6-29.1

Probabalistic sensitivity analysis charts for all agricultural and biodiesel production CBA scenarios could be found in the Appendix VIII: “Sensitivity analysis”.

8.2 Results of correlation analysis

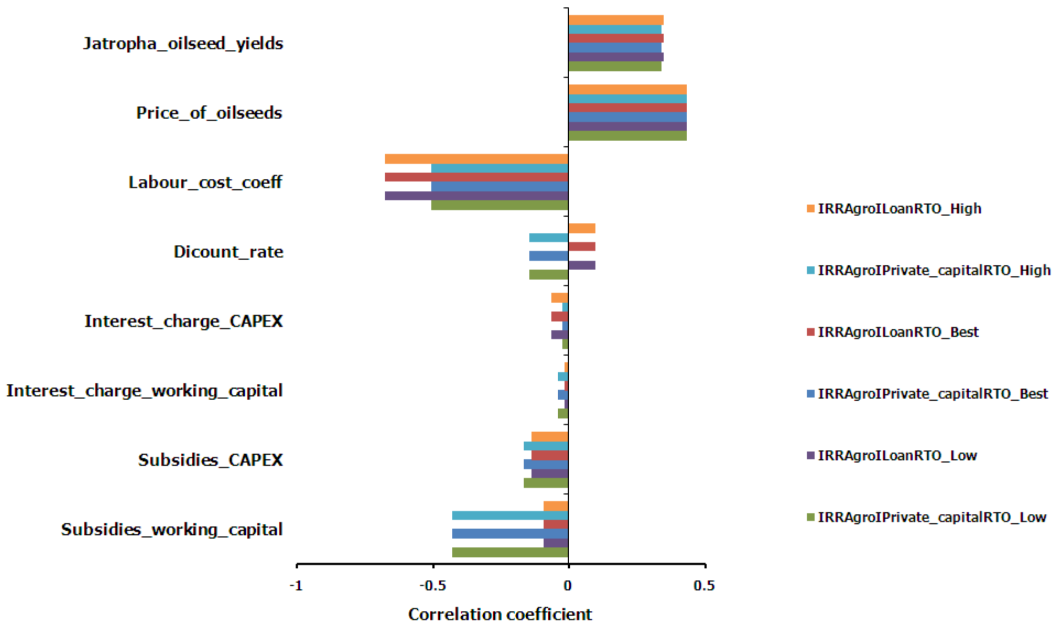
To understand which parameters are most contribute the most to the NPV fluctuations, the parameters that contribute the most to the NPV uncertainty were plotted in Charts 8.7 and 8.8 for Irrigated (IRR_Agro I and IRR_Agro II) agriculture scenarios, and Chart 8.9 for Rainfed (RAIN_Agro) agriculture scenario. These charts illustrate contribution (%) of each parameter to both NPV and NPV/GHG avoided ratio per life cycle.

8.2.1 Jatropha oilseed cultivation

8.2.1.1 Irrigated (large scale) *Jatropha* oilseeds cultivation

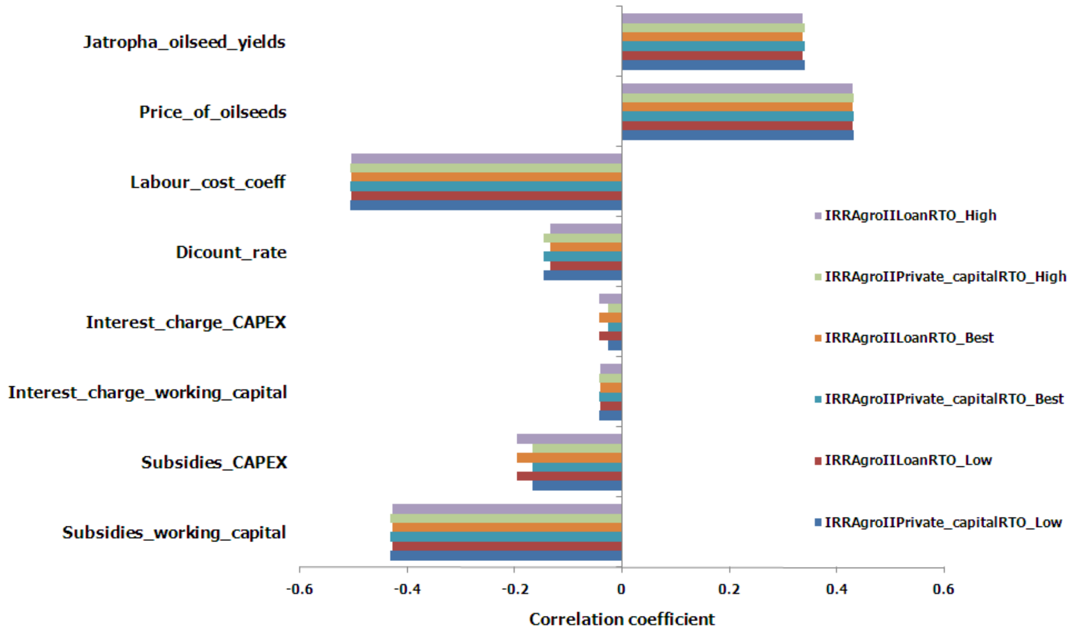
For the Irrigated I (IRR I_Agro) scenario, the correlation results demonstrate that price of oilseeds, the *Jatropha* oilseed yields, the labour cost coefficient, and subsidies on working capital (Private Capital) are all significantly correlated with NPV and NPV/GHG avoided ratio. Thus, the labour cost coefficient has the Pearson correlation coefficient (r = -0.507 - for the Private Capital scenario and r = -0.678 - for the Loan scenario), price of oilseeds (r = 0.429 (Private Capital) and r = 0.432 (Loan)), subsidies on working capital (r = -0.4318 (Private Capital)), and the *Jatropha* oilseed yields (r = 0.338 (Private Capital) and r = 0.346 (Loan)).

Chart 8.7: Correlation. Agriculture. Irrigated I scenario (IRR I_Agro_Correlation).



Some other parameters, such as discount rate, interest charges on CAPEX, interest charges on working capital, subsidies on working capital (Loan) and subsidies on CAPEX much less correlated with NPV and NPV/GHG avoided ratio. Thus, discount rate has the Pearson correlation coefficient (r = -0.148 (Private Capital) and r = 0.098 (Loan)), interest charges on CAPEX (r = -0.0267 (Private Capital) and r = -0.066 (Loan)), interest charges on working capital (r = -0.0428 (Private Capital) and r = -0.0182 (Loan)), subsidies on working capital (r = -0.095 (Loan)), and subsidies on CAPEX (r = -0.167 (Private Capital) and r = -0.1395 (Loan)).

Chart 8.8: Correlation. Agriculture. Irrigated II scenario (IRR II_Agro_Correlation).

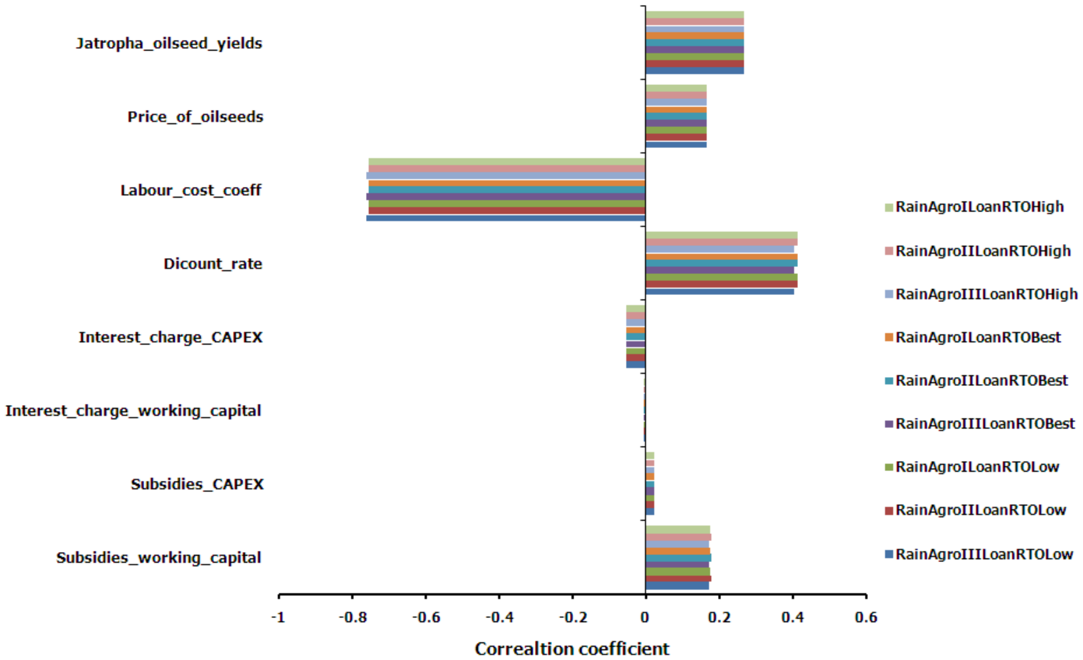


For the Irrigated II (IRR II_Agro) scenario, the correlation results demonstrate results similar to the Irrigated I (IRR I_Agro) scenario. In this scenario, price of oilseeds, the *Jatropha* oilseed yields, the labour cost coefficient, and subsidies on working capital are all significantly correlated with NPV and NPV/GHG avoided ratio as well. Thus, the labour cost coefficient has the Pearson correlation coefficient (r = -0.501 - for the Private Capital scenario and r = -0.505 - for the Loan scenario), price of oilseeds (r = 0.429 (Private Capital) and r = 0.428 (Loan)), subsidies on working capital (r = -0.4315 (Private Capital) and r = -0.429 (Loan)), and the *Jatropha* oilseed yields (r = 0.338 (Private Capital) and r = 0.336 (Loan)). Some other parameters, such as discount rate, interest charges on CAPEX, interest charges on working capital and subsidies on CAPEX much less correlated with NPV and NPV/GHG avoided ratio. Thus, discount rate has the

Pearson correlation coefficient (r = -0.147 (Private Capital) and r = -0.135 (Loan)), interest charges on CAPEX (r = -0.0266 (Private Capital) and r = -0.043 (Loan)), interest charges on working capital (r = -0.0428 (Private Capital) and r = -0.0417 (Loan)), and subsidies on CAPEX (r = -0.167 (Private Capital) and r = -0.196 (Loan)).

8.2.1.2 Rainfed (small-scale) *Jatropha* oilseeds cultivation

Chart 8.9: Correlation. Agriculture. Small-scale scenario (RAIN_Agro_Correlation).



For the Rainfed I (RAIN I_Agro), Rainfed II (RAIN II_Agro) and Rainfed III (RAIN III_Agro) scenarios, the correlation results demonstrate that, the *Jatropha* oilseed yields, the labour cost coefficient, discount rate, price of oilseeds, and subsidies on working capital are all significantly correlated with NPV and NPV/GHG avoided ratio. Thus, the labour cost coefficient has the Pearson correlation coefficient (r = -0.757 (RAIN I_Agro), r = -0.756 (RAIN II_Agro), and r = -0.761 (RAIN III_Agro scenarios)), price of oilseeds (r = 0.1637 (RAIN I_Agro), r = 0.1635 (RAIN II_Agro), and r = 0.165 (RAIN III_Agro scenarios)), discount rate (r = 0.412 (RAIN I_Agro), r = 0.414 (RAIN II_Agro), and r = 0.403 (RAIN III_Agro scenarios)), and the *Jatropha* oilseed yields (r = 0.2665 (RAIN I_Agro), r = 0.2663 (RAIN II_Agro), and r = 0.268 (RAIN III_Agro scenarios)), and subsidies on working capital (r = 0.1761 (RAIN I_Agro), r = 0.1763 (RAIN II_Agro), and r = 0.170 (RAIN III_Agro scenarios)).

Some other parameters, such as interest charges on CAPEX, interest charges on working capital and subsidies on CAPEX much less correlated with NPV and NPV/GHG avoided ratio. Thus, interest charges on CAPEX has the Pearson correlation coefficient (r = -0.053 (RAIN I_Agro, RAIN II_Agro and RAIN III_Agro scenarios), interest charges on working capital (r = -0.007236 (RAIN I_Agro), r = -0.007244 (RAIN II_Agro), and r = -0.0066 (RAIN III_Agro scenarios)), subsidies on CAPEX (r = 0.0215 (RAIN I_Agro), r = 0.0214 (RAIN II_Agro), and r = 0.0217 (RAIN III_Agro scenarios)).

8.2.2 Biodiesel production

8.2.2.1 Large scale biodiesel production

For the large scale production scenarios (IRR I_Production and IRR II_Production), the correlation results demonstrate that the only price of *Jatropha* oil significantly correlated with NPV and NPV/GHG avoided ratio. Some other parameters such as discount rate, price of crude glycerine, interest charges on CAPEX, interest charges on working capital, and subsidies on working capital also correlated with NPV and NPV/GHG avoided ratio, but in much less extend than Price of *Jatropha* oil. Other parameters such as biodiesel production, transportation distances for *Jatropha* oilseed, hulls and biomass, and transportation distances for methanol, biodiesel and glycerine very little correlated with NPV and NPV/GHG avoided ratio. All Pearson correlation coefficients (r) for the (IRR_Production I and IRR_Production II scenarios (Low, Best and High) presented in Table 8.12.

Chart 8.10: Correlation. Production. Large scale scenario. IRR_Production_Corelation). CAPEX 8.0 MGBP

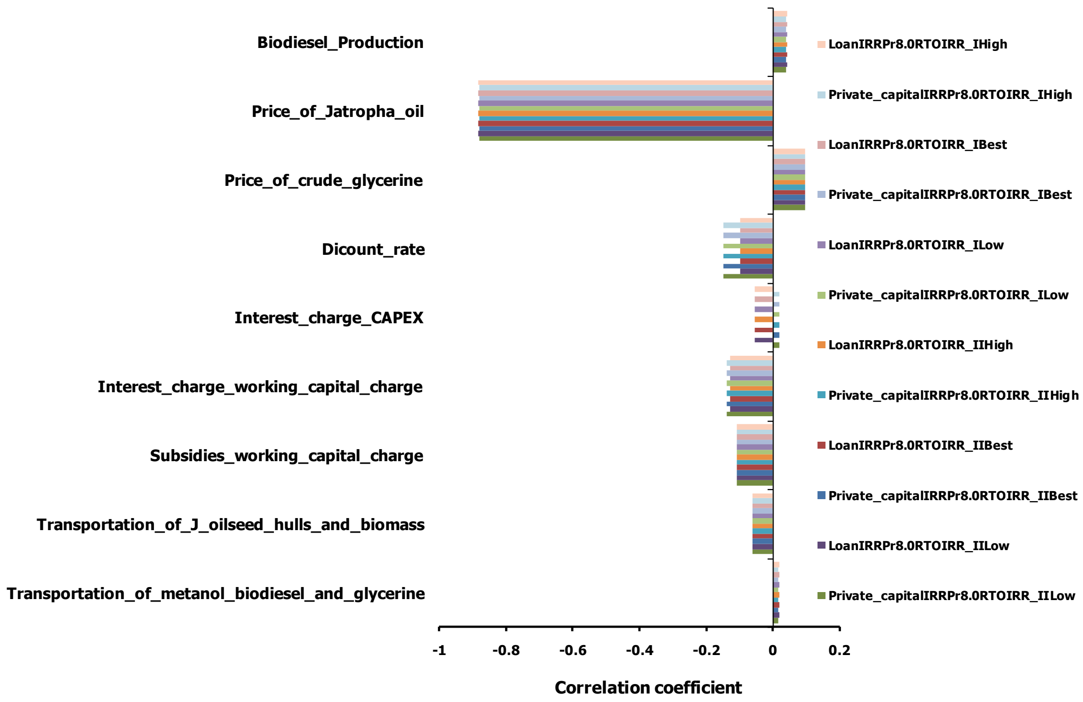


Chart 8.11: Correlation. Production. Large scale scenario. (IRR_Production_Corelation). CAPEX 18.5 MGBP

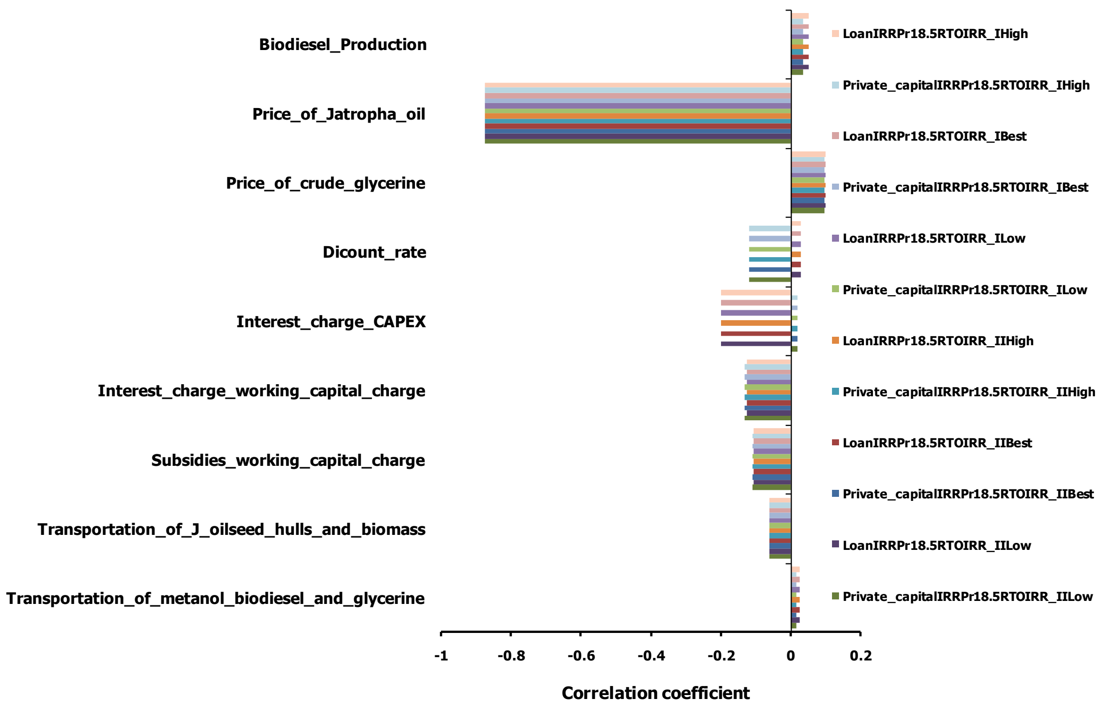


Table 8.12: Simply correlations among variables. Large scale production (IRR I _Production and IRR II_Production scenarios (Low, Best and High)

Scenario/CAPEX	**8.0 MGBP**		**11.5 MGBP**	
Parameter	**IRR_Prod Loan**	**IRR_Prod Private capital**	**IRR_Prod Loan**	**IRR_Prod Private capital**
Biodiesel production	0.042	0.038	0.047	0.037
Price of Jatropha oil	-0.882	-0.88	-0.884	-0.864
Price of crude glycerine	0.097	0.096	0.098	0.095
Discount rate	-0.098	-0.147	-0.08	-0.167
Interest charge (CAPEX)	-0.054	-0.02	-0.079	-0.02
Interest charge (working capital charge)	-0.128	-0.139	-0.127	-0.128
Subsidies (working capital charge)	-0.107	-0.107	-0.107	-0.106
Transportation of Jatropha oilseed, hulls and biomass	-0.061	-0.061	-0.062	-0.06
Transportation of methanol, biodiesel and glycerine	0.02	0.016	0.021	0.017

Scenario/CAPEX	**15.0 MGBP**		**18.5 MGBP**	
Parameter	**IRR_Prod Loan**	**IRR_Prod Private capital**	**IRR_Prod Loan**	**IRR_Prod Private capital**
Biodiesel production	0.046	0.036	0.051	0.036
Price of Jatropha oil	-0.888	-0.873	-0.874	-0.873
Price of crude glycerine	0.099	0.097	0.099	0.097
Discount rate	-0.026	-0.125	0.0031	-0.119
Interest charge (CAPEX)	-0.108	-0.02	-0.20	-0.02
Interest charge (working capital charge)	-0.131	-0.131	-0.123	-0.131
Subsidies (working capital charge)	-0.109	-0.11	-0.106	-0.11
Transportation of Jatropha oilseed, hulls and biomass	-0.061	-0.061	-0.061	-0.061
Transportation of methanol, biodiesel and glycerine	0.021	0.017	0.025	0.017

Scenario/CAPEX	**20.3 MGBP**	
Parameter	**IRR_Prod Loan**	**IRR_Prod Private capital**
Biodiesel production	0.053	0.036
Price of Jatropha oil	-0.87	-0.874
Price of crude glycerine	0.10	0.097
Discount rate	0.046	-0.115
Interest charge (CAPEX)	-0.22	-0.02
Interest charge (working capital charge)	-0.122	-0.132
Subsidies (working capital charge)	-0.106	-0.11
Transportation of Jatropha oilseed, hulls and biomass	-0.061	-0.061
Transportation of methanol, biodiesel and glycerine	0.026	0.017

8.2.2.2 Small-scale biodiesel production

For the small-scale production scenarios (RAIN I_Production and RAIN II_Production), the correlation results are similar to the large scale production (IRR I_Production and IRR II_Production) scenarios. They demonstrate that the only price of *Jatropha* oil significantly correlated with NPV and NPV/GHG avoided ratio. Some other parameters such as discount rate, price of crude glycerine, interest charges on CAPEX, and subsidies on working capital also correlated with NPV and NPV/GHG avoided ratio, but in much less extend than Price of *Jatropha* oil. Other parameters such as biodiesel production, interest charges on working capital, transportation distances for *Jatropha* oilseed, hulls and biomass, and transportation distances for methanol, biodiesel and glycerine very little correlated with NPV and NPV/GHG avoided ratio. All Pearson correlation coefficients (r) for the (RAIN_Production I and RAIN_Production II scenarios (Low, Best and High) presented in Table 8.13.

Chart 8.12: Correlation. Production. Small- scale scenario. (RAIN_Production_Corelation). CAPEX 0.11 MGBP

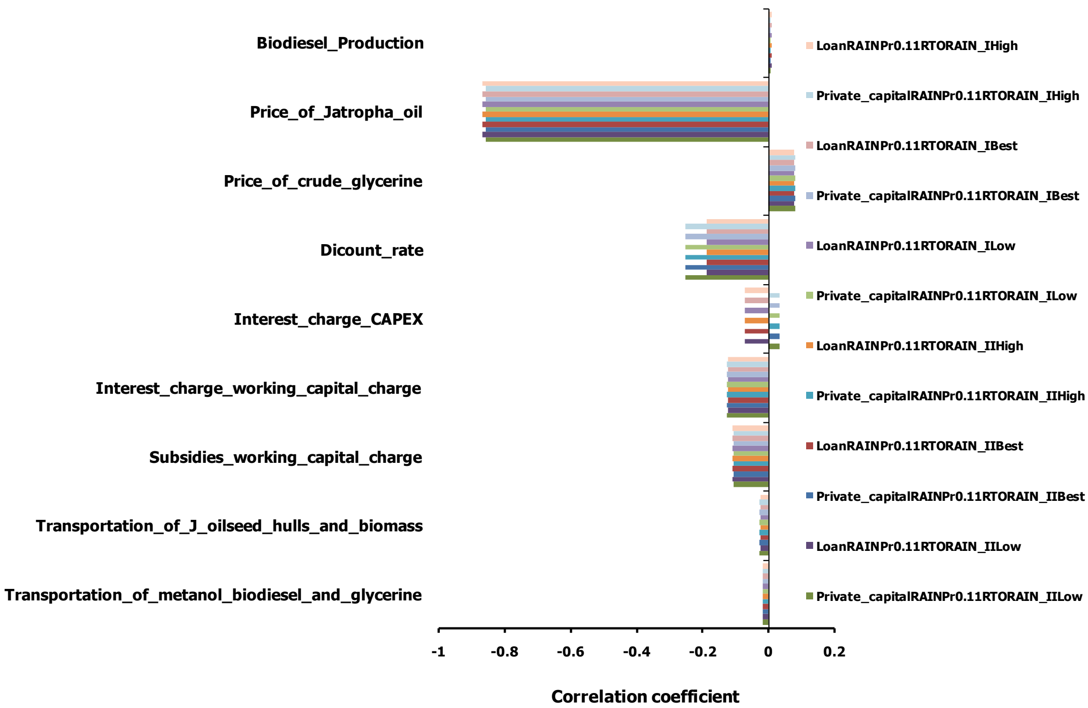


Chart 8.13: Correlation. Production. Small- scale scenario. (RAIN_Production_Corelation). CAPEX 0.30 MGBP

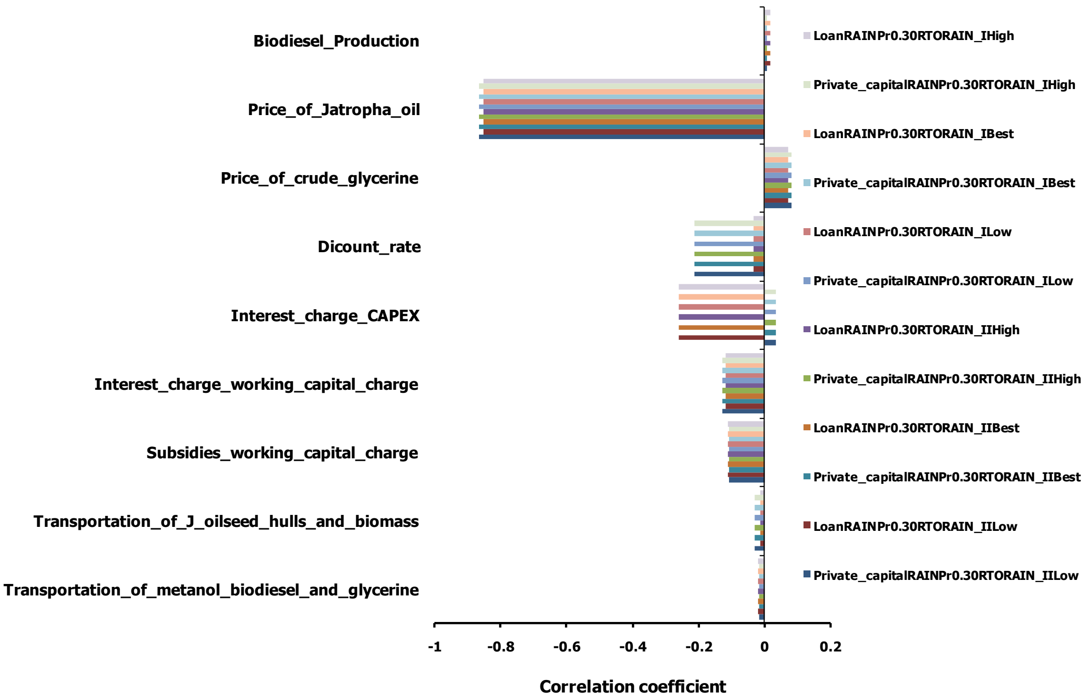


Table 8.13: Simply correlations among variables. Small-scale production (RAIN I _Production and RAIN II_Production scenarios (Low, Best and High)

Scenario/CAPEX	**0.11 MGBP**		**0.16 MGBP**	
Parameter	**RAIN_Prod Loan**	**RAIN_Prod Private capital**	**RAIN_Prod Loan**	**RAIN_Prod Private capital**
Biodiesel production	0.01	0.008	0.012	0.008
Price of Jatropha oil	-0.868	-0.858	-0.870	-0.860
Price of crude glycerine	0.078	0.082	0.077	0.082
Discount rate	-0.186	-0.252	-0.145	-0.242
Interest charge (CAPEX)	-0.071	0.035	-0.122	0.035
Interest charge (working capital charge)	-0.124	-0.126	-0.123	-0.126
Subsidies (working capital charge)	-0.108	-0.105	-0.109	-0.106
Transportation of Jatropha oilseed, hulls and biomass	-0.025	-0.029	-0.022	-0.029
Transportation of methanol, biodiesel and glycerine	-0.019	-0.017	-0.019	-0.018

Table 8.13: Simply correlations among variables.. Small-scale production (RAIN I_Production and RAIN II_Production scenarios (Low, Best and High) (cont.)

Scenario/CAPEX	0.21 MGBP		0.26 MGBP	
Parameter	**RAIN_Prod Loan**	**RAIN_Prod Private capital**	**RAIN_Prod Loan**	**RAIN_Prod Private capital**
Biodiesel production	0.015	0.008	-0.003	0.008
Price of Jatropha oil	-0.867	-0.862	-0.882	-0.865
Price of crude glycerine	0.076	0.082	0.064	0.082
Discount rate	-0.104	-0232	0.047	-0.222
Interest charge (CAPEX)	-0.182	0.034	-0.202	0.035
Interest charge (working capital charge)	-0.121	-0.1217	-0.018	-0.127
Subsidies (working capital charge)	-0.11	-0.106	-0.009	-0.107
Transportation of Jatropha oilseed, hulls and biomass	-0.019	-0.029	-0.014	-0.029
Transportation of methanol, biodiesel and glycerine	-0.019	-0.018	-0.021	-0.018

Scenario/CAPEX	0.3 MGBP	
Parameter	**RAIN_Prod Loan**	**RAIN_Prod Private capital**
Biodiesel production	0.018	0.008
Price of Jatropha oil	-0.852	-0.866
Price of crude glycerine	0.073	0.082
Discount rate	-0.034	-0.214
Interest charge (CAPEX)	-0.259	0.034
Interest charge (working capital charge)	-0.117	-0.127
Subsidies (working capital charge)	-0.110	-0.0107
Transportation of Jatropha oilseed, hulls and biomass	-0.014	-0.029
Transportation of methanol, biodiesel and glycerine	-0.020	-0.018

Correlation charts for all agricultural and biodiesel production CBA scenarios could be found in the Appendix IX: "Correlation charts".

8.3 Results of deterministic sensitivity analysis (DSA)

Pindyck and Rubinfeld (1998) state that a model is deterministic when no reference is made to the sources or nature of the underlying randomness (de Bruinm, *et. al.*: 2008). The one-way sensitivity analysis (SA) is the most common type of DSA, which is found in more than 70% of publications. In this type of SA, one parameter is set to vary over a reasonable range (e.g. minimum-maximum, standard deviation, 95% confidence interval), one in a time. Then, the resulting cost, NPV, effectiveness, and cost-effectiveness ratio are decided consequently (Limwattananon: 2008). The performed one-way SA shows a variation in NPV of *Jatropha* oilseeds cultivation (large scale (Irrigated) and small-scale (Rainfed) scenarios) and biodiesel production (large scale and small-scale scenarios) due to varying price of oilseeds, price of *Jatropha* oil, subsidies on CAPEX and subsidies on working capital. The following assumptions were made for this DSA:

- Price of *Jatropha* oilseeds: 5,000 Rs./t (63.1 GBP/t, April 2008) (Subramanian, *et. al.*: 2005);
- Price of *Jatropha* oil: 16.5 Rs./l (0.21 GBP/l) (Singh & Kalha: 2006);
- Average oil content in *Jatropha curcas* oilseeds: 30-35% (NOVOD: no date; PRAYAS: 2006);
- Density of *Jatropha* oil at 20^{o}C: 0.9186 kg/l (de Castro: 2007, Vyas: 2009).

8.3.1 Jatropha oilseed cultivation

In first sensitivity test, the price of oilseeds was varied (to both a higher and lower value) in both Irrigated and Rainfed scenarios for Agriculture. All other values such as *Jatropha* oilseed yields (5.2 t/ha for Irrigated scenario and 3.45 t/ha for Rainfed scenario), labour cost coefficient (equal to 1 for both Irrigated and Rainfed scenarios), discount rate (15%), interest charges on CAPEX (15%) and working capital (15%), and subsidies on CAPEX (0% - for Irrigated scenarios only) and working capital (0%), were leaved unvarying.

In second sensitivity test, the subsidies on working capital was varied (to both a higher and lower value) in both large scale (Irrigated) and small-scale (Rainfed) scenarios for Agriculture. All other values such as *Jatropha* oilseed yields (5.2 t/ha for Irrigated scenario and 3.45 t/ha for Rainfed scenario), labour cost coefficient (equal to 1 for both Irrigated and Rainfed scenarios), price of oilseeds (5,000 Rs./t), discount rate (15%), interest charges on CAPEX (15% - for Irrigated scenarios only) and working capital (15%), and subsidies on CAPEX (0% - for Irrigated scenarios only), were leaved unvarying.

In third sensitivity test, the subsidies on CAPEX was varied (to both a higher and lower value) in large scale (Irrigated) Agriculture scenarios only. All other values such as *Jatropha* oilseed yields (5.2 t/ha for Irrigated scenario), labour cost coefficient (equal to 1 for both Irrigated scenario), price of oilseeds (5,000 Rs./t), discount rate (15%), interest charges on CAPEX (15% - for Irrigated scenarios only) and working capital (15%), and subsidies on working capital (0%), were leaved unvarying.

8.3.1.1 Irrigated (industrial scale) Jatropha oilseeds cultivation

The results of varying the price of *Jatropha* oilseed for the large scale oilseed cultivation are shown in Table 8.14.

Table 8.14: Sensitivity analysis. Agriculture. Irrigated scenario. Price of Jatropha oilseeds

Price of Jatropha oilseeds		Ratio	NPV per life cycle (GBP/ha)			
			IRR_Agro I Loan	IRR_Agro I Private capital	IRR_Agro II Loan	IRR_Agro II Private capital
Rs./t	GBP/t					
5000	63.1	1	(1,481.67)	(1,269.57)	(1,464.96)	(1,252.86)
9570	120.8	1.914	(228.12)	(16.02)	(211.42)	**0.69**
9630	121.5	1.926	(211.66)	**0.44**	(194.96)	17.14
10345	130.56	2.069	(15.54)	196.56	**1.17**	213.27
10405	131.32	2.081	**0.92**	213.02	17.62	229.73
12500	157.76	2.5	575.58	787.68	592.28	804.38
15000	189.31	3.0	1,261.32	1,473.43	1,278.03	1,490.13
17500	220.87	3.5	1,947.07	2,159.18	1,963.78	2,175.88
20000	252.41	4.0	2,632.82	2,844.92	2,649.53	2,861.63
22500	283.97	4.5	3,318.57	3,530.67	3,335.27	3,547.38
25000	315.52	5.0	4,004.32	4,216.42	4,021.02	4,233.13
27500	347.07	5.5	4,690.07	4,902.17	4,706.77	4,918.87
30000	378.62	6.0	5,375.81	5,587.92	5,392.52	5,604.62

Note: GBR/ INR = 79.23 - April 02, 2008. www.xe.com/ucc/convert.cgi

The results of varying subsidies on working capital for the large scale oilseed cultivation are shown in Table 8.15.

Table 8.15: Sensitivity analysis. Agriculture. Irrigated scenario. Subsidies on working capital

Subsidy on working capital (%)	NPV per life cycle (GBP/ha)			
	IRR_Agro I Loan	IRR_Agro I Private capital	IRR_Agro II Loan	IRR_Agro II Private capital
0	(1,481.67)	(1,269.57)	(1,464.96)	(1,252.86)
41.55	(600.20)	(8.56)	(210.90)	**1.21**
41.85	(593.83)	**0.55**	201.84)	10.26
48.55	(451.69)	203.89	**0.38**	212.48
69.85	**0.18**	850.33	643.26	855.36
75.0	109.44	1,006.62	798.70	1,010.80
80.0	215.51	1,158.37	949.61	1,161.71

The results of varying subsidies on CAPEX for the large scale oilseed cultivation are shown in Table 8.16.

Table 8.16: Sensitivity analysis. Agriculture. Irrigated scenario. Subsidies on CAPEX

Subsidy on CAPEX (%)	NPV per life cycle (GBP/ha)			
	IRR_Agro I Loan	IRR_Agro I Private capital	IRR_Agro II Loan	IRR_Agro II Private capital
0	(1,481.67)	(1,269.57)	(1,464.96)	(1,252.86)
27.25	(79.96)	(47.08)	**1.31**	(30.37)
27.95	(43.96)	(15.68)	38.98	**1.03**
28.30	(25.95)	**0.03**	57.81	16.73
28.81	**0.28**	22.91	85.25	39.61
30.0	61.49	76.29	149.28	93.00
50.0	1,090.27	973.53	1,225.45	990.24
75.0	2,376.24	2,095.08	2,570.66	2,111.78

8.3.1.2 Rainfed (small-scale) *Jatropha* oilseeds cultivation

The results of varying the price of *Jatropha* oilseed for the small-scale oilseed cultivation are shown in Table 8.17.

**Table 8.17: Sensitivity analysis. Agriculture. Rainfed scenario.
Price of Jatropha oilseeds**

Price of Jatropha oilseeds		Ratio	NPV per life cycle (GBP/ha)		
Rs./t	GBP/t		RAIN_Agro I	RAIN_Agro II	RAIN_Agro III
5000	63.1	1	(1,285.58)	(1,299.08)	(869.18)
9540	121.29	1.922	(416.3)	(429.53)	**0.37**
11745	148.23	2.35	**0.82**	(12.68)	417.23
11890	150.06	2.378	14.03	**0.52**	430.43
12000	151.45	2.4	34.78	21.27	451.18
12500	157.76	2.5	129.09	115.58	545.49
15000	189.31	3.0	600.64	587.14	1017.04
17500	220.87	3.5	1,072.2	1,058.69	1,488.60
20000	252.41	4.0	1,543.75	1,530.25	1,960.15
22500	283.97	4.5	2,015.31	2,001.80	2,431.71
25000	315.52	5.0	2,486.86	2,473.36	2,903.26
27500	347.07	5.5	2,958.42	2,944.91	3,374.82
30000	378.62	6.0	3,429.97	3,416.47	3,846.37

Note: GBR/ INR = 79.23 - April 02, 2008. www.xe.com/ucc/convert.cgi

The results of varying the subsidies on working capital for the small-scale oilseed cultivation are shown in Table 8.18.

**Table 8.18: Sensitivity analysis. Agriculture. Rainfed scenario.
Subsidies on working capital**

Subsidy on working capital (%)	NPV per life cycle (GBP/ha)		
	RAIN_Agro I	RAIN_Agro II	RAIN_Agro III
0	(1,285.58)	(1,299.08)	(869.18)
41.5	(233.8)	(241.71)	**9.49**
50.8	**1.9**	(4.75)	(206.77)
51.0	6,96	**0.34**	211.0
55.0	108.34	102.26	295.72

8.3.2 Biodiesel production

In the sensitivity test, the price of *Jatropha* oil was varied to both a higher and lower value in both large scale (Irrigated) and small-scale (Rainfed) scenarios for biodiesel production. All other values such as the annual biodiesel production (101,524.4 tonnes of biodiesel per annum - for large scale (IRR I_Production and IRR II_Production) scenarios and 1,015.2 tonnes of biodiesel per annum - for small-scale (RAIN I_Production and RAIN II_Production) scenarios), price of crude glycerine (22,000 Rs./t (277.64 GBP/t)), discount rate (15%), interest charges on CAPEX (15%) and working capital (15%), subsidies on working capital (0%), transportation distance for *Jatropha* oilseed, hulls and biomass (100 km one way - for large scale (IRR I_Production and IRR II_Production) scenarios and 55 km one way - for small-scale (RAIN I_Production and RAIN II_Production) scenarios), and transportation distance for methanol, biodiesel and glycerine (300 km one way - for large scale (IRR I_Production and IRR II_Production) scenarios and 55 km one way - for small-scale (RAIN I_Production and RAIN II_Production) scenarios), were leaved unvarying.

8.3.2.1 Large scale biodiesel production

The results of varying the price of *Jatropha* oilseed for the large scale biodiesel production are shown in Table 8.19.

Table 8.19: Sensitivity analysis. Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production). Price of Jatropha oil

Scenario/CAPEX			**8.0 MGBP**		**11.5 MGBP**	
Price of Jatropha oil		**Ratio**	**IRR_Prod Loan**	**IRR_Prod Private capital**	**IRR_Prod Loan**	**IRR_Prod Private capital**
Rs./l	**GBP/l**		**NPV (GBP)**			
16.5	0.21	1	22,912,789.87	21,556,264.47	19,210,871.35	17,548,559.19
17.49	0.221	1.06	19,227,748.55	17,969,469.40	15,445,391.49	14,226,722.78
18.15	0.229	1.1	16,745,596.47	15,578,272.69	12,935,071.57	12,012,165.18
19.8	0.25	1.2	10,406,675.16	9,600,280.91	6,572,355.44	6,475,711.18
20.625	0.26	1.25	7,142,525.74	6,611,285.02	3,293,466.15	3,707,574.18
21.45	0.271	1.3	3,770,322.36	3,622,289.13	(230,693.67)	939,377.18
21.78	0.275	1.32	2.376,854.45	2,426,690.77	(1,658,530.38)	(167,901.62)
22.44	0.283	1.36	(553,470.25)	35,494.06	(4,514,203.81)	(2,382,459.22)
23.1	0.292	1.4	(3,483,794.94)	(2,355,702.65)	(7,369,877.24)	(4,579,016.82)
33.0	0.42	2.0	(55,249,063.84)	(51,855,085.57)	(56,855,250.99)	(48,330,620.52)

Table 8.19: Sensitivity analysis. Biodiesel production. Large scale scenarios (IRR I_Production and IRR II_Production). Price of Jatropha oil (cont.)

Scenario/CAPEX			15.0 MGBP		18.5 MGBP	
Price of Jatropha oil		Ratio	IRR_Prod Loan	IRR_Prod Private capital	IRR_Prod Loan	IRR_Prod Private capital
Rs./l	GBP/l		NPV (GBP)			
16.5	0.21	1	14,737,171.36	13,055,531.53	6,838,784.76	8,805,165.06
17.49	0.221	1.06	10,769,699.98	9,468,736.46	2,649,730.71	5,218,369.99
18.15	0.229	1.1	8,002,127.36	7,077,539.75	(142,971.98)	2,827,173.28
19.8	0.25	1.2	775,450.79	1,099,547.97	(8,694,590.06)	(3,150,818.50)
20.625	0.26	1.25	(3,250,143.06)	(1,889,447.92)	(12,970,519.88)	(6,139,814.39)
21.45	0.271	1.3	(7,275,736.90)	(4,878,443.81)	(17,246,449.71)	(9,128,810.28)
21.78	0.275	1.32	(8,885,974.44)	(6,074,042.17)	(18,956,821.64)	(10,324,408.63)
22.44	0.283	1.36	(12,106,449.51)	(8,465,238.88)	(22,377,565.50)	(12,715,605.35)
23.1	0.292	1.4	(15,326,924.59)	(10,856,435.59)	(25,798,309.36)	(15,106,802.06)
33.0	0.42	2.0	(72,458,143.86)	(65,120,657.32)	(83,762,601.44)	(69,642,693.55)

Scenario/CAPEX			20.3 MGBP	
Price of Jatropha oil		Ratio	IRR_Prod Loan	IRR_Prod Private capital
Rs./l	GBP/l		NPV (GBP)	
16.5	0.21	1	3,972,313.81	6,619,262.31
17.49	0.221	1.06	(235,312.03)	3,032,467.24
18.15	0.229	1.1	(3,656,055.89)	641,270.53
19.8	0.25	1.2	(12,207,915.54)	(5,336,721.25)
20.625	0.26	1.25	(16,483,845.37)	(8,325,717.14)
21.45	0.271	1.3	(20,759,775.19)	(11,314,713.03)
21.78	0.275	1.32	(22,470,147.12)	(12,510,311.39)
22.44	0.283	1.36	(25,890,890.98)	(14,901,508.10)
23.1	0.292	1.4	(29,311,634.84)	(17,292,704.81)
33.0	0.42	2.0	(87,319,683.63)	(71,968,312.19)

8.3.2.2 Small-scale biodiesel production

The results of varying the price of *Jatropha* oilseed for the small-scale biodiesel production are shown in Table 8.20.

Table 8.20: Sensitivity analysis. Biodiesel production. Small-scale scenarios (RAIN I_Production and RAIN II_Production). Price of Jatropha oil

Scenario/CAPEX			0.11 MGBP		0.16 MGBP	
Price of Jatropha oil		Ratio	RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod II Loan	RAIN_Prod Private capital
Rs./l	GBP/l		NPV (GBP)			
15.345	0.194	0.93	309,969.37	324,366.01	233,777.23	262,282.21
16.5	0.21	1	265,775.14	281,250.71	188,644.47	219,166.92
17.16	0.217	1.04	239,984.99	256,613.40	162,505.68	194,529.61
18.15	0.229	1.1	201,299.77	219,657.43	122,216.51	157,573.64
19.8	0.25	1.2	136,824.39	158,064.15	55,067.89	95,980.35
20.625	0.26	1.25	103,944.96	127,267.51	20,510.16	65,183.71
21.45	0.271	1.3	70,370.65	96,470.87	(14,662.29)	34,387.07
23.1	0.292	1.4	2,070.91	34,792.83	(89,835.36)	(27,825.42)
23.925	0.302	1.45	(33,101.54)	3,554.27	(129,983.59	(59,063.98
24.09	0.304	1.46	(40,247.31)	(2,693.44)	(138,013.23)	(65,311.69)
24.75	0.312	1.5	(72,365.89)	(27,684.29)	(170,131.81)	(90,302.54)
33.0	0.42	2.0	(533,130.66)	(460,528.47)	(632,312.39)	(526,709.21)

Scenario/CAPEX			0.21 MGBP		0.26 MGBP	
Price of Jatropha oil		Ratio	RAIN_Prod Loan	RAIN_Prod Private capital	RAIN_Prod Loan	RAIN_Prod Private capital
Rs./l	GBP/l		NPV (GBP)			
15.345	0.194	0.93	154,153.30	200,433.95	71,810.92	138,467.91
16.5	0.21	1	107,149.27	157,318.65	22,569.50	95,352.62
17.16	0.217	1.04	80,289.82	132,681.34	(5,568.46)	70,715.31
18.15	0.229	1.1	39,184.93	95,725.37	(47,775.40)	33,759.34
19.8	0.25	1.2	(31,159.96)	34,132.09	(124,048.94)	(27,833.95)
20.625	0.26	1.25	(66,673.03)	3,335.44	(164,197.16)	(58,992.95)
21.45	0.271	1.3	(106,821.25)	(27,731.02)	(204,345.39)	(90,231.51)
23.1	0.292	1.4	(187,117.70)	(90,208.15)	(284,641.83)	(152,708.63)
23.925	0.302	1.45	(227,265.93)	(121,446.71)	(324,947.20)	(183,947.20)
24.09	0.304	1.46	(235,295.57)	(127,694.42)	(332,819.70)	(190,194.91)
24.75	0.312	1.5	(267,414.15)	(152,685.27)	(364,938,28)	(215,185.76)
33.0	0.42	2.0	(592,513.22)	(737,175.25)	(830,110.77)	(658,505.60)

Scenario/CAPEX			0.3 MGBP	
Price of Jatropha oil		Ratio	RAIN_Prod Loan	RAIN_Prod Private capital
Rs./l	GBP/l		NPV (GBP)	
15.345	0.194	0.93	2,492.79	89,145.22
16.5	0.21	1	(46,748.63)	46,029.93
17.16	0.217	1.04	(74,886.59)	21,392.62
18.15	0.229	1.1	(121,483.77)	(15,563.35)
19.8	0.25	1.2	(201,780.21)	(77,504.64)
20.625	0.26	1.25	(241,928.44)	(108,743.21)
21.45	0.271	1.3	(282,076.66)	(139,981.77)
23.1	0.292	1.4	(362,373.11)	(202,458.89)
23.925	0.302	1.45	(402,521.34)	(233,697.45)
24.09	0.304	1.46	(410,550.98)	(239,945.16)
24.75	0.312	1.5	(442,669.56)	(264,936.01)
33.0	0.42	2.0	(908,905.37)	(710,899.41)

Chapter 9: Conclusions and recommendations for further research

> "We should not use biofuels if it leads to other environmental and social problems."
>
> Robert Watson, Chief Scientific Adviser to the DEFRA (UK).
> January 2008

9.1 Review of work completed

This chapter will draw out the key findings of this study and discuss their implications for policy. Analogous to the Menichetti and Otto's (2009) approach, this will allow the evaluation of the absolute impacts of mass-scale deployment of *Jatropha curcas* in Southern India.

The new analysis developed for this model combined a Life Cycle Assessment with technological and economic modelling for *Jatropha curcas* cultivation and biodiesel production in conditions of Southern India. The model is also suitable for analyses of other biofuels production chains in different areas of the World with suitable data available. The model has been designed to allow objective decisions whilst taking into consideration a wide range of economic, environmental, technological and social factors.

The aims of the study were:

- To produce energy and GHG balances for conventional biodiesel production;
- To compare the economic and environmental effectiveness for different biodiesel production models;
- To recommend an optimal biodiesel production model, taking into account subsidy requirements;
- To find a level of subsidy required for cost effective feedstock cultivation and biodiesel production;
- To consider technical and social factors, and their influence on how biodiesel is produced;
- To explore the importance of both spatial and temporal scales;
- Finally, to investigate the sensitivity of the results and conclusions to a number of input assumptions.

9.2 Existing understanding of *Jatropha curcas* (L.)

It is commonly said by various authors (Patil & Singh: 1991; Heller: 1996; GOI. Planning Commission of India: 2003; Becker & Francis: 2003; Paramathma, *et. al.*: 2004; Hegde, *et. al.*: 2004; Lele: 2004; Amissah-Arthur, *et. al.*: 2007, *etc*) is the belief that *Jatropha curcas* is a hardy, rapidly growing plant which thrives in difficult conditions with minimal management, checks soil erosion, and its byproduct, seed meal, is an excellent organic manure but this not yet backed by any worthwhile research yet. Experience of research institutions and practitioners in the past years has shown that even though *Jatropha* survives in harsh and dry conditions, oilseed yields are too low to be of economic interest (Paramathma: pers. comm., Lele: pers. comm., Altenburg, *et. al.*: 2009), and hence, *Jatropha* oilseeds cultivation may be seen as a risky investment. Besides, The German Development Institute studies (Altenburg, *et. al.*: 2009) also consider TBOS-based biodiesel production as a risky business because: a) markets are not yet established, b) the long-term nature of investments as most TBOS have very long gestation periods, and c) some TBOS can only be used for the production of non-edible oil and are thus worthless if the biodiesel market does not take off.

Many challenges exist in the case of Tree Born Oil Seeds (e.g. *Jatropha curcas*) cultivation as a feedstock for biodiesel production in India. Firstly, the perennial nature of TBOS. Secondly, the vast number of various climatic and rain zones and soil variations in Karnataka State, let alone in the entire Indian subcontinent, which adds to the complexity in selection of appropriate fertilizers and agrochemicals applications for each particular region or block-plantation. Thirdly, as *Jatropha* has only recently been introduced as an agroforestry crop, many critical data are still ambiguous (e.g. crop data, N_2O from fertilizer usage, N_2O from crop residues returned to soils, *etc*). Also, low yields and plant to plant variability is a limitation in *Jatropha curcas* (Sharma, *et. al.*: 2008).

To integrate the scattered experience and observations on *Jatropha curcas*, priority research areas may include the characterization and preservation of the genetic base and to link it with crop characteristics (especially yield components) that define oil production on an area base. Yield components research may be plant specific, such as dry matter distribution, female-male flower ratio, seed size, seed oil content, oil quality and toxicity. Additional research should focus on oil production on an area base, such as number of branches, number of flowers, number of fruits, number of seeds per ha. The timing component should also be priority research, such as for flower induction and synchrony in maturing to enable mechanical harvesting (Rijssenbeek, *et. al.*: 2007). The development of disease/pest and fire resistant varieties of *Jatropha curcas* through research should be encouraged and vigorously pursued (Amissah-Arthur, *et. al*.: 2007, Ganeshkumar: no date).

A senior scientist from ICAR, who wants to remain anonymous during his interview to the Friends of Earth, said that organisations like ICAR and CRIDA will need at least 10 years of research on *Jatropha* before coming out with a set of data and relevant information for its successful and sustainable cultivation (Friends of Earth: 2008).

9.3 Key conclusions and recommendations

Since just about all liquid biofuels are manufactured from agricultural crops, the biofuel markets are indivisible linked to agriculture. A major hope for biofuels is that feedstock crops can be grown on idle and marginal lands. Governments have claimed that significant land areas are under-utilized and available for biofuel production.

Though *Jatropha* plantation is being propagated as a tool of wasteland development, it is really to be seen whether targeted lands are wastelands indeed. Yet growing evidence raises doubts about the concept of "idle" land. In many cases, lands perceived to be "idle", "under-utilised", "marginal" or "abandoned" by government and large private operators provide a wide range of physical products (e.g. food, fuel and fodder), income and employment benefits (e.g. supplementary crops or livestock, drought period sustenance and offseason activities) for the rural poor and socially excluded groups (Friends of Earth: 2008; Shiva: no date; Mearns: 1999 cited by Altenburg, *et. al*.: 2009). *Jatropha* has several drawbacks in this context. First, the leaves of *Jatropha* are not suitable for livestock, i.e. not suitable as fodder. Second, *Jatropha* yields insignificant amount of wood per tree (Rajagopal: 2007, Negi, *et. al*.: 2006 cited by Nagar: no date), Third, *Jatropha* planting is being promoted through state agencies without seeing all the consequences such as blocking the migration routes of animals and encroaching upon herd-passing pathways (Planning Commission of India: 2006).

Mature *Jatropha* plantations are expected to yield more than 3.5 t/ha. However, to achieve such yields, fertile soil, irrigation or high rainfall and inputs of fertiliser and pesticides are required (Altenburg, *et. al*.: 2009). Under rainfed condition *Jatropha* oilseed yield recorded never exceeded 0.5-1.5 t/ha even for 10 years old trees. It is very difficult to get more than 1.5 kg per tree under rainfed conditions (Paramathma: pers.comm.). Report of the Committee on Development of Bio-fuels (2003) says that the annual seed-yield of *Jatropha* in Maharashtra is highly variable and could be as low as 0.4 t/ha (PRAYAS: 2006). However, results of *Jatropha* plantation raised in Maharashtra on over 20,000 acres of land between 1986 to 1994-1995 were not very encouraging, with yields of 1.0 to 1.5 t/ha in the third and fourth years (NABARD: 2005).

In order to achieve economically viable yields, farmers would have to bear high input and opportunity costs. Current figures suggest that in order to reach economic viability, *Jatropha* must yield 2.0 kg of seeds per plant without investments in irrigation and fertilizers, whereas actual yields under these conditions tend to be well below 1.0 kg. Achieving higher yields is a necessary condition to make the industry viable and to increase rural income (NOVOD: 2007 cited by Altenburg, *et. al*.: 2009).

None of the systems studied in this Thesis can be economic without applying subsidies for all Irrigated and Rainfed agricultural scenarios.

For large scale agricultural (IRR_Agro I and IRR_Agro II, both Loan and Private Capital) scenarios the following options could be applied to make NPV of the feedstock production positive: a) to raise *Jatropha* oilseed price by 1.91-2.08 times, b) to impose government's subsidies on working capital of at least ~41.5-70.0%, or c) to impose government's subsidies on CAPEX of at least ~27.0-29.0%.

For small-scale agricultural scenarios the following options could be applied to make NPV of the feedstock production positive: a) to raise *Jatropha* oilseed price by 1.92-2.38 times, or b) to impose government's subsidies on working capital of at least 41.5-51.0%.

In both large scale and small-scale production scenarios the life-cycle NPV reduces as the CAPEX growth.

For the large scale production scenarios with CAPEX of 8.0, 11.5 and 15.0 MGBP, the life-cycle NPV is lower in options with the equities issuance (Private Capital) than in options where initial capital for biodiesel development consists entirely of borrowed capital (Bank Loan). However, scenarios with CAPEX of 18.5 and 20.3 MGBP, initial capital for biodiesel development consists entirely of borrowed capital (Bank Loan) produced lower life-cycle NPV than options with the equities issuance (Private Capital).

All large scale biodiesel production scenarios produce positive NPV (Tables 6.41 & 6.45) which indicates that the project delivers a surplus of benefit over cost and return on investment could be made. However, results of a sensitivity analysis demonstrate that in these scenarios, NPV becomes negative if the Price of *Jatropha* oil rises by 6.0-36.5% compared to the current *Jatropha* oilseed price of 5,000 Rs./t (63.1 GBP/t).

In all small-scale production scenarios, for CAPEX range of 0.11-0.30 MGBP, options where initial capital for biodiesel development is entirely consists on borrowed capital (Bank Loan) produced lower life-cycle NPV than options with the equities issuance (Private Capital).

All small-scale biodiesel production scenarios, with the only exception of 0.30 MGBP (Loan) scenario, produce positive NPV (Tables 6.42 & 6.46) which indicates that, with one only exception, the project delivers a surplus of benefit over cost and investment should be made. However, for these scenarios, NPV shifts to negative if Price of *Jatropha* oil rises by 1.0-46.0% compared to the current Jatropha oilseed price of 5,000 Rs./t (63.1 GBP/t).

The Total labour cost is responsible for ~46.0% of the Total production cost in all large scale agricultural scenarios (Table 6.43) and for ~67.0-76.5% of the Total production cost (Table 6.44) in all small-scale (Rainfed) agricultural scenarios. The harvesting, pruning and trimming cost is responsible for ~68.0% of the Total labour costs allocation for large scale (Irrigated) (Table 6.13, Chart 6.5) and ~43.0% to the small-scale (Rainfed) (Table 6.17, Chart 6.8) agricultural scenarios. This is significantly higher than share for the weeding, soil working and fertilizer application costs - ~15.5% and ~31.0% for large and small-scale scenarios respectively, and share for the maintenance and irrigation costs - ~11.0% and ~21.0% for large and small-scale scenarios respectively. One way to reduce the Total production cost is to reduce the Total labour cost as the biggest single share of overall production cost.

The harvesting labour requirement and labour cost are strongly influenced by the canopy spread. Terminal pruning at 45-60 cm in the first year of planting and similarly continuous light pruning of secondary and tertiary branches during the dormant period is necessary for maintaining a suitable canopy spread at a height to facilitate manual picking of seeds. This will result in a lower and wider tree shape, induce earlier seed production and decrease cost of the manual *Jatropha* seeds harvesting (ICRISAT: 2008. Activity 7.2.1.2). Since it is a wild plant, its seeds do not ripen at the same time, so a field of Jatropha cannot all be harvested at once. University of California - Davis agronomist Sham Goyal says they are trying to solve that problem through breeding and genetic modification. Once Jatropha is cultivated, technology will need to be developed to mechanically harvest it. But this is still years away.

Cost of CO_2eq abatement (12.7-72.6 GBP/tCO_2eq) for all biodiesel production Irrigated and Rainfed scenarios are in conformity with results (78.8-106.4 GBP/tCO_2eq) reported by Fulton (2004) and Larive (2005) and recited by Worldwatch Institute (2007) and with costs of CO_2eq abatement for other renewable technology options (i.e. 67.4 GBP/tCO_2eq for wind energy, excluding back up generation). All others renewable technology options have much higher costs of CO_2eq abatement (i.e. 578.3 GBP/tCO_2eq for wind energy, including back up generation (Australia) and 417.8 GBP/tCO_2eq for wind energy, including back up generation (UK)) presented in Table 9.1.

9.4 Cost-benefit analysis

9.4.1 Agriculture

The research results for the oleaginous plant of *Jatropha curcas* cultivation and associated biodiesel production indicate that results of both cost-benefit and cost-effectiveness analyses are much more significant than results of the life-cycle assessment.

In terms of overall cost-benefit analysis the agricultural sector has to be examined closely, from the analysis it appears that it is not possible to produce *Jatropha* oilseeds with positive NPV under the current conditions in Indian agricultural economics (e.g. *Jatropha* oilseed price of 5,000 Rs./t (63.1 GBP/t) conditions) (Tables 6.39 & 6.40). Following straight forward cost-benefit analysis theory it would be appropriate to conclude that if NPV is negative - investment should not be made and large block-plantations of *Jatropha curcas* should be replaced with any other food or cash crop which will have a more beneficial NPV.

Detailed analysis of CBA results for large scale (Irrigated) agricultural scenarios (Table 6.43) reveals that in all mentioned above scenarios the Net income per life cycle is negative for (IRR_Agro I (Loan) and IRR_Agro II (Loan)) scenarios and positive for (IRR_Agro I (Private Capital) and IRR_Agro II (Private Capital)) scenarios. At the same time, the Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA) per life cycle are positive for all large scale agricultural scenarios. Even though, in all large scale scenarios, the options with the equities issuance (Private Capital) produced better financial performance than options in which the initial capital for biodiesel development is entirely consists on borrowed capital (Bank Loan).

In all large scale agricultural scenarios, the Total labour cost is responsible for ~46.0%; Materials and energy costs for ~36.0%; and Total transportation cost of oilseeds for ~13.0% of the Total production cost. Other costs do not make significant contribution to the Total production cost.

Analysis of CBA results for small-scale (Rainfed) agricultural scenarios (Table 6.44) reveals that in all small-scale agricultural scenarios the Net income per life cycle is negative and EBITDA per life cycle is also negative for all small-scale agricultural scenarios. In all small-scale scenarios with the only borrowed capital (Bank Loan) option, the difference in NPV between all three scenarios is insignificant with small prevalence of RAIN_Agro III scenario as costs of the chemical fertilizers, agrochemicals and energy for irrigation inputs are equal to zero in this case.

In all small-scale agricultural scenarios, the Total labour cost is responsible for ~67.0% for RAIN_Agro I and RAIN_Agro II, and 76.5% for RAIN_Agro III scenarios; Materials and energy costs - for ~14.0% for RAIN_Agro I and RAIN_Agro II, and 2.4% for RAIN_Agro III scenarios; and Total transportation cost of oilseeds for ~12.0% for RAIN_Agro I and RAIN_Agro II, and 13.5% for RAIN_Agro III scenarios of the Total production cost. Other costs do not make significant contribution to the Total production cost.

The establishment cost of *Jatropha* plantation in India is relatively high compared to the similar costs in other parts of the World due to the predominance of the manual labour used, despite the fact that agricultural labour in India is fairly cheap. The calculated labour cost fraction in the oilseeds cultivation component of CBA reached as much as ~46.0% of the Total Production Cost in IRR_Agro I and IRR_Agro II scenarios, ~67.0% in RAIN_Agro I and RAIN_Agro II scenarios and ~76.5% in RAIN_Agro III scenarios. It is considerably larger than the labour cost fraction in biodiesel production scenarios where it stays as low as 0.45% of Total Production Cost in all large scale and 1.3% in small-scale scenarios.

As the Planning Commission and the National Mission on Biodiesel are targeting waste lands and dry lands for *Jatropha* cultivation, no machinery for plantation site preparation, tillage, ploughing, digging and weeding can be widely used, with the exception of the draft animal usage for the local logistics operations.

The harvesting, pruning and trimming cost is responsible for ~68.0% of the Total labour costs allocation for large scale (Irrigated) (Table 6.13, Chart 6.5) and ~43.0% to the small-scale (Rainfed) (Table 6.17, Chart 6.8) agricultural scenarios. This is significantly higher than share for the weeding, soil working and fertilizer application costs - ~15.5% and ~31.0% for large and small-scale scenarios respectively, and share for the maintenance and irrigation costs - ~11.0% and ~21.0% for large and small-scale scenarios respectively. The cumulative costs of other agricultural operations are not so much significant for both large and small-scale scenarios.

The high cost of *Jatropha* fruits harvesting is augmented by the fact that they do not ripen all at once, but over a time span of 2-3 month. Under some conditions, flowering and fruits ripening may occur all year around and, therefore, yearlong harvesting will be required. Also, there is no currently harvesting machinery designed factured specifically for *Jatropha curcas* fruits.

For all agricultural scenarios in CBA the chemical fertilizers and agrochemicals, and energy for irrigation are the main contributors to the material and irrigation costs. Thus, for large scale IRR_Agro_I scenario they are responsible for ~53.0% and ~40.0%, for IRR_Agro_II scenario - ~66.0% and ~34.0% correspondingly of the total materials and energy costs (Tables 6.11 & 6.12, Charts 6.3 & 6.4). For Rainfed scenarios the chemical fertilizers and agrochemicals are responsible for ~83.5% of the total material costs in RAIN_Agro_I and 100.0% in RAIN_Agro_II scenarios (Tables 6.15 & 6.16, Charts 6.6 & 6.7).

The results of the sensitivity analysis (Chapter 8) for large scale agricultural (IRR_Agro I and IRR_Agro II, both Loan and Private Capital) scenarios demonstrate the following options to make NPV of the feedstock production positive: a) to raise *Jatropha* oilseed price by 1.91-2.08 times, b) to impose government's subsidies on working capital of at least ~41.5-70.0%, or c) to impose government's subsidies on CAPEX of at least ~27.0-29.0%.

For small-scale agricultural scenarios sensitivity analysis produces the following options: a) to raise *Jatropha* oilseed price by 1.92-2.38 times, or b) to impose government's subsidies on working capital of at least 41.5-51.0%.

The National Biodiesel Mission has a target of least 2.0 million ha of *Jatropha* on wastelands, along with 2.4 million ha on culturable fallow lands, 2.0 million ha on wastelands under integrated watershed development, 1.0 million ha of strip lands, 3.0 million ha of the forest lands, 3.0 million ha of hedges, 2.0 million ha as agroforestry, and 4.0 million ha of additional wastelands (GOI: 2003, Kumar & Srivastava: 2009). The biocrops producers might get some benefit from the subsidies and soft loans for acquiring agricultural and haulage machinery designed specifically for small-scale operations. At the same time, local automotive and farm machinery industries will benefit from the supported from the Indian Government orders to design, test and mass-produce of these small-scale tools and machinery.

Additional research is required to identify relationships between *Jatropha* oilseed yields and organic and chemical fertilizers applications in different agro-climatic zones allowing optimization of these applications.

There is no real scope for agricultural labour costs reductions, as real daily wages in the agricultural sector reported in the "Range of Minimum Wages" by the GOI Labour Bureau, already appears to be much lower than the medium wage, especially relating to informal hiring practices (Lerche: pers. comm., GOI Labour Bureau: no date).

There should be a closer link between the extension and research services, so that both services see their joint role as generating, adapting and disseminating appropriate technology to farmers (Mattee: 1994, Rasheed & Van den Ban: 2000). The emphasis, even now continues to be on food grains, though broad basing of agricultural extension (including messages for other crops/enterprises) is an accepted philosophy (Rasheed & Van den Ban: 2000). Cho and Boland (2004 cited by Allahyari: 2008) say that extension objectives toward sustainability could range from the effective transfer of technology to the building up of strong rural organizations, which can exert influence over future research and policy agendas and also take and enforce collective decisions over natural resource management.

The current extension system should include the widespread involvement of farmers in the generation of new technologies, so these technologies will have a significant impact on agricultural practices. Two current trends should be stressed: a) instead of technology transfer with its top-down character, it is preferable to talk about knowledge networks, knowledge exchange and knowledge co-creation; and b) the introduction of market relationships between farmers, knowledge workers (advisors, researchers, *etc*) and other stakeholders, and recognition that knowledge has got a price, as a product in the knowledge market (Wielinga (Eelke): 2008).

The initiative of the State Agricultural Universities, which have expanded their extension activities to provide more comprehensive services to farmers, should be expanded both within India and include energy crops also. Thus, Punjab Agricultural University employs its own multi-disciplinary extension team in each district, engaged in adaptive research, training and consultancy. In Andhra Pradesh, Acharya N. G. Ranga Agricultural University (ANGRAU) has established District Agricultural Advisory and Transfer of Technology Centres in all the districts. These comprise of a team of 2-4 scientists from various disciplines to refine technology, make diagnostic visits and organize field programmes in collaboration with Department of Agriculture and other line departments (Sulaiman: 2003).

The TBOS cultivation and associated biodiesel production will also benefit from a broad range of activities to improve rural infrastructure. For example, creation of irrigation facilities (including minor irrigation facilities) and construction rural roads for better connectivity are two major activities taken up through the Rural Infrastructure Development Fund. Several recently published reports (NCAER: 2006, Rajeev: 2008, KPMG in India: 2009) address the gaps in infrastructure supporting the agricultural sector (e.g. a) marketing infrastructure; b) soft infrastructure; and c) basic infrastructure including power, roads, telecom, transport, and drinking water supply and sanitation). They stress the strong positive correlation between rural poverty and deficiency of infrastructure and analyse the considerable efforts are made to extricate the agricultural sector from stagnation. These include the privatization and commercialization of infrastructure, although privatization should be limited in scale and gradual in the initial stages. Finally, existing reports offer adequate measures and policy recommendations for the Indian rural infrastructure improvement including central government schemes as well as involvement of broad range of stakeholders (e.g. local residents and self-governments) in projects formulation and implementation.

9.4.2 Production

All large scale biodiesel production scenarios produce positive NPV (Tables 6.41 & 6.45) which indicates that the project delivers a surplus of benefit over cost and return on investment could be made. However, results of a sensitivity analysis demonstrate that in large scale production scenarios, NPV becomes negative if the Price of *Jatropha* oil rises by 6.0% for 20.3 MGBP scenario to 36.5% for 8.0 MGBP scenario compared to the current *Jatropha* oilseed price of 5,000 Rs./t (63.1 GBP/t).

All small-scale biodiesel production scenarios, with the only exception of 0.30 MGBP (Loan) scenario, produce positive NPV (Tables 6.42 & 6.46) which indicates that, with one only exception, the project delivers a surplus of benefit over cost and investment should be made. Results of a sensitivity analysis demonstrates that for small-scale production scenarios, NPV shifts to negative if Price of *Jatropha* oil rises by 1.0% for 0.3 MGBP scenario to 46.0% for 0.11 MGBP scenario compared to the current Jatropha oilseed price of 5,000 Rs./t (63.1 GBP/t).

For the large scale production scenarios with CAPEX for biodiesel plant, seed procurement centres and sub-centres, and drip irrigation of 8.0, 11.5 and 15.0 MGBP, the life-cycle NPV is lower in options with the equities issuance (Private Capital) than in options where initial capital for biodiesel development consists entirely of borrowed capital (Bank Loan). However, scenarios with CAPEX of 18.5 and 20.3 MGBP, initial capital for biodiesel development consists entirely of borrowed capital (Bank Loan) produced lower life-cycle NPV than options with the equities issuance (Private Capital). This is the impact of significant interest expense charges resulted from extensive capital borrowings to finance CAPEX expenditures.

In all large scale production scenarios (Table 6.45), Materials costs are responsible for ~91.0%, and Costs of transportation for ~8.5% of the Total production cost. Other costs do not make significant contribution to the Total production cost.

In this case, the cost of *Jatropha* oil contributes 74.0%, cost of Methanol - 16.5%, cost of water (in circulation) - 4.8%, and cost of catalyst - 3.5% to the Total material costs (Table 6.47, Chart 6.9). Other costs make significantly lesser contribution to the Total material costs.

In all small-scale production scenarios, for all range of CAPEX from 0.11 to 0.30 MGBP, options where initial capital for biodiesel development is entirely consists on borrowed capital (Bank Loan) produced lower life-cycle NPV than options with the equities issuance (Private Capital). In both large scale and small-scale scenarios the life-cycle NPV reduces as the CAPEX growth.

In these scenarios (Table 6.46), Materials costs are responsible for ~96.5%, Cost of labour for ~1.3%, and Costs of transportation for ~1.6% of the Total production cost. Other costs make significantly lesser contribution to the Total production cost. The distribution of the Total material costs (Table 6.49, Chart 6.11) is similar to the large scale production scenarios.

9.4.3 Subsidies

As would be expected, in an established market the price of *Jatropha* oilseeds, as a final product of agricultural enterprise, has a strong influence on price of *Jatropha* SVO, the main raw material for biodiesel production. To make the feedstock cultivation profitable (when NPV in agricultural scenarios shifts to positive, or, at least, to reach break-even point), it is required to increase the market price of *Jatropha* oilseeds by 2.0-2.5 times. However, this boost will lead to increase in price of *Jatropha* SVO, as a feedstock for biodiesel production and affect economic performance of biodiesel production industry. The NPV of the production industry switches to negative, if *Jatropha* SVO price will increase by only 6.0%-30.0%, depending on biodiesel plant and infrastructure CAPEX.

Development of biodiesel production industry in India is highly political and, therefore, the cancellation, reduction in scale of operation, or delay in the launched 2003 action programme of the National Mission on Bio-diesel is certainly not an option, the Indian government should intervene and support the higher price of *Jatropha* oilseeds for farmers who were lured to switch to the *Jatropha* biocrop, and at the same time to keep the *Jatropha* SVO price at an acceptable level for the biodiesel industry. As such, it will require strong and direct government's intervention to both agricultural and industrial phases of this chain, to keep them in business. In other words, the Indian Government should ensure the balance of, and mitigate the conflict which is proven to happen at the feedstock price point.

As such, the Indian Government should consider supporting the farmers and biodiesel industry by subsidizing *Jatropha* oilseed and *Jatropha* SVO prices, working capital and capital expenditures for establishment of *Jatropha* plantations and biodiesel production industry. Another option is a low-interest loans guaranteed by the Indian Government, buy-back agreements for both *Jatropha* oilseeds and biodiesel guaranteed by Government minimum prices, and subsidies for retail price of biodiesel to ensure it will be affordable for the broad-spectrum of population.

The results of this work do not show a way in which subsidies could be removed. In deciding whether to support this technology, the public support for early stage commercialization investment might be considered as illustrated in the "Stern Review: The Economics of Climate Change" (2006) by experience curves. However, practically speaking, the time span of reaching and passing the equilibrium point of biodiesel (new technology) price with petrodiesel (incumbent technology) price should be reasonable. In this case reasonable means a 5 to 10 years life span, which should be strictly attached to the Five Years Planning practice accepted in India. The Government subsidies applied to biodiesel production and development can be reflected in the budget either as a discount from revenue or expenses. As such, discount from revenue will be reflected as a tax relief or tax discount, and expenses as an amount of money which actually returns to the *Jatropha*/feedstock growers or biodiesel producers. Subsidies should be stopped as soon as biodiesel and petrodiesel prices will reach a breakeven point, or *Jatropha*/feedstock and biodiesel producers will reach at least zero accounting profit.

Once government has a good reason to support establishment and biodiesel development with subsidies, subsidies should not be excessive and should be removed or significantly reduced as soon as oilseeds production will increase and cost of *Jatropha* oilseeds cultivation is going to fall. However, before paying subsidies on *Jatropha* oilseeds cultivation, the government should make a decision, if this is the best crop to be subsidized, as this money has opportunity cost.

Government must ensure that imposed subsidies will be waived in the reasonably short time span if they are no longer necessary (Stern: 2006, Altenburg, *et. al.*: 2009). "Experience curves illustrate that new technologies may not become cost effective until significant investment has been made and experience developed. Significant learning effects may reduce the incentive to invest in innovation, if companies wait until the innovator has already proven a market for a new cost effective technology" (Stern: 2006).

9.4.4 Correlation analysis

The correlation analyses for all agricultural and production scenarios were completed utilizing the corresponding results of sensitivity analyses. The original data for these analyses has been taken from the "Sensitivity" worksheets of the Sensitivity Analysis tables, which has been produced utilizing the Pearson product moment correlation (parametric) method in which input data generated by a Monte Carlo type random sampling (2000 iterations) using the Visual Basic Code for Stochastic Sensitivity Analysis (Appendix VII). For all large scale agricultural scenarios, the correlation results demonstrate that the price of oilseeds, the yields, the labour cost, and subsidies on working capital (Private Capital) are all significantly correlated with NPV and NPV/GHG avoided ratio. Some other parameters, such as discount rate, interest charges on CAPEX, interest charges on working capital, subsidies on working capital (Loan) and subsidies on CAPEX show less correlation with the NPV and NPV/GHG avoided ratio.

For all small-scale agricultural scenarios, the price, the yield, the labour cost, discount rate, and subsidies on working capital are all significantly correlated with NPV and NPV/GHG avoided ratio. Some other parameters, such as interest charges on CAPEX, interest charges on working capital and subsidies on CAPEX show less correlation with NPV and NPV/GHG avoided ratio.

For both large scale and small-scale production scenarios, only the price of oil is significantly correlated with NPV and NPV/GHG avoided ratio. The remaining parameters show little or no correlation.

9.5 Cost-effectiveness analysis

The NPV to GHG avoided ratio has been selected as a performance indicator in Cost-effectiveness analysis. The detailed discussion of the cost-effectiveness analysis results can be found in Chapter 7 of this thesis. All large scale and small-scale agricultural scenarios produced negative NPV/CO_2eq avoided ratios due to a negative NPV in all agricultural scenarios.

9.5.1 Large scale agriculture

In the large scale agricultural scenarios there is no difference in NPV1/tCO_2eq avoided ratio between IRR I (Loan) and IRR II (Loan) scenarios and in NPV2/tCO_2eq avoided ratio between IRR I (Private Capital) and IRR II (Private Capital) scenarios where hulls and seed shells fruit utilized as compost (IRR I), or as combustibles (IRR II) respectively. Also, NPV2/tCO_2eq avoided ratio is better than NPV1/tCO_2eq avoided ratio for both IRR I and IRR II scenarios by 9.2-14.2%.

In all large scale both NPV1/tCO_2eq avoided and NPV2/tCO_2eq avoided ratios are getting better with growth of CAPEX from 8.0 to 20.3 MGBP.

In large scale scenarios, which employs "One-stage Henkel Transesterification process" (IRR I_Production) the NPV1/tCO_2eq avoided ratio is ~12.5 times better in 20.3 MGBP scenarios than in 8.0 MGBP scenarios, and NPV2/tCO_2eq avoided ratio is ~7.0 times better in 20.3 MGBP scenarios than in 8.0 MGBP scenarios with the growth of CAPEX only in 2.54 times.

In large scale scenarios which employs "Two-stages Lurgi process: Fat-splitting and Esterification" (IRR II_Production), the NPV1/tCO_2eq avoided ratio is ~8.25 times better in 20.3 MGBP scenarios than in 8.0 MGBP scenarios, and NPV2/tCO_2eq avoided ratio is ~4.65 times better in 20.3 MGBP scenarios than in 8.0 MGBP scenarios with the growth of CAPEX only in 2.54 times.

Both NPV1/tCO_2eq avoided and NPV2/tCO_2eq avoided ratios is better in scenarios which employs "Two-stages Lurgi process" (Table 7.1) than in scenarios which employs "One-stage Henkel Transesterification process" (Table 7.3) by 0.0-16.2%, with reduction trend simultaneously with CAPEX growth from 8.0 MGBP to 18.5 MGBP. The only exception occurs at 20.3 MGBP CAPEX where both specified above ratios in scenarios which employs "One-stage Henkel Transesterification process" is better than in scenarios which employs "Two-stage Lurgi" process by 21.4-22.2%.

9.5.2 Small-scale agriculture

In small-scale agricultural scenarios the NPV1/tCO_2eq avoided ratio is 1.4-2.6% better in RAIN I (Loan) scenario than in RAIN II (Loan) scenario. Small-scale (RAIN III - no chemical fertilizers applied) scenario has better performance than RAIN I and RAIN II scenarios by 42.0-42.5%, and better than both IRR I and IRR II by 41.0-42.9%, as in this scenario emissions from the chemical fertilizers usage are equal to zero.

In all small-scale production scenarios both NPV1/tCO_2eq avoided and NPV2/tCO_2eq avoided ratios are getting better with growth of CAPEX from 0.11 to 0.3 MGBP.

In both small-scale scenarios - "Organic, chemical fertilizers and agro-chemicals applied" (RAIN I_Production) and "No fertilizers and agro-chemicals used" (RAIN II_Production), the NPV1/tCO_2eq avoided ratio is ~7.0 times better in 0.30 MGBP scenarios than in 0.11 MGBP scenarios, and NPV2/tCO_2eq avoided ratio is ~7.5 times better in 0.30 MGBP scenarios than in 0.11 MGBP scenarios with the growth of CAPEX only in 2.73 times.

Both NPV1/tCO_2eq avoided and NPV2/tCO_2eq avoided ratios is better in small-scale, No fertilizers and agro-chemicals used (RAIN II_Production) scenarios than in small-scale, organic, chemical fertilizers and agro-chemicals applied (RAIN I_Production) scenarios by ~7.0% for 0.11 MGBP scenario and by 2.2-3.9% for 0.16 MGBP-0.30 MGBP scenarios with no particular tendency established in this case.

9.6 Life cycle assessment

To show the potential savings, the energy use and CO_2eq emissions for each model have been compared with the Well-to-Tank (WTT) energy and GHG emissions for conventional diesel.

The results show that most biodiesel models, with exception of Irrigated I, a12 (High) scenario which utilize coal boiler and grid electricity, and press-cake used as fertilizer and b12 (High) scenario which utilized coal boiler combined with CHP, and press-cake used as fertilizer, give lower WTT greenhouse gas emissions when compared with petrodiesel, but that the process models and how the by-products are used strongly affect the results. Some other scenarios such as Irrigated I, a12 (High) scenario which utilize coal boiler and grid electricity, and press-cake used as co-fuel for power plant and b12 (High) scenario which utilized coal boiler combined with CHP, and press-cake used as co-fuel for power plant, produce GHG savings as low as ~6% compare to WTT greenhouse gas emissions for petrodiesel.

All of the models considered generate net fossil energy savings from 0.26 $GJ_f/GJ_{biodiesel}$ in Model a21 which utilizes outdated industrial scheme of NG boiler and grid electricity to 0.47 $GJ_f/GJ_{biodiesel}$ in Model c12 which utilizes NG GT and co-fired HRSG. All other models provide better energy and GHG results generally because they export electricity produced by CHP, instead of using grid electricity. The best performance is demonstrated by Model e which shows the combined benefits of integrated biomass gasifier, CHP and fuelling the biodiesel production with press-cake as co-fuel for power plant. Additional benefits have been produced by displacing additional electricity from Indian National Grid with renewable electricity from *Jatropha* press-cake. The most likely commercial option is Model c11 or c21 which utilize a natural gas fired gas turbine with unfired HRSG, and press-cake as fertilizer.

In the Irrigated II scenario, the worst performance is displayed by Model c12 which utilizes advanced CHP industrial configuration such as NG GT and co-fired HRSG and also utilizes press-cake as fertilizer, and, at the same time, Models a11, a12, a21 without CHP configuration, which can presently be considered as outdated industrial configuration. All other models provide better energy and GHG results generally because they export electricity produced by CHP, instead of using grid electricity.

The best performance is demonstrated by Model d2, where electricity is generated with a backpressure turbine to match heat requirement augmented by a condensing turbine for surplus steam and fuelling biodiesel production with press-cake. Model e which combines benefits of biomass gasification and CHP augmented by backpressure and condensing turbine for surplus steam also gives a good performance. Other benefits have been produced by displacing additional electricity from the Indian National Grid with renewable electricity. Once again, the most likely commercial option is Model c11 or c21 which utilize a natural gas fired gas turbine with unfired HRSG, and press-cake as fertilizer.

Both Rainfed I and Rainfed II scenarios demonstrate much better energy and GHG emissions performance than both Irrigated I and Irrigated II scenarios. In both Rainfed scenarios the best performance is again demonstrated by Models which employs CHP and utilizes press-cake as co-fuel for power plant, and the worst performance by Models which without a CHP configuration can presently be considered as outdated industrial configuration. The most likely commercial option is Model h11 which utilize anaerobic digester and externally fired microturbine with HUB, and press-cake as fertilizer.

Some Models actually save more fossil energy than is contained in the produced biodiesel as a result of the large energy savings attached to electricity production and other by-products utilization. The GHG savings has a pattern which is clearly corresponding with the energy. The emissions from farming, especially excessive N_2O emissions, are responsible for significant fraction of total GHG emissions. Unfortunately, considerable benefits of energy and GHG savings produced by small-scale in comparison to large scale *Jatropha* cultivation have been challenged by the negative results of the Cost-benefit analysis for the same Models.

The results of preliminary cost-effectiveness analysis such as costs of GHG avoided (GBP/tCO_2eq) for all Irrigated and Rainfed scenarios were compared to the current price of 1 tonne of GHG avoided which is equal to the price of 1 Certified Emissions Reduction (CER) of ~6.3-14.2 GBP/tCO_2eq (additional comments related to this issue can be found in subchapter 7.1: "Costs of GHG avoided").

In Irrigated I scenario cost of GHG abatement has a range from -0.74 GBP/tCO_2eq in Model c21 (NG GT and unfired HRSG with BPSTG) to 72.56 GBP/tCO_2eq in Model a11 (oil boiler and grid electricity). This is between 0.052 in Model c21 and 11.52 in Model a11 times more than current market CER price range.

In Irrigated II scenario cost of GHG abatement has a range from 12.67 GBP/tCO_2eq in Model d2 (biomass-fuelled boiler and BP/cond STG), to 42.04 GBP/tCO_2eq in Model a11 (oil boiler and grid electricity). This is between 0.89 in Model d2 and 6.67 in Model a11 times more than current market CER price range.

In Rainfed I scenario cost of GHG abatement has a range from 16.75 GBP/tCO_2eq in Model h11 (anaerobic digester, externally fired microturbine with HUB) to 58.86 GBP/tCO_2eq in Model h12 (integrated biomass gasifier, gas engine genset with HUB). This is between 1.81 in Model h11 and 9.34 in Model h12 times more than current market CER price range.

In Rainfed II scenario cost of GHG abatement has a range from 24.15 GBP/tCO_2eq in Model h11 to 54.25 GBP/tCO_2eq in Model h12. This is between 1.70 in Model h11 and 8.61 in Model h12 times more than current market CER price range.

These numbers are in conformity with results reported by Fulton (2004) and Larive (2005) and recited by Worldwatch Institute (2007) and with costs of CO_2eq abatement for other renewable technology options (i.e. wind energy, excluding back up generation) presented in Table 9.1. Thus, according to estimates analysed by Fulton (2004), biofuels are currently a relatively expensive means of reducing GHG emissions compared to other mitigation measures, with the cost of CO_2eq reductions exceeding € 135.0 (106.4 GBP) per tonne CO_2 avoided. Larive (2005) says there are no biofuiel options that cost less than € 100.0 (78.8 GBP) per tonne CO_2 avoided. For example, several studies in EU have concluded that GHG emissions savings from fuel ethanol, based on domestic production using wheat and sugar beets, have cost a minimum of € 200.0 (157.6 GBP) per tonne CO_2 - about ten times the marginal abatement cost in the EU emissions trading scheme of € 20.0 (15.8 GBP) per tonne (Ibid.).

Researchers from the Battelle, Joint Global Change Research Institute (Maryland, USA) estimated that carbon capture at a coal-fueled power plant would cost 25-65 USD/tCO_2 (~12.6-32.7 GBP/tCO_2) with CO_2 transport and storage adding 12.0-15.0 USD/tCO_2 (~6.0-7.5 GBP/tCO_2). Mohammed Al-Juaied and Adam Whitmore of the Belfer Center for Science and International Affairs, Harvard University say that a likely representative range of costs of abatement from CCS excluding transport and storage costs appears to be 100.0-150.0 USD/tCO_2 (~50.0-75.5 GBP/tCO_2) for first-of-a-kind plants and perhaps 30.0-50.0 USD/tCO_2 (~15.0-25.0 GBP/tCO_2) for nth-of-a-kind plants (Al-Juaied & Whitmore: 2009). The costs of emissions avoided for the several other options summarized in Tables 9.1 and 9.2. The investment costs for power projects and the investment costs for biomass power projects and production of transportation fuels are presented in Tables 9.3 and 9.4 respectively.

Table 9.1: Technology options for reducing emissions

Technology option	Cost of abatement		
	€ tCO_2^{-1}	USD tCO_2^{-1}	GBP tCO_2^{-1}
Wind (excluding back up generation) (Aus)[1]		134	67.4
Wind (including back up generation) (Aus)[1]		1149	578.3
Wind (including back up generation) (UK)[1]		830	417.8
'Clean Coal' (IGCC + CCS)[1]		56	28.2
'Clean Coal' (IGCC + CCS)[3]		32	16.1
Combined Cycle Gas Turbine + CCS[1]		47	23.7
Combined Cycle Gas Turbine[1]		33	16.6
Nuclear Power[1]		22	11.1
Nuclear Power[2]	15-50		11.8-39.4
Waste to Energy Power Plant[4]	77		60.7
Domestic Solar Hot Water Heating[5]			600

Sources:
1) Lang: 2009;
2) Fritsche: 2006;
3) Carnegie Mellon University: 2007;
4) Dijkgraaf & Vollebergh: 2004;
5) McKinzey: 2007

Table 9.2: Costs of GHG abatement for power plants with CO_2 capture

Type of plant	Cost of abatement	
	€ tCO_2^{-1}	GBP tCO_2^{-1}
Pre-combustion capture		
Natural Gas (NGCC)	43	33.9
Coal (IGCC)	26	20.5
Post-combastion capture		
Natural Gas (NGCC)	37	29.2
Natural Gas fired (steam)	30	23.6
Coal (pulverized)	29	22.9

Source: Balat: 2008

To make average costs of GHG avoided comparable with current CER price, the price of *Jatropha* oilseeds should be reduced by 0.91-1.99 times in Irrigated I, by 0.98-1.40 times in Irrigated II, by 1.23-1.91 times for Rainfed I, and by 1.22-1.89 times for Rainfed II scenarios. However, in this case, the effect on economics of *Jatropha* oilseeds cultivation (agricultural scenarios) will be disastrous.

Table 9.3: Investment costs for power projects

Power plant	**Million GBP per MW**	**Country/ Region**	**Reference**
Coal-fired plant	0.81-1.01	The Philippines	The Brattle Group: 2008
Coal-fired plant	0.12-0.20	Europe	Faaij: 2006
Coal-fired plant	0.45	Turkey	a) Guner: 2007; b) McKeigue, De Cunha & Severino: 2009
Natural Gas/LPG/Fuel oil-fired plant	0.45	Turkey	a) Guner: 2007; b) McKeigue, De Cunha & Severino: 2009
Hydroelectricity	0.73	Turkey	a) Guner: 2007; b) McKeigue, De Cunha & Severino: 2009
Small hydro plant	1.58	Greece	Terra Energy S.A.: 2009
On-land wind	0.79	Greece	Terra Energy S.A.: 2009
On-land wind	1.01	Turkey	Guner: 2007
On-land wind	0.79-1.1 (0.97 ave.)	Europe	European Wind Energy Association, in 2006
On-land wind	0.63	India	Rajagopalan: 2005
Offshore wind, 2006	1.42-1.89 (1.66 ave.)	Europe	European Wind Energy Association
Offshore wind, 2015	1.22-1.62 (1.43 ave.)	Europe	European Wind Energy Association
Offshore wind	3.0	United Kingdom	Centrica: 2008
Offshore wind, 2006	1.60	United Kingdom	IEA: 2006
Offshore wind, 2011	1.75	United Kingdom	IEA: 2006
Wind	0.95-1.34	Europe	Slungård & Holt: 2008
Wind	1.51	Indonesia	Wirasantosa: 2008
Micro hydro	0.10-1.0	Indonesia	Wirasantosa: 2008
Ocean	1.0-3.52	Indonesia	Wirasantosa: 2008
Solar photovoltaic: a) Module b) System	 1.76-2.52 3.52-5.03	Indonesia	Wirasantosa: 2008
Solar photovoltaic	3.24	New Jersey, USA	Public Service Electric & Gas: 2009
Geothermal power plant	0.50-0.70	Indonesia	PT Rekazasa Industry: 2009
Geothermal power plants in a known field	0.55-0.86	Iceland	Stefánsson: 2002
Geothermal power plants in a unknown field	0.56-1.0	Iceland	Stefánsson: 2002
Waste-to-Energy power plant	4.20/MW electric; 1.18/MW thermal	Belgium	CEWP congress: 2008

Table 9.4: Investment costs for biomass power projects and production of transportation fuels

Power plant	Million GBP per MW	Country/ Region	Reference
Biomass power projects:			
Rice husk	0.60-1.41	Asia	Balasankari & Arul: 2009
Wood waste	0.50-1.26	Asia	Balasankari & Arul: 2009
Sugarcane cogeneration plants	0.45-1.01	Asia	Balasankari & Arul: 2009
Sugarcane cogeneration plants	0.83-1.16	Brazil	Trusted Sources: 2008
Straw/wood CHP 400 MW	1.03	Denmark	Danish Energy Authorities: 2005
Domestic boiler, 2008 and 2020	0.35-0.47/ MW thermal	Europe	Dornburg, *et. al.*: 2008
Industrial boiler, 2008 and 2020	0.34-0.37/ MW thermal	Europe	Dornburg, *et. al.*: 2008
Biomass plant	0.45-0.71	Indonesia	Wirasantosa: 2008
Biomass plant	0.50-0.63	India	NGO "Centre for Science and Environment": 2007
Biomass plant	0.50-2.52	Europe	IEA: 2007
Biomass combustion including grate firing and fluidized bed combustion	1.26-1.97 (1.50 ave.)	Europe	a) Faaj: 2006; b) Dornburg, *et. al.*: 2006
BIGCC power plants, 2007	1.0-1.51	USA	IEA: 2007
BIGCC power plants, 2020	1.18/MW electric	Europe	Dornburg, *et. al.*: 2008
Co-gasification, 2020	0.64/MW electric	Europe	Dornburg, *et. al.*: 2008
Biomass combustion steam cycle and CHP plants	0.50	USA	IEA: 2007
Co-firinng in coal power stations, 2008 and 2020	0.20/MW electric	Europe	Dornburg, *et. al.*: 2008
Grate-firing boiler, 2008 and 2020	1.50/MW electric	Europe	Dornburg, *et. al.*: 2008
CFB/BFB, 2008	1.58/MW electric	Europe	Dornburg, *et. al.*: 2008
CFB/BFB, 2020	1.26/MW electric	Europe	Dornburg, *et. al.*: 2008
CHP combustion, 2008	1.66/MW electric	Europe	Dornburg, *et. al.*: 2008
CHP combustion, 2020	1.50/MW electric	Europe	Dornburg, *et. al.*: 2008
Conversion to transportation fuels:			
Bio-oil unit	0.44-0.5	India	Rajagopalan: 2005
Lignocellulosic ethanol plant at 400 MW_{HHV} input	1.66/MW_{HHV}	Europe	Hamelinck, van Hooijdonk, & Faaij: 2005
Lignocellulosic ethanol plant at 2.0 GW_{HHV} input	0.71/MW_{HHV}	Europe	Hamelinck, van Hooijdonk, & Faaij: 2005
Lignocellulosic ethanol, 2008	1.64/MW fuel	Europe	Dornburg, *et. al.*: 2008
Lignocellulosic ethanol, 2020	0.18/MW fuel	Europe	Dornburg, *et. al.*: 2008
Methanol, 2008	0.99/MW fuel	Europe	Dornburg, *et. al.*: 2008
Methanol, 2020	0.87/MW fuel	Europe	Dornburg, *et. al.*: 2008
Fischer-Tropsch liquids, 2008	1.26/MW fuel	Europe	Dornburg, *et. al.*: 2008
Fischer-Tropsch liquids, 2020	0.95/MW fuel	Europe	Dornburg, *et. al.*: 2008
Hydrogen via gasification, 2008	0.63/MW fuel	Europe	Dornburg, *et. al.*: 2008
Hydrogen via gasification, 2020	0.52/MW fuel	Europe	Dornburg, *et. al.*: 2008
Biodiesel from palm oil, 2008	0.09/MW fuel	South-East Asia	Dornburg, *et. al.*: 2008
Biodiesel from palm oil, 2020	0.08/MW fuel	South-East Asia	Dornburg, *et. al.*: 2008
Biodiesel from *Jatropha*, 2008	0.15/MW fuel	South Asia	Dornburg, *et. al.*: 2008
Biodiesel from *Jatropha*, 2020	0.13/MW fuel	South Asia	Dornburg, *et. al.*: 2008

9.7 Life cycle assessment and techno-economic models improvement

The Royal Society (UK) stresses that while the efficiency of biofuels production should improve, policymakers must ensure life-cycle assessments become a routine requirement for decision-making (The Petroleum Economist: February, 2008 (Ed.)).

The current LCA model does not account for indirect land use change (LUC) (e.g. GHG from indirect LUC: approach and methodologies (risk adder, deterministic, econometric, *etc*) presented by Uwe Fritsche (2008)). The appropriate figures to be included for indirect LUC remain controversial since the Searchinger-Wang debate (2008). The models used in this thesis were already completed by this time and significant changes are not longer feasible.

Menichetti and Otto's (2009) review demonstrate that only a few studies take into account direct land use impacts driven by biofuel crop production. More specifically, less than one third of the studies defines an alternative land use reference system and calculates the intrinsic carbon stock. Potential impacts in terms of indirect land use change are not considered in the studies.

As discussed in subchapter 2.3: "Searchinger-Wang debate (2008)", LUC for biofuel production can occur in two ways: directly, when non-crop land is converted to energy crop lands (e.g. grassland is used to plant rapeseed for biodiesel), or indirectly, when existing food and feed crop acreage is converted for use as energy crops, thus inducing new production of the food/feed crop elsewhere, at the expense of native habitats, to meet total demand. Second order effects may also occur (e.g. expanded soybean production in pastureland leads to the conversion of rainforests into pastureland) (Ibid.).

A number of recent studies draw the conclusion that the effects of land use may completely offset the potential GHG emission reduction of biofuels, and even substantially increase emissions compared to conventional transport fuels. Thus, the conversion from forest peatland to oil palm plantation releases about 3,452 tCO_2/ha over 50 years and requires 423 years to pay the "carbon debt" (Fargione, *et. al.*: 2008)). As such, land use change impact calculations must be integrated to the further Life Cycle Analysis (LCA) for bioenergy crops and biofuels production, e.g. CO_2 emission from conversion of 1) abandoned cropland to *Jatropha* plantation, 2) grassland to *Jatropha* plantation, 3) forest to *Jatropha* plantation, and 4) peatland to *Jatropha* plantation.

Other impacts that should be included are the indirect impact of LUC on the carbon balance of surrounding areas. For instance, the hydrology of peatlands bordering *Jatropha* plantations may be negatively affected by drainage taking place in the plantations. Surrounding terrestrial and aquatic ecosystems may be affected by sediments in rivers caused by soil erosion and by fertilizer and pesticide runoff from plantations (Danielsen, *et. al.*: 2008).

Schmidt (2008) reveals that the modeling of increased yield is extremely sensitive to the choice of reference fertilizer application. Presently, the relationship between fertilizer applications and *Jatropha* oilseed yield is not yet established, and, therefore, was not included within both the life cycle and techno-economic models. As such, appropriate modifications to the above mentioned models should be considered as soon as this information is available. Furthermore, the technology performance and cost data should be constantly updated based on latest information, and costs and benefits should be compared in a consistent matter.

Besides the energy balance and GHG balance, other environmental impacts need to be carefully understood when discussing the possibility of using biofuel. Following Zah, *et. al.* (2007) recommendations, the framework for Life Cycle Analysis should be expanded by inclusion of impacts on soil degradation, resource depletion, biodiversity loss, ecotoxicity, air pollution and water contamination. Results of the recent study based on Zah, *et. al.* (2007) reveal that to date almost all biofuels are beyond the environmental benchmark for fossil fuels.

The certification of biofuels guidelines need not be used for certification per se, but as guidelines to assess the biofuels production sustainability (e.g. a) the environmental criteria and indicators: carbon storage (above and below ground), biodiversity loss/conservation, degradation of soil and erosion, impacts on the local water supply leading to scarcity and poor water quality, and air pollution, as well as a reporting on land-use change (displacement effect and carbon report); b) the social criteria and indicators: child labour, freedom of association, discrimination, health and safety, forced labour, wages, working hours, contracts and subcontractors, and finally land rights) (Woods & Diaz-Chavez: 2007, Wallis & Chalmers: 2007). However, the certification of biofuels is not covered in this Thesis and is considered to be outside the main research topic.

9.8 Comparing biodiversity

As countries strive to meet obligations to reduce carbon emissions under one international agreement (Kyoto Protocol), they may not only fail to meet their obligations under another

(Convention on Biological Diversity) but may actually hasten global climate change. Bekunda, *et. al*. (2009) state that global conventions such as for biodiversity (CBD), climate change (UNFCCC), and desertification (CCD) should all be summoned and used to ensure local and global communities can benefit from biofuel production. Thus, Danielsen, *et. al*. (2008) findings suggest that replacing high-carbon and high-biodiversity forest or peatland with oil-palm (or TBOS (AE)) monocultures in an effort to reduce the use of fossil fuels will accelerate both climate change and biodiversity loss. The broader recommendations of the Cramer Commission and the Roundtable on Sustainable Biofuels (RSB) would require that biofuels avoid areas of high biodiversity. In the U.S. the Energy Independence and Security Act of 2007 (EISA) contains the toughest restrictions on land conversion by forbidding any new clearing of natural areas for biofuel production. As such, the direct sources of biofuel feedstock has been restricted to existing actively managed or fallow agricultural lands and privately owned tree plantations, as well as wastes and residuals (e.g. waste products of pulp and paper industry (AE)) (Searchinger: 2009).

A potential method to assess the impact of monocrop biofuel plantation is described in Danielsen, *et. al*. (2008), where species number, richness and co-existence between monocrop and original habitat is compared.

In terms of liquid fuels for transport, biofuels contributed only 1.8% globally and, considering utilization for heating and industrial uses, made up just over 1.0% of total liquid fuel use globally (IEA: 2008, OECD/FAO: 2008, Jank: 2008 cited by Searchinger: 2009). For the foreseeable future, biofuel production will remain a small fraction of total petroleum fuel production. As the production of biofuel feedstocks increases, the marginal cost of supply increases as well because of limitations of suitable lands and available water, among other causes. As such, biofuels are unlikely to become the answer to high crude oil prices (ESMAP: 2007).

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Appendixes

Appendix I: Oil-producing crops

Plant	Latin name	kg oil ha^{-1}
Corn	*Zea mays*	145
Cashew nut	*Anacardium ccidentale*	148
Oat	*Avena sativa*	183
Palm	*Eruthea salvadorensis*	189
Lupine	*Lupinus albus*	195
Rubber seed	*Hevea brasiliensis*	217
Kenaf	*Hibiscus cannabinua L.*	230
Calendula	*Calendula officinalis*	256
Cotton	*Gossupium hirsutum*	273
Hemp	*Cannabis sativa*	305
Soybean	*Glucine max*	375
Coffee	*Coffea Arabica*	386
Linseed	*Linum usitatissium*	402
Hazelnut	*Corulus avellana*	404
Euphorbia	*Euphorbia lagasse*	440
Pumpkin seed	*Cucurbita pepo*	449
Coriander	*Coriandrum sativum*	450
Mustard	*Brassica alba*	481
Camelina	*Camelina sativa*	490
Sesame	*Sesamum indicum*	585
Crambe	*Crambe abyssinica*	589
Safflower	*Carthamus tinctorius*	655
Buffalo gourd	*Cucurbita foetidissima*	665
Rice	*Oriza sativa L.*	696
Tung oil tree	*Aleurites fordii*	790
Sunflower	*Helianthus annuus*	800
Cocoa	*Theobroma cacao*	863
Peanut	*Arachis hypogaea*	890
Opium poppy	*Papaver somniferum*	978
Rapeseed	*Brassica napus*	1000
Olive tree	*Olea europaea*	1019
Piassava	*Attalea funifera*	1112
Gopher plant	*Euphorbia lathuris*	1119
Castor bean	*Ricinus communis*	1188
Bacuri	*Platonia insignis*	1197

Pecan	*Carya illinoensi*	1505
Jojoba	*Simmondsia chinesi*	1528
Babassu palm	*Orbignua martianass*	1541
Jatropha	*Jatropha curcas*	1590
Macadamia nut	*Macadamia terniflora*	1887
Brazil nut	*Bertholletia excels*	2010
Avocado	*Persea Americana*	2217
Coconut	*Cocos nucifera*	2260
Oitica	*Licania rigida*	2520
Buriti palm	*Mauritia flexuosa*	2743
Pequi	*Caryocar brasiliense*	3142
Macauba palm	*Acrocomia aculeate*	3775
Oil palm	*Elaesis guineensis*	5000

Source: Tickell: 2000, cited by Faupel & Kurki: 2002

Appendix II: Availability of wasteland

State	Potential area for *Jatropha* cultivation, ha
Andhra Pradesh	4,396,000
Arunachal Pradesh	997,000
Assam	1,456,000
Bihar/Jharkhand	186,000
Goa	40,000
Gujarat	2,871,000
Haryana	262,000
Karnataka	1,789,000
Kerala	100,000
Madhya Pradesh/Chhattisgarh	6,620,000
Maharashtra	4,855,000
Manipur	1,262,000
Meghalaya	937,000
Mizoram	407,000
Nagaland	840,000
Orissa	1,888,000
Punjab	106,000
Rajasthan	5,888,000
Sikkim	213,000
Tamil Nadu	1,795,000
Tripura	128,000
Uttar Pradesh/Uttaranchal	1,214,000
West Bengal	258,000
Grand Total	**40,060,000**

Sources:
a) National Oilseeds and Vegetable Oils Development Board (NOVOD), GOI, Ministry of Agriculture: no date;
b) Friends of Earth: 2008;
c) Winrock International India: 2008

Appendix III: GHG emissions from selected fertilizers

Type of fertilizer	GHG emissions ($kgCO_2eq/kg$)
Ammonium nitrate phosphate, as N	5.27
Ammonium nitrate phosphate, as P_2O_5	1.36
Ammonium nitrate, as N	8.40
Ammonium sulphate, as N	2.60
Calcium ammonium nitrate, as N	8.49
Calcium nitrate, as N	3.74
Diammonium phosphate, as N	2.74
Diammonium phosphate, as P_2O_5	1.53
Monoammonium phosphate, as N	2.75
Monoammonium phosphate, as P_2O_5	1.56
Potassium chloride (Muriate of Potash), as K_2O	0.47
Potassium nitrate, as K_2O	0.83
Potassium nitrate, as N	15.70
Potassium sulphate, as K_2O	1.36
Single superphosphate, as P_2O_5	2.56
Thomas meal, as P_2O_5	0.75
Triple superphosphate, as P_2O_5	1.98

Source: Center for Ecological Sciences (CES), IISc: 2005

Appendix IV: LCA results: Low, Best and High scenarios

Table IV. 1: Energy supply scenarios. Irrigated.

Fruit hulls and seed shells	Energy generation scheme
Used as fertilizer	a11 Conventional oil boiler
	a12 Conventional coal boiler
	a21 Conventional NG boiler
	b11 Conventional oil boiler, backpressure turbogenerator
	b12 Conventional coal boiler, backpressure turbogenerator
	b21 Conventional NG boiler, backpressure turbogenerator
	c11 NG GT + unfired HRSG
	c12 NG GT + co-firing HRSG
	c21 NG GT + unfired HRSG, backpressure turbogenerator
	c21 NG GT + co-fired HRSG, backpressure turbogenerator
Used as fuel	d1 Biomass boiler + CHP
	d2 Biomass boiler + CHP and combined cycle
	c Biomass gasification + GT + unfired HRSG + BP/cond STG

Table IV. 2: Energy supply scenarios. Rainfed.

Fruit hulls and seed shells	Energy generation scheme
Used as fertilizer	a11 Conventional oil boiler
	a12 Conventional coal boiler
	a21 Conventional NG boiler
	f11 Diesel genset with heat utilization block
	f12 NG genset with heat utilization block
	g NG CHP Microturbibe
Used as fuel	h11 Anaerobic digester + CHP externally fired micro gas turbine
	h12 Integrated biomass gasifier + CHP gas engine genset

LOW Scenario

Irrigated Scenario 1

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C).

Table IV. 3: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (90 bar, 240°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.479**	**0.479**	**0.484**	**0.527**	**0.527**	**0.533**	**0.804**	**0.677**	**0.986**	**0.819**	**0.172**	**0.172**	**0.172**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.479**	**0.479**	**0.484**	**0.527**	**0.527**	**0.533**	**0.804**	**0.677**	**0.986**	**0.819**	**1.160**	**1.160**	**1.160**	**1.16**
	GJp/t biodiesel		17.85	17.85	18.03	19.63	19.63	19.85	29.98	25.22	36.73	30.51	43.24	43.24	43.2	
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**37.03**	**54.08**	**32.98**	**40.59**	**62.23**	**35.45**	**50.47**	**43.41**	**60.49**	**51.25**	**13.18**	**13.18**	**13.18**	**89.3**
	kg CO_2eq/t biodiesel		1380.01	2015.57	1228.98	1512.70	2319.16	1321.05	1881.02	1617.86	2254.37	1910.13	491.24	491.24	491.24	
Farming (CO_2)			231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	35.82	35.82	35.82	
Farming (N_2O)			251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table IV. 4: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.4	-4.4	-4.4	-24.0	-6.71	-36.74	-14.09	-11.27	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.85	-305.85	-305.85	-1654.31	-461.83	-2530.12	-970.19	-776.36	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.257**	**0.257**	**0.262**	**0.186**	**0.186**	**0.192**	**-0.062**	**0.275**	**-0.222**	**0.219**	**-0.352**	**-0.431**	**-0.876**
Fossil energy saved		**%**	**77.9%**	**77.9%**	**77.4%**	**84.0%**	**84.0%**	**83.5%**	**105.4%**	**76.3%**	**119.2%**	**81.2%**	**130.37%**	**137.14%**	**175.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.257**	**0.257**	**0.262**	**0.186**	**0.186**	**0.192**	**-0.062**	**0.275**	**-0.222**	**0.219**	**0.636**	**0.557**	**0.112**
	GJp/t biodiesel		9.58	9.6	9.8	6.9	6.9	7.1	-2.3	10.2	-8.3	8.1	23.7	20.8	4.2
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			1.50	1.50	1.68	-1.16	-1.16	-0.93	-10.38	2.17	-16.35	0.08	17.28	14.35	-2.23
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**17.30**	**34.35**	**13.25**	**12.66**	**34.29**	**7.51**	**-13.64**	**11.29**	**-27.12**	**5.49**	**-27.38**	**-32.79**	**-63.43**
GHG avoided		**%**	**80.6%**	**61.5%**	**85.2%**	**85.8%**	**61.61%**	**91.6%**	**115.3%**	**87.4%**	**130.4%**	**93.9%**	**130.64%**	**136.70%**	**171.00%**
GHG emissions	kg CO_2eq/t biodiesel		644.84	1280.40	493.80	471.67	1278.13	280.03	-508.47	420.86	-1010.93	204.76	-1020.30	-1221.94	-2364.01
Farming			483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	287.4	287.4	287.4
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-24.55	611.01	-175.58	-197.71	608.75	-389.36	-1177.85	-248.53	-1680.32	-464.63	-1511.54	-1713.18	-2855.26
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 5: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Intetgated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.4	-4.4	-4.4	-24.0	-6.71	-36.74	-14.09	-11.27	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.85	-305.85	-305.85	-1654.31	-461.83	-2530.12	-970.19	-776.36	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input	**GJf/GJ biodiesel**		**0.069**	**0.069**	**0.074**	**-0.002**	**-0.002**	**0.004**	**-0.250**	**0.087**	**-0.410**	**0.031**	**-0.540**	**-0.619**	**-1.06**
Fossil energy saved		**%**	**94.1%**	**94.1%**	**93.6%**	**100.2%**	**100.2%**	**99.7%**	**121.6%**	**92.5%**	**135.4%**	**97.4%**	**146.6%**	**153.3%**	**191.7%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.069**	**0.069**	**0.074**	**0.00**	**0.00**	**0.004**	**-0.250**	**0.087**	**-0.410**	**0.031**	**0.448**	**0.369**	**-0.076**
	GJp/t biodiesel		2.6	2.6	2.8	-0.1	-0.1	0.1	-9.3	3.2	-15.3	1.1	16.7	13.8	-2.8
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-5.50	-5.50	-5.32	-8.16	-8.16	-7.93	-17.39	-4.83	-23.36	-6.93	10.28	7.35	-9.24
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**10.37**	**27.43**	**6.32**	**5.73**	**27.36**	**0.58**	**-20.57**	**4.36**	**-34.05**	**-1.44**	**-34.31**	**-39.72**	**-70.36**
GHG avoided		**%**	**88.4%**	**69.3%**	**92.9%**	**93.6%**	**69.4%**	**99.3%**	**123.0%**	**95.1%**	**138.1%**	**101.6%**	**138.4%**	**144.5%**	**178.8%**
GHG emissions	kg CO_2eq/t biodiesel		386.58	1022.14	235.54	213.42	1019.88	21.77	-766.72	162.60	-1269.19	-53.50	-1278.55	-1480.20	-2622.27
Farming			483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	287.4	287.4	287.4
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.3	145.3	145.3
Manufacture			-282.81	352.75	-433.84	-455.97	350.49	-647.62	-1436.11	-506.79	-1938.57	-722.89	-1769.79	-1971.44	-3113.51
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Irrigated Scenario 2

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260^oC) and Esterification (10 bar, 240 ^oC).

Table IV. 6: Overall Gross balance. Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260 ^oC) and Esterification (10 bar, 240^oC) (without by-products credits)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**	**Diesel**
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.312**	**0.312**	**0.314**	**0.287**	**0.287**	**0.289**	**0.386**	**0.35**	**0.392**	**0.354**	**0.449**	**0.449**	**0.854**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.312**	**0.312**	**0.314**	**0.287**	**0.287**	**0.289**	**0.386**	**0.35**	**0.392**	**0.354**	**1.16**	**1.16**	**1.16**	**1.16**
	GJp/t biodiesel		11.63	11.63	11.69	10.71	10.71	10.77	14.39	13.02	14.63	13.20	43.24	43.24	43.2	
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**24.83**	**29.75**	**23.66**	**23.14**	**28.09**	**21.96**	**27.34**	**25.30**	**27.69**	**25.58**	**13.18**	**13.18**	**13.18**	**89.3**
	kg CO_2eq/t biodiesel		925.52	1108.84	881.95	862.29	1046.77	818.45	1018.87	942.97	1031.95	953.20	491.24	491.24	491.24	
Farming (CO_2)			231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	231.63	35.82	35.82	35.82	
Farming (N_2O)			251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	251.6	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.00	0.00	0.00	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table IV. 7: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.090**	**0.090**	**0.092**	**0.041**	**0.041**	**0.042**	**-0.0104**	**0.087**	**-0.052**	**0.049**	**-0.016**	**-0.473**	**-0.431**
Fossil energy saved		**%**	**92.2%**	**92.2%**	**92.1%**	**96.5%**	**96.5%**	**96.3%**	**100.9%**	**92.5%**	**104.5%**	**95.8%**	**101.4%**	**140.8%**	**137.2%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.090**	**0.090**	**0.092**	**0.041**	**0.041**	**0.042**	**-0.010**	**0.087**	**-0.052**	**0.049**	**0.634**	**0.515**	**0.557**
	GJp/t biodiesel		3.36	3.4	3.4	1.5	1.5	1.6	-0.4	3.2	-1.9	1.8	23.6	19.2	20.8
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-4.71	-4.71	-4.66	-6.54	-6.54	-6.49	-8.46	-4.84	-10.02	-6.26	17.23	12.77	14.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**5.11**	**10.03**	**3.94**	**3.37**	**8.31**	**2.19**	**7.29**	**5.50**	**7.55**	**5.70**	**-7.11**	**-7.33**	**-6.55**
GHG avoided		**%**	**94.3%**	**88.8%**	**95.6%**	**96.2%**	**90.7%**	**97.5%**	**91.8%**	**93.8%**	**91.5%**	**93.6%**	**108.0%**	**108.2%**	**107.3%**
GHG emissions	kg CO_2eq/t biodiesel		190.3	373.7	146.8	125.4	309.9	81.6	271.7	205.00	281.43	212.26	-264.9	-273.1	-244.2
Farming			483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	287.4	287.4	287.4
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-479.04	-295.72	-522.61	-543.96	-359.49	-587.80	-397.71	-464.39	-387.96	-457.13	-756.11	-764.35	-735.43
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 8: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Intetgated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input (per annum)	**GJf/GJ biodiesel**		**-0.098**	**-0.098**	**-0.096**	**-0.147**	**-0.147**	**-0.146**	**-0.198**	**-0.101**	**-0.240**	**-0.139**	**-0.021**	**-0.661**	**-0.619**
Fossil energy saved (per annum)		**%**	**108.4%**	**108.4%**	**108.3%**	**112.7%**	**112.7%**	**112.5%**	**117.1%**	**108.7%**	**120.7%**	**112.0%**	**101.8%**	**157.0%**	**153.4%**
Primary Total Energy Input (per annum)	**GJp/GJ biodiesel**		**-0.098**	**-0.098**	**-0.096**	**-0.147**	**-0.147**	**-0.146**	**-0.198**	**-0.101**	**-0.240**	**-0.139**	**0.446**	**0.33**	**0.37**
	GJp/t biodiesel		-3.6	-3.6	-3.6	-5.5	-5.5	-5.4	-7.4	-3.8	-9.0	-5.2	16.6	12.2	13.8
Farming			5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	5.65	3.77	3.77	3.77
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-11.71	-11.71	-11.66	-13.55	-13.55	-13.50	-15.46	-11.84	-17.02	-13.27	10.22	5.76	7.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**-1.82**	**3.10**	**-2.99**	**-3.56**	**1.39**	**-4.74**	**0.36**	**-1.43**	**0.62**	**-1.23**	**-14.04**	**-14.26**	**-13.48**
GHG avoided		**%**	**102.0%**	**96.5%**	**103.3%**	**104.0%**	**98.4%**	**105.3%**	**99.6%**	**101.6%**	**99.3%**	**101.4%**	**115.7%**	**116.0%**	**115.1%**
GHG emissions	kg CO_2eq/t biodiesel		-67.9	115.4	-111.5	-132.8	51.6	-176.7	13.4	-53.3	23.2	-46.0	-523.1	-531.4	-502.4
Farming			483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	483.2	287.4	287.4	287.4
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-737.30	-553.98	-780.87	-802.22	-617.74	-846.06	-655.97	-722.65	-646.22	-715.39	-1014.36	-1022.61	-993.69
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Rainfed Scenario 1

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C).

Table IV. 9: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (1.4 bar, 60°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.208**	**0.208**	**0.209**	**0.199**	**0.195**	**0.198**	**1.543**	**1.543**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.208**	**0.208**	**0.209**	**0.199**	**0.195**	**0.198**	**1.594**	**1.594**	**1.16**
	GJp/t biodiesel		7.75	7.75	7.77	7.42	7.27	7.36	59.41	59.41	
Farming			5.04	5.04	5.04	5.04	5.04	5.04	1.23	1.23	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**31.14**	**33.30**	**30.62**	**30.70**	**29.69**	**29.83**	**18.03**	**18.03**	**89.3**
	kg CO_2eq/t biodiesel		1160.52	1241.09	1141.37	1144.10	1106.67	1111.78	671.88	671.88	
Farming (CO_2)			457.62	457.62	457.62	457.62	457.62	457.62	61.42	61.42	
Farming (N_2O)			503.0	503.0	503.0	503.0	503.0	503.0	503.0	503.0	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 10: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Intetgated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.020**	**-0.020**	**-0.020**	**-0.036**	**-0.034**	**-0.033**	**-0.687**	**-0.339**
Fossil energy saved		**%**	**101.8%**	**101.8%**	**101.70%**	**103.10%**	**103.0%**	**102.84%**	**159.26%**	**129.20%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.020**	**-0.020**	**-0.020**	**-0.036**	**-0.034**	**-0.033**	**0.836**	**1.185**
	GJp/t biodiesel		-0.76	-0.8	-0.7	-1.3	-1.3	-1.2	31.2	44.2
Farming			5.04	5.04	5.04	5.04	5.04	5.04	1.23	1.23
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions (per annum)	**kg CO_2eq/GJ biodiesel**		**11.16**	**13.32**	**10.64**	**10.25**	**9.63**	**9.69**	**-38.42**	**-14.40**
GHG avoided (per annum)		**%**	**87.5%**	**85.1%**	**88.1%**	**88.5%**	**89.2%**	**89.2%**	**143.0%**	**116.1%**
GHG emissions	kg CO_2eq/t biodiesel		415.8	496.4	396.6	382.0	358.9	361.2	-1431.8	-536.8
Farming			960.6	960.6	960.6	960.6	960.6	960.6	564.41	564.41
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 11: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**0.0**	**-0.001**	**-0.002**	**-0.530**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.3	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.5**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.3	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.209**	**-0.209**	**-0.208**	**-0.225**	**-0.223**	**-0.222**	**-0.876**	**-0.527**
Fossil energy saved		**%**	**118.0%**	**118.0%**	**118.0%**	**119.4%**	**119.2%**	**119.1%**	**175.5%**	**145.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.209**	**-0.209**	**-0.208**	**-0.225**	**-0.223**	**-0.222**	**0.647**	**0.996**
	GJp/t biodiesel		-7.8	-7.8	-7.8	-8.4	-8.3	-8.3	24.1	37.1
Farming			5.04	5.04	5.04	5.04	5.04	5.04	1.23	1.23
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions	**kg CO_2eq/GJ biodiesel**		**4.17**	**6.34**	**3.66**	**3.27**	**2.65**	**2.71**	**-45.40**	**-21.38**
GHG avoided		**%**	**95.3%**	**92.9%**	**95.9%**	**96.3%**	**97.0%**	**97.0%**	**150.8%**	**123.9%**
	kg CO_2eq/t biodiesel		155.56	236.13	136.42	121.80	98.72	100.99	-1692.07	-797.00
Farming			960.61	960.61	960.61	960.61	960.61	960.61	564.41	564.41
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Rainfed Scenario 2

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C).

Table IV. 12: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (1.4 bar, 60°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**0.140**	**0.140**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**1.663**	**1.663**	**1.16**
	GJp/t biodiesel		6.53	6.53	6.55	6.20	6.05	6.14	62.0	62.0	
Farming			3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**28.53**	**30.69**	**28.01**	**28.09**	**27.08**	**27.22**	**26.05**	**26.05**	**89.3**
	kg CO_2eq/t biodiesel		1063.24	1143.81	1044.10	1046.82	1009.40	1014.50	970.80	970.80	
Farming (CO_2)			396.36	396.36	396.36	396.36	396.36	396.36	396.36	396.36	
Farming (N_2O)			467.0	467.0	467.0	467.0	467.0	467.0	467.0	467.0	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 13: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60^oC). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.053**	**-0.053**	**-0.053**	**-0.069**	**-0.067**	**-0.066**	**-0.618**	**-0.269**
Fossil energy saved		**%**	**104.6%**	**104.6%**	**104.5%**	**105.9%**	**105.8%**	**105.7%**	**153.27%**	**123.2%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.053**	**-0.053**	**-0.053**	**-0.069**	**-0.067**	**-0.066**	**0.91**	**1.254**
	GJp/t biodiesel		-1.98	-2.0	-2.0	-2.6	-2.5	-2.5	33.8	46.8
Farming			3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**8.5**	**10.7**	**8.0**	**7.6**	**7.0**	**7.1**	**-30.4**	**-6.4**
GHG avoided		**%**	**90.4%**	**88.0%**	**91.0%**	**91.4%**	**92.1%**	**92.1%**	**134.0%**	**107.1%**
GHG emissions	kg CO_2eq/t biodiesel		318.51	399.08	299.37	284.75	261.67	263.95	-1132.9	-237.8
Farming			863.33	863.33	863.33	863.33	863.33	863.33	863.33	863.33
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 14: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Intergtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.242**	**-0.242**	**-0.241**	**-0.257**	**-0.256**	**-0.254**	**-0.807**	**-0.458**
Fossil energy saved		**%**	**120.8%**	**120.8%**	**120.8%**	**122.2%**	**122.1%**	**121.9%**	**169.5%**	**139.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.242**	**-0.242**	**-0.241**	**-0.257**	**-0.256**	**-0.254**	**0.717**	**1.066**
	GJp/t biodiesel		-9.0	-9.0	-9.0	-9.6	-9.5	-9.5	26.7	39.7
Farming			3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**1.56**	**3.73**	**1.05**	**0.66**	**0.04**	**0.10**	**-37.38**	**-13.36**
GHG avoided		**%**	**98.2%**	**95.8%**	**98.8%**	**99.3%**	**100.0%**	**99.9%**	**141.8%**	**115.0%**
	kg CO_2eq/t biodiesel		58.3	138.9	39.1	24.5	1.4	3.7	-1393.15	-498.1
Farming			863.33	863.33	863.33	863.33	863.33	863.33	863.33	863.33
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

BEST Scenario

Irrigated Scenario 1

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240^{o}C).

Table IV. 15: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (90 bar, 240^{o}C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.563**	**0.563**	**0.568**	**0.611**	**0.611**	**0.617**	**0.888**	**0.761**	**1.070**	**0.903**	**0.256**	**0.256**	**0.256**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.563**	**0.563**	**0.568**	**0.611**	**0.611**	**0.617**	**0.888**	**0.761**	**1.070**	**0.903**	**1.24**	**1.24**	**1.24**	**1.16**
	GJp/t biodiesel		20.98	20.98	21.16	22.76	22.76	22.99	33.11	28.36	39.86	33.64	46.38	46.38	46.4	
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**58.77**	**75.82**	**54.72**	**62.33**	**83.97**	**57.19**	**72.21**	**65.15**	**82.23**	**72.99**	**34.93**	**34.93**	**34.93**	**89.3**
	kg CO_2eq/t biodiesel		2190.34	2825.89	2039.30	2323.02	3129.48	2131.38	2691.34	2428.18	3064.69	2720.45	1301.66	1301.66	1301.66	
Farming (CO_2)			534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	339.16	339.16	339.16	
Farming (N_2O)			758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table: IV. 16: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Intetgated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.442	-4.442	-4.442	-24.024	-6.707	-36.743	-14.090	-11.275	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.853	-305.853	-305.853	-1654.307	-461.830	-2530.124	-970.195	-776.360	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.341**	**0.341**	**0.346**	**0.270**	**0.270**	**0.276**	**0.022**	**0.359**	**-0.138**	**0.303**	**-0.268**	**-0.347**	**-0.792**
Fossil energy saved		**%**	**70.6%**	**70.6%**	**70.2%**	**76.8%**	**76.8%**	**76.2%**	**98.1%**	**69.1%**	**111.9%**	**73.9%**	**123.12%**	**129.89%**	**168.3%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.341**	**0.341**	**0.346**	**0.270**	**0.270**	**0.276**	**0.022**	**0.359**	**-0.138**	**0.303**	**0.720**	**0.641**	**0.196**
	GJp/t biodiesel		12.71	12.7	12.9	10.0	10.0	10.3	0.8	13.4	-5.1	11.3	26.8	23.9	7.3
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			1.50	1.50	1.68	-1.16	-1.16	-0.93	-10.38	2.17	-16.35	0.08	17.28	14.35	-2.23
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**39.04**	**56.10**	**34.99**	**34.40**	**56.04**	**29.26**	**8.10**	**33.03**	**-5.38**	**27.24**	**-5.63**	**-11.04**	**-41.68**
GHG avoided		**%**	**56.3%**	**37.2%**	**60.8%**	**61.5%**	**37.28%**	**67.3%**	**90.9%**	**63.0%**	**106.0%**	**69.5%**	**106.30%**	**112.36%**	**146.66%**
GHG emissions	kg CO_2eq/t biodiesel		1455.16	2090.72	1304.12	1282.00	2088.46	1090.35	301.85	1231.18	-200.61	1015.08	-209.87	-411.52	-1553.59
Farming			1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1097.9	1097.9	1097.9
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-24.55	611.01	-175.58	-197.71	608.75	-389.36	-1177.85	-248.53	-1680.32	-464.63	-1511.54	-1713.18	-2855.26
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 17: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.4	-4.4	-4.4	-24.0	-6.71	-36.74	-14.09	-11.27	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.85	-305.85	-305.85	-1654.31	-461.83	-2530.12	-970.19	-776.36	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input	**GJf/GJ biodiesel**		**0.153**	**0.153**	**0.158**	**0.082**	**0.082**	**0.088**	**-0.166**	**0.171**	**-0.326**	**0.115**	**-0.456**	**-0.535**	**-0.98**
Fossil energy saved		**%**	**86.8%**	**86.8%**	**86.4%**	**93.0%**	**93.0%**	**92.4%**	**114.3%**	**85.3%**	**128.1%**	**90.1%**	**139.3%**	**146.1%**	**184.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.153**	**0.153**	**0.158**	**0.08**	**0.08**	**0.088**	**-0.166**	**0.171**	**-0.326**	**0.115**	**0.532**	**0.453**	**0.008**
	GJp/t biodiesel		5.7	5.7	5.9	3.0	3.0	3.3	-6.2	6.4	-12.2	4.3	19.8	16.9	0.3
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-5.50	-5.50	-5.32	-8.16	-8.16	-7.93	-17.39	-4.83	-23.36	-6.93	10.28	7.35	-9.24
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**32.11**	**49.17**	**28.06**	**27.47**	**49.11**	**22.33**	**1.17**	**26.10**	**-12.31**	**20.31**	**-12.56**	**-17.97**	**-48.61**
GHG avoided		**%**	**64.1%**	**45.0%**	**68.6%**	**69.3%**	**45.0%**	**75.0%**	**98.7%**	**70.8%**	**113.8%**	**77.3%**	**114.1%**	**120.1%**	**154.4%**
GHG emissions	kg CO_2eq/t biodiesel		1196.90	1832.46	1045.86	1023.74	1830.20	832.09	43.60	972.92	-458.87	756.82	-468.13	-669.78	-1811.85
Farming			1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1097.9	1097.9	1097.9
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.3	145.3	145.3
Manufacture			-282.81	352.75	-433.84	-455.97	350.49	-647.62	-1436.11	-506.79	-1938.57	-722.89	-1769.79	-1971.44	-3113.51
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Irrigated Scenario 2

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C).

Table IV. 18: Overall Gross balance. Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260 °C) and Esterification (10 bar, 240°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.396**	**0.396**	**0.398**	**0.372**	**0.372**	**0.373**	**0.470**	**0.43**	**0.477**	**0.438**	**0.533**	**0.533**	**0.938**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.396**	**0.396**	**0.398**	**0.372**	**0.372**	**0.373**	**0.470**	**0.43**	**0.477**	**0.438**	**1.2**	**1.2**	**1.2**	**1.16**
	GJp/t biodiesel		14.77	14.77	14.82	13.85	13.85	13.90	17.52	16.15	17.76	16.34	46.38	46.38	46.4	
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.9	6.9	6.90	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**46.57**	**51.49**	**45.41**	**44.88**	**49.83**	**43.70**	**49.08**	**47.04**	**49.43**	**47.32**	**34.93**	**34.93**	**34.93**	**89.3**
	kg CO_2eq/t biodiesel		1735.84	1919.16	1692.27	1672.62	1857.09	1628.78	1829.19	1753.29	1842.27	1763.53	1301.66	1301.66	1301.66	
Farming (CO_2)			534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	534.87	339.16	339.16	339.16	
Farming (N_2O)			758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	758.7	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table IV. 19: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.174**	**0.174**	**0.176**	**0.13**	**0.13**	**0.126**	**0.0737**	**0.171**	**0.03**	**0.133**	**-0.014**	**-0.389**	**-0.347**
Fossil energy saved		**%**	**85.0%**	**85.0%**	**84.9%**	**89.2%**	**89.2%**	**89.1%**	**93.6%**	**85.3%**	**97.3%**	**88.6%**	**101.2%**	**133.6%**	**129.9%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.174**	**0.174**	**0.176**	**0.125**	**0.125**	**0.126**	**0.074**	**0.171**	**0.032**	**0.133**	**0.718**	**0.599**	**0.641**
	GJp/t biodiesel		6.50	6.5	6.5	4.7	4.7	4.7	2.7	6.4	1.2	4.9	26.8	22.3	23.9
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-4.71	-4.71	-4.66	-6.54	-6.54	-6.49	-8.46	-4.84	-10.02	-6.26	17.23	12.77	14.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**26.85**	**31.77**	**25.68**	**25.11**	**30.06**	**23.93**	**29.03**	**27.24**	**29.29**	**27.44**	**14.64**	**14.42**	**15.19**
GHG avoided		**%**	**69.9%**	**64.4%**	**71.3%**	**71.9%**	**66.4%**	**73.2%**	**67.5%**	**69.5%**	**67.2%**	**69.3%**	**83.6%**	**83.9%**	**83.0%**
GHG emissions	kg CO_2eq/t biodiesel		1000.7	1184.0	957.1	935.7	1120.2	891.9	1082.0	1015.32	1091.75	1022.58	545.6	537.3	566.2
Farming			1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1097.9	1097.9	1097.9
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-479.04	-295.72	-522.61	-543.96	-359.49	-587.80	-397.71	-464.39	-387.96	-457.13	-756.11	-764.35	-735.43
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 20: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260^oC) and Esterification (10 bar, 240^oC). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input (per annum)	**GJf/GJ biodiesel**		**-0.014**	**-0.014**	**-0.012**	**-0.063**	**-0.063**	**-0.061**	**-0.114**	**-0.017**	**-0.156**	**-0.055**	**-0.019**	**-0.577**	**-0.535**
Fossil energy saved (per annum)		**%**	**101.2%**	**101.2%**	**101.1%**	**105.4%**	**105.4%**	**105.3%**	**109.8%**	**101.5%**	**113.5%**	**104.8%**	**101.6%**	**149.8%**	**146.1%**
Primary Total Energy Input (per annum)	**GJp/GJ biodiesel**		**-0.014**	**-0.014**	**-0.012**	**-0.063**	**-0.063**	**-0.061**	**-0.114**	**-0.017**	**-0.156**	**-0.055**	**0.531**	**0.41**	**0.45**
	GJp/t biodiesel		-0.5	-0.5	-0.5	-2.3	-2.3	-2.3	-4.3	-0.6	-5.8	-2.1	19.8	15.3	16.9
Farming			8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	8.79	6.90	6.90	6.90
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-11.71	-11.71	-11.66	-13.55	-13.55	-13.50	-15.46	-11.84	-17.02	-13.27	10.22	5.76	7.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**19.92**	**24.84**	**18.75**	**18.18**	**23.13**	**17.00**	**22.10**	**20.31**	**22.36**	**20.51**	**7.71**	**7.49**	**8.26**
GHG avoided		**%**	**77.7%**	**72.2%**	**79.0%**	**79.7%**	**74.1%**	**81.0%**	**75.3%**	**77.3%**	**75.0%**	**77.0%**	**91.4%**	**91.6%**	**90.8%**
GHG emissions	kg CO_2eq/t biodiesel		742.4	925.7	698.8	677.5	862.0	633.6	823.7	757.1	833.5	764.3	287.3	279.1	308.0
Farming			1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1293.6	1097.9	1097.9	1097.9
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-737.30	-553.98	-780.87	-802.22	-617.74	-846.06	-655.97	-722.65	-646.22	-715.39	-1014.36	-1022.61	-993.69
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Rainfed Scenario 1

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C).

Table IV. 21: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (1.4 bar, 60°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.235**	**0.235**	**0.236**	**0.226**	**0.222**	**0.225**	**1.570**	**1.570**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.235**	**0.235**	**0.236**	**0.226**	**0.222**	**0.225**	**1.62**	**1.62**	**1.16**
	GJp/t biodiesel		8.75	8.75	8.78	8.43	8.28	8.37	60.41	60.41	
Farming			6.04	6.04	6.04	6.04	6.04	6.04	2.23	2.23	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**41.39**	**43.56**	**40.88**	**40.95**	**39.95**	**40.09**	**28.28**	**28.28**	**89.3**
	kg CO_2eq/t biodiesel		1542.73	1623.30	1523.58	1526.31	1488.88	1493.99	1054.09	1054.09	
Farming (CO_2)			551.34	551.34	551.34	551.34	551.34	551.34	155.14	155.14	
Farming (N_2O)			791.5	791.5	791.5	791.5	791.5	791.5	791.5	791.5	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 22: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**0.007**	**0.007**	**0.007**	**-0.009**	**-0.007**	**-0.006**	**-0.660**	**-0.312**
Fossil energy saved		**%**	**99.4%**	**99.4%**	**99.37%**	**100.77%**	**100.6%**	**100.52%**	**156.94%**	**126.87%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.007**	**0.007**	**0.007**	**-0.009**	**-0.007**	**-0.006**	**0.863**	**1.212**
	GJp/t biodiesel		0.25	0.2	0.3	-0.3	-0.3	-0.2	32.2	45.2
Farming			6.04	6.04	6.04	6.04	6.04	6.04	2.23	2.23
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions (per annum)	**kg CO_2eq/GJ biodiesel**		**21.41**	**23.57**	**20.90**	**20.51**	**19.89**	**19.95**	**-28.16**	**-4.15**
GHG avoided (per annum)		**%**	**76.0%**	**73.6%**	**76.6%**	**77.0%**	**77.7%**	**77.7%**	**131.5%**	**104.6%**
GHG emissions	kg CO_2eq/t biodiesel		798.0	878.6	778.9	764.2	741.2	743.4	-1049.6	-154.6
Farming			1342.8	1342.8	1342.8	1342.8	1342.8	1342.8	946.62	946.62
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 23: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.182**	**-0.182**	**-0.181**	**-0.198**	**-0.196**	**-0.195**	**-0.849**	**-0.500**
Fossil energy saved		**%**	**115.7%**	**115.7%**	**115.6%**	**117.0%**	**116.9%**	**116.8%**	**173.2%**	**143.1%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.182**	**-0.182**	**-0.181**	**-0.198**	**-0.196**	**-0.195**	**0.674**	**1.023**
	GJp/t biodiesel		-6.8	-6.8	-6.8	-7.4	-7.3	-7.3	25.1	38.1
Farming			6.04	6.04	6.04	6.04	6.04	6.04	2.23	2.23
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions	**kg CO_2eq/GJ biodiesel**		**14.43**	**16.59**	**13.92**	**13.52**	**12.90**	**12.96**	**-35.15**	**-11.13**
GHG avoided		**%**	**83.8%**	**81.4%**	**84.4%**	**84.9%**	**85.6%**	**85.5%**	**139.3%**	**112.5%**
	kg CO_2eq/t biodiesel		537.77	618.34	518.62	504.01	480.93	483.20	-1309.86	-414.79
Farming			1342.82	1342.82	1342.82	1342.82	1342.82	1342.82	946.62	946.62
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Rainfed Scenario 2

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C).

Table IV. 24: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (1.4 bar, 60°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**0.140**	**0.140**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.175**	**0.175**	**0.176**	**0.166**	**0.162**	**0.165**	**1.66**	**1.66**	**1.16**
	GJp/t biodiesel		6.53	6.53	6.55	6.20	6.05	6.14	62.0	62.0	
Farming			3.82	3.82	3.82	3.82	3.82	3.82	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**32.70**	**34.87**	**32.19**	**32.26**	**31.26**	**31.40**	**30.22**	**30.22**	**89.3**
	kg CO_2eq/t biodiesel		1218.90	1299.47	1199.75	1202.48	1165.06	1170.16	1126.45	1126.45	
Farming (CO_2)			396.36	396.36	396.36	396.36	396.36	396.36	396.36	396.36	
Farming (N_2O)			622.6	622.6	622.6	622.6	622.6	622.6	622.6	622.6	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 25: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.053**	**-0.053**	**-0.053**	**-0.069**	**-0.067**	**-0.066**	**-0.618**	**-0.269**
Fossil energy saved		**%**	**104.6%**	**104.6%**	**104.5%**	**105.9%**	**105.8%**	**105.7%**	**153.27%**	**123.2%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.053**	**-0.053**	**-0.053**	**-0.069**	**-0.067**	**-0.066**	**0.91**	**1.254**
	GJp/t biodiesel		-1.98	-2.0	-2.0	-2.6	-2.5	-2.5	33.8	46.8
Farming			3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**12.7**	**14.9**	**12.2**	**11.8**	**11.2**	**11.3**	**-26.2**	**-2.2**
GHG avoided		**%**	**85.8%**	**83.3%**	**86.3%**	**86.8%**	**87.5%**	**87.4%**	**129.4%**	**102.5%**
GHG emissions	kg CO_2eq/t biodiesel		474.17	554.74	455.03	440.41	417.33	419.60	-977.3	-82.2
Farming			1018.99	1018.99	1018.99	1018.99	1018.99	1018.99	1018.99	1018.99
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 26: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.242**	**-0.242**	**-0.241**	**-0.257**	**-0.256**	**-0.254**	**-0.807**	**-0.458**
Fossil energy saved		**%**	**120.8%**	**120.8%**	**120.8%**	**122.2%**	**122.1%**	**121.9%**	**169.5%**	**139.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.242**	**-0.242**	**-0.241**	**-0.257**	**-0.256**	**-0.254**	**0.717**	**1.066**
	GJp/t biodiesel		-9.0	-9.0	-9.0	-9.6	-9.5	-9.5	26.7	39.7
Farming			3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**5.74**	**7.90**	**5.23**	**4.83**	**4.22**	**4.28**	**-33.20**	**-9.19**
GHG avoided		**%**	**93.6%**	**91.2%**	**94.1%**	**94.6%**	**95.3%**	**95.2%**	**137.2%**	**110.3%**
	kg CO_2eq/t biodiesel		213.9	294.5	194.8	180.2	157.1	159.4	-1237.49	-342.4
Farming			1018.99	1018.99	1018.99	1018.99	1018.99	1018.99	1018.99	1018.99
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

HIGH Scenario

Irrigated Scenario 1

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C).

Table IV. 27: Overall Gross balance. Industrial scale production. One-stage Transesterification Process (90 bar, 240°C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT + co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.671**	**0.671**	**0.676**	**0.719**	**0.719**	**0.725**	**0.997**	**0.869**	**1.178**	**1.011**	**0.365**	**0.365**	**0.365**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.671**	**0.671**	**0.676**	**0.719**	**0.719**	**0.725**	**0.997**	**0.869**	**1.178**	**1.011**	**1.4**	**1.4**	**1.4**	**1.16**
	GJp/t biodiesel		25.02	25.02	25.20	26.80	26.80	27.03	37.16	32.40	43.91	37.68	50.42	50.42	50.4	
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95	
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			9.77	9.77	9.96	11.56	11.56	11.78	21.91	17.15	28.66	22.44	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**93.59**	**110.64**	**89.54**	**97.15**	**118.79**	**92.01**	**107.03**	**99.97**	**117.05**	**107.82**	**69.74**	**69.74**	**69.74**	**89.3**
	kg CO_2eq/t biodiesel		3488.16	4123.72	3337.12	3620.85	4427.31	3429.20	3989.16	3726.00	4362.51	4018.27	2599.38	2599.38	2599.38	
Farming (CO_2)			932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	736.48	736.48	736.48	
Farming (N_2O)			1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			710.63	1346.19	559.59	843.32	1649.78	651.67	1211.63	948.48	1584.99	1240.74	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table IV. 28: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.4	-4.4	-4.4	-24.0	-6.71	-36.74	-14.09	-11.27	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.85	-305.85	-305.85	-1654.31	-461.83	-2530.12	-970.19	-776.36	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.450**	**0.450**	**0.454**	**0.378**	**0.378**	**0.384**	**0.130**	**0.467**	**-0.030**	**0.411**	**-0.160**	**-0.238**	**-0.683**
Fossil energy saved		**%**	**61.2%**	**61.2%**	**60.8%**	**67.4%**	**67.4%**	**66.9%**	**88.8%**	**59.7%**	**102.6%**	**64.6%**	**113.76%**	**120.54%**	**158.9%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.450**	**0.450**	**0.454**	**0.378**	**0.378**	**0.384**	**0.130**	**0.467**	**-0.030**	**0.411**	**0.828**	**0.750**	**0.305**
	GJp/t biodiesel		16.75	16.8	16.9	14.1	14.1	14.3	4.9	17.4	-1.1	15.3	30.9	27.9	11.4
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			1.50	1.50	1.68	-1.16	-1.16	-0.93	-10.38	2.17	-16.35	0.08	17.28	14.35	-2.23
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**73.87**	**90.92**	**69.81**	**69.22**	**90.86**	**64.08**	**42.92**	**67.86**	**29.44**	**62.06**	**29.19**	**23.78**	**-6.87**
GHG avoided		**%**	**17.3%**	**-1.8%**	**21.9%**	**22.5%**	**-1.7%**	**28.3%**	**52.0%**	**24.0%**	**67.0%**	**30.5%**	**67.33%**	**73.38%**	**107.68%**
GHG emissions	kg CO_2eq/t biodiesel		2752.98	3388.54	2601.94	2579.82	3386.28	2388.17	1599.68	2529.00	1097.21	2312.90	1087.85	886.20	-255.87
Farming			2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2395.6	2395.6	2395.6
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-24.55	611.01	-175.58	-197.71	608.75	-389.36	-1177.85	-248.53	-1680.32	-464.63	-1511.54	-1713.18	-2855.26
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 29: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT + unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT + unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.12**	**-0.12**	**-0.12**	**-0.64**	**-0.18**	**-0.99**	**-0.38**	**-0.30**	**-0.38**	**-0.83**
	GJp/ t biodiesel		0.0	0.0	0.0	-4.4	-4.4	-4.4	-24.0	-6.71	-36.74	-14.09	-11.27	-14.20	-30.79
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-8.21**	**-8.21**	**-8.21**	**-44.39**	**-12.39**	**-67.89**	**-26.03**	**-20.83**	**-26.24**	**-56.88**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-305.85	-305.85	-305.85	-1654.31	-461.83	-2530.12	-970.19	-776.36	-978.01	-2120.08
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input	**GJf/GJ biodiesel**		**0.262**	**0.262**	**0.266**	**0.190**	**0.190**	**0.196**	**-0.057**	**0.280**	**-0.218**	**0.223**	**-0.348**	**-0.426**	**-0.87**
Fossil energy saved		**%**	**77.4%**	**77.4%**	**77.0%**	**83.6%**	**83.6%**	**83.1%**	**104.9%**	**75.9%**	**118.8%**	**80.8%**	**130.0%**	**136.7%**	**175.1%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.262**	**0.262**	**0.266**	**0.19**	**0.19**	**0.196**	**-0.057**	**0.280**	**-0.218**	**0.223**	**0.640**	**0.562**	**0.117**
	GJp/t biodiesel		9.7	9.7	9.9	7.1	7.1	7.3	-2.1	10.4	-8.1	8.3	23.9	20.9	4.4
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-5.50	-5.50	-5.32	-8.16	-8.16	-7.93	-17.39	-4.83	-23.36	-6.93	10.28	7.35	-9.24
Distribution of biodiesel			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**66.94**	**83.99**	**62.88**	**62.29**	**83.93**	**57.15**	**35.99**	**60.93**	**22.51**	**55.13**	**22.26**	**16.85**	**-13.79**
GHG avoided		**%**	**25.1%**	**6.0%**	**29.6%**	**30.3%**	**6.1%**	**36.0%**	**59.7%**	**31.8%**	**74.8%**	**38.3%**	**75.1%**	**81.1%**	**115.4%**
GHG emissions	kg CO_2eq/t biodiesel		2494.72	3130.28	2343.69	2321.56	3128.02	2129.91	1341.42	2270.74	838.96	2054.64	829.59	627.94	-514.13
Farming			2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2395.6	2395.6	2395.6
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.3	145.3	145.3
Manufacture			-282.81	352.75	-433.84	-455.97	350.49	-647.62	-1436.11	-506.79	-1938.57	-722.89	-1769.79	-1971.44	-3113.51
Distribution of biodiesel			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Irrigated Scenario 2

Jatropha to Biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260 ^oC) and Esterification (10 bar, 240^oC).

Table IV. 30: Overall Gross balance. Industrial scale production. Two-stage process. Fat-Splitting (60 bar, 260 ^oC) and Esterification (10 bar, 240^oC) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	b11 Oil boiler + BPSTG	b12 Coal boiler + BPSTG	b21 NG boiler + BPSTG	c11 NG GT +unfired HRSG	c12 NG GT + co-fired HRSG	c21 NG GT+ unfired HRSG+ BPSTG	c22 NG GT+ co-fired HRSG+ BPSTG	d1 Biomass boiler + BPSTG	d2 Biomass boiler + BP/cond STG	e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG	Diesel
Overall gross balance																
Total fossil energy input	**GJf/GJ biodiesel**		**0.505**	**0.505**	**0.506**	**0.480**	**0.480**	**0.481**	**0.579**	**0.54**	**0.585**	**0.547**	**0.642**	**0.642**	**1.047**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.505**	**0.505**	**0.506**	**0.480**	**0.480**	**0.481**	**0.579**	**0.54**	**0.585**	**0.547**	**1.4**	**1.4**	**1.4**	**1.16**
	GJp/t biodiesel		18.81	18.81	18.86	17.89	17.89	17.94	21.57	20.20	21.80	20.38	50.42	50.42	50.4	
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95	
Harvesting + storage + drying + transport ation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89	
Manufacture			3.56	3.56	3.61	2.64	2.64	2.70	6.32	4.95	6.56	5.13	36.82	36.82	36.82	
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**81.40**	**86.32**	**80.23**	**79.70**	**84.65**	**78.52**	**83.90**	**81.87**	**84.25**	**82.14**	**69.74**	**69.74**	**69.74**	**89.3**
	kg CO_2eq/t biodiesel		3033.66	3216.98	2990.10	2970.44	3154.91	2926.60	3127.02	3051.11	3140.09	3061.35	2599.38	2599.38	2599.38	
Farming (CO_2)			932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	932.29	736.48	736.48	736.48	
Farming (N_2O)			1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	1659.1	
Harvesting + storage + drying + transport ation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34	
Manufacture			256.13	439.46	212.57	192.91	377.39	149.07	349.49	273.58	362.56	283.82	0.0	0.0	0.0	
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	

Table IV. 31: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). Net balance: Press-cake as fertilizer (green manure)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake as fertilizer (green manure)															
Press-cake credit															
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**													
	GJp/t biodiesel	-6.23													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**													
	kg CO_2eq / t biodiesel	-652.88													
Total fossil energy input	**GJf/GJ biodiesel**		**0.283**	**0.283**	**0.284**	**0.234**	**0.234**	**0.235**	**0.1822**	**0.279**	**0.140**	**0.241**	**-0.011**	**-0.281**	**-0.238**
Fossil energy saved		**%**	**75.6%**	**75.6%**	**75.5%**	**79.9%**	**79.9%**	**79.7%**	**84.3%**	**75.9%**	**87.9%**	**79.2%**	**100.9%**	**124.2%**	**120.6%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.283**	**0.283**	**0.284**	**0.234**	**0.234**	**0.235**	**0.182**	**0.279**	**0.140**	**0.241**	**0.827**	**0.707**	**0.750**
	GJp/t biodiesel		10.54	10.5	10.6	8.7	8.7	8.8	6.8	10.4	5.2	9.0	30.8	26.4	27.9
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-4.71	-4.71	-4.66	-6.54	-6.54	-6.49	-8.46	-4.84	-10.02	-6.26	17.23	12.77	14.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**61.67**	**66.59**	**60.50**	**59.93**	**64.88**	**58.75**	**63.85**	**62.06**	**64.12**	**62.26**	**49.46**	**49.24**	**50.01**
GHG avoided		**%**	**31.0%**	**25.5%**	**32.3%**	**32.9%**	**27.4%**	**34.2%**	**28.5%**	**30.5%**	**28.2%**	**30.3%**	**44.6%**	**44.9%**	**44.0%**
GHG emissions	kg CO_2eq/t biodiesel		2298.5	2481.8	2254.9	2233.6	2418.0	2189.7	2379.8	2313.14	2389.57	2320.40	1843.3	1835.0	1864.0
Farming			2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2395.6	2395.6	2395.6
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-479.04	-295.72	-522.61	-543.96	-359.49	-587.80	-397.71	-464.39	-387.96	-457.13	-756.11	-764.35	-735.43
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Table IV. 32: Jatropha to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260^oC) and Esterification (10 bar, 240^oC). Net balance: Press-cake use as co-fuel for power plant (biogas production)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**b11 Oil boiler + BPSTG**	**b12 Coal boiler + BPSTG**	**b21 NG boiler + BPSTG**	**c11 NG GT +unfired HRSG**	**c12 NG GT + co-fired HRSG**	**c21 NG GT+ unfired HRSG+ BPSTG**	**c22 NG GT+ co-fired HRSG+ BPSTG**	**d1 Biomass boiler + BPSTG**	**d2 Biomass boiler + BP/cond STG**	**e Integtated biomass gasifier + GT + unfired HRSG + BP/ cond STG**
Overall net balance															
Credit for surplus electricity															
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.02**	**-0.02**	**-0.02**	**-0.17**	**-0.04**	**-0.22**	**-0.08**	**-0.30**	**-0.42**	**-0.38**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.92	-0.92	-0.92	-6.51	-1.51	-8.31	-3.12	-11.33	-15.79	-14.21
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.05**	**-0.05**	**-0.05**	**-0.32**	**-0.07**	**-0.41**	**-0.15**	**-0.56**	**-0.78**	**-0.01**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-1.70	-1.70	-1.70	-12.02	-2.79	-15.35	-5.77	-20.93	-29.17	-0.25
Credit for glycerine															
Primary energy credit	**GJp/ GJ biodiesel**		**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**	**-0.05**
	GJp/ t biodiesel		-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04	-2.04
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**	**-2.21**
	kg CO_2eq/t biodiesel		-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30	-82.30
Net balance: Press-cake use as co-fuel for power plant (biogas production)															
Press-cake credit															
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02													
Electricity consumption for biogas production	GJe/t biodiesel	0.0063													
Primary energy credit	**GJp/GJ biodiesel**	**-0.355**													
	GJp/t biodiesel	-13.23													
Electricity generation	GJe/t biodiesel	5.84													
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.4**													
	kg CO_2/t biodiesel	-911.14													
Total fossil energy input (per annum)	**GJf/GJ biodiesel**		**0.095**	**0.095**	**0.096**	**0.046**	**0.046**	**0.047**	**-0.006**	**0.091**	**-0.048**	**0.053**	**-0.016**	**-0.469**	**-0.426**
Fossil energy saved (per annum)		**%**	**91.8%**	**91.8%**	**91.7%**	**96.1%**	**96.1%**	**95.9%**	**100.5%**	**92.1%**	**104.1%**	**95.4%**	**101.4%**	**140.4%**	**136.8%**
Primary Total Energy Input (per annum)	**GJp/GJ biodiesel**		**0.095**	**0.095**	**0.096**	**0.046**	**0.046**	**0.047**	**-0.006**	**0.091**	**-0.048**	**0.053**	**0.639**	**0.52**	**0.56**
	GJp/t biodiesel		3.5	3.5	3.6	1.7	1.7	1.8	-0.2	3.4	-1.8	2.0	23.8	19.4	20.9
Farming			12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	12.83	10.95	10.95	10.95
Harvesting + storage + drying + transportation			1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.66	1.89	1.89	1.89
Manufacture			-11.71	-11.71	-11.66	-13.55	-13.55	-13.50	-15.46	-11.84	-17.02	-13.27	10.22	5.76	7.34
Distribution of biodiesel + glycerine transportation			0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759	0.759
GHG emissions	**kg CO_2eq/GJ biodiesel**		**54.74**	**59.66**	**53.57**	**53.00**	**57.95**	**51.82**	**56.92**	**55.14**	**57.19**	**55.33**	**42.53**	**42.31**	**43.08**
GHG avoided		**%**	**38.7%**	**33.2%**	**40.0%**	**40.7%**	**35.1%**	**42.0%**	**36.3%**	**38.3%**	**36.0%**	**38.1%**	**52.4%**	**52.6%**	**51.8%**
GHG emissions	kg CO_2eq/t biodiesel		2040.2	2223.5	1996.7	1975.3	2159.8	1931.5	2121.6	2054.9	2131.3	2062.1	1585.0	1576.8	1605.7
Farming			2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2591.4	2395.6	2395.6	2395.6
Harvesting + storage + drying + transportation			127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	127.68	145.34	145.34	145.34
Manufacture			-737.30	-553.98	-780.87	-802.22	-617.74	-846.06	-655.97	-722.65	-646.22	-715.39	-1014.36	-1022.61	-993.69
Distribution of biodiesel + glycerine transportation			58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46	58.46

Rainfed Scenario 1

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60^{o}C).

Table IV. 33: Overall Gross balance. Organic, chemical fertilizers and agro-chemicals applied. Small-scale production. Transesterification Process (1.4 bar, 60^{o}C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.337**	**0.337**	**0.337**	**0.328**	**0.324**	**0.326**	**1.666**	**1.666**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.337**	**0.337**	**0.337**	**0.328**	**0.324**	**0.326**	**1.72**	**1.72**	**1.16**
	GJp/t biodiesel		12.54	12.54	12.57	12.21	12.06	12.16	64.0	64.0	
Farming			9.83	9.83	9.83	9.83	9.83	9.83	5.80	5.80	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**77.49**	**79.65**	**76.98**	**77.05**	**76.05**	**76.18**	**63.97**	**63.97**	**89.3**
	kg CO_2eq/t biodiesel		2888.09	2968.66	2868.95	2871.67	2834.25	2839.35	2384.14	2384.14	
Farming (CO_2)			941.07	941.07	941.07	941.07	941.07	941.07	529.57	529.57	
Farming (N_2O)			1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	1747.1	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.6	94.6	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 34: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake as fertilizer (green manure)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.167**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**0.108**	**0.108**	**0.109**	**0.093**	**0.094**	**0.096**	**-0.565**	**-0.216**
Fossil energy saved		**%**	**90.7%**	**90.7%**	**90.61%**	**92.01%**	**91.9%**	**91.75%**	**148.69%**	**118.62%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.108**	**0.108**	**0.109**	**0.093**	**0.094**	**0.096**	**0.959**	**1.308**
	GJp/t biodiesel		4.04	4.0	4.1	3.5	3.5	3.6	35.7	48.7
Farming			9.83	9.83	9.83	9.83	9.83	9.83	5.80	5.80
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions (per annum)	**kg CO_2eq/GJ biodiesel**		**57.51**	**59.67**	**57.00**	**56.60**	**55.98**	**56.04**	**7.52**	**31.54**
GHG avoided (per annum)		**%**	**35.6%**	**33.2%**	**36.2%**	**36.6%**	**37.3%**	**37.3%**	**91.6%**	**64.7%**
GHG emissions	kg CO_2eq/t biodiesel		2143.4	2223.9	2124.2	2109.6	2086.5	2088.8	280.4	1175.5
Farming			2688.2	2688.2	2688.2	2688.2	2688.2	2688.2	2276.68	2276.68
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 35: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.080**	**-0.080**	**-0.080**	**-0.096**	**-0.094**	**-0.093**	**-0.753**	**-0.405**
Fossil energy saved		**%**	**106.9%**	**106.9%**	**106.9%**	**108.3%**	**108.1%**	**108.0%**	**165.0%**	**134.9%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.080**	**-0.080**	**-0.080**	**-0.096**	**-0.094**	**-0.093**	**0.770**	**1.119**
	GJp/t biodiesel		-3.0	-3.0	-3.0	-3.6	-3.5	-3.5	28.7	41.7
Farming			9.83	9.83	9.83	9.83	9.83	9.83	5.80	5.80
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
GHG emissions	**kg CO_2eq/GJ biodiesel**		**50.53**	**52.69**	**50.01**	**49.62**	**49.00**	**49.06**	**0.54**	**24.56**
GHG avoided		**%**	**43.4%**	**41.0%**	**44.0%**	**44.5%**	**45.2%**	**45.1%**	**99.4%**	**72.5%**
	kg CO_2eq/t biodiesel		1883.14	1963.70	1863.99	1849.37	1826.29	1828.57	20.20	915.27
Farming			2688.18	2688.18	2688.18	2688.18	2688.18	2688.18	2276.68	2276.68
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Rainfed Scenario 2

Jatropha to Biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60^{o}C).

Table IV. 36: Overall Gross balance. No fertilizers and agro-chemicals used. Small-scale production. Transesterification Process (1.4 bar, 60^{o}C) (without by-products credits)

Model		Basic Energy inputs	a11 Oil boiler + grid	a12 Coal boiler + grid	a21 NG boiler + grid	f11 Diesel genset with HUB	f12 NG genset with HUB	g NG CHP Microturbine	h11 Anaerobic digester + EFmGT with HUB	h12 Integtated biomass gasifier + Gas engine genset with HUB	Diesel
Overall gross balance											
Total fossil energy input	**GJf/GJ biodiesel**		**0.241**	**0.241**	**0.241**	**0.232**	**0.228**	**0.230**	**0.14**	**0.14**	**1.16**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.241**	**0.241**	**0.241**	**0.232**	**0.228**	**0.230**	**1.663**	**1.663**	**1.16**
	GJp/t biodiesel		8.97	8.97	8.99	8.64	8.49	8.58	62.0	62.0	
Farming			6.26	6.26	6.26	6.26	6.26	6.26	3.82	3.82	
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23	
Manufacture			1.67	1.67	1.69	1.34	1.19	1.28	56.78	56.78	
Distribution of biodiesel + glycerine transportation			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167	
GHG emissions	**kg CO_2eq/GJ biodiesel**		**57.05**	**59.21**	**56.54**	**56.61**	**55.60**	**55.74**	**34.40**	**34.40**	**89.3**
	kg CO_2eq/t biodiesel		2126.23	2206.79	2107.08	2109.81	2072.38	2077.49	1282.11	1282.11	
Farming (CO_2)			649.93	649.93	649.93	649.93	649.93	649.93	396.36	396.36	
Farming (N_2O)			1276.4	1276.4	1276.4	1276.4	1276.4	1276.4	778.3	778.3	
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60	
Manufacture			119.69	200.25	100.54	103.27	65.84	70.95	0.0	0.0	
Distribution of biodiesel + glycerine transportation			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86	

Table IV. 37: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). Net balance: Press-cake as fertilizer (green manure)

Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake as fertilizer (green manure)										
Press-cake credit										
Primary energy credit	**GJp/GJ biodiesel**	**-0.17**								
	GJp/t biodiesel	-6.23								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-17.5**								
	kg CO_2eq / t biodiesel	-652.88								
Total fossil energy input	**GJf/GJ biodiesel**		**0.012**	**0.012**	**0.013**	**-0.003**	**-0.002**	**-0.0003**	**-0.618**	**-0.269**
Fossil energy saved		**%**	**98.9%**	**98.9%**	**98.9%**	**100.3%**	**100.1%**	**100.0%**	**153.27%**	**123.2%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**0.012**	**0.012**	**0.013**	**-0.003**	**-0.002**	**-0.0003**	**0.91**	**1.254**
	GJp/t biodiesel		0.46	0.5	0.5	-0.1	-0.1	0.0	33.8	46.8
Farming			6.2559	6.2559	6.2559	6.2559	6.2559	6.2559	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-6.84	-6.84	-6.82	-7.42	-7.36	-7.31	28.54	41.54
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**37.1**	**39.2**	**36.6**	**36.2**	**35.5**	**35.6**	**-22.0**	**2.0**
GHG avoided		**%**	**58.5%**	**56.1%**	**59.1%**	**59.5%**	**60.2%**	**60.1%**	**124.7%**	**97.8%**
GHG emissions	kg CO_2eq/t biodiesel		1381.50	1462.07	1362.35	1347.73	1324.65	1326.93	-821.6	73.5
Farming			1926.32	1926.32	1926.32	1926.32	1926.32	1926.32	1174.65	1174.65
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-625.04	-544.48	-644.19	-658.81	-681.89	-679.61	-2103.72	-1208.64
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Table IV. 38: Jatropha to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60^{o}C). Net balance: Press-cake used as co-fuel for power plant (biogas production)

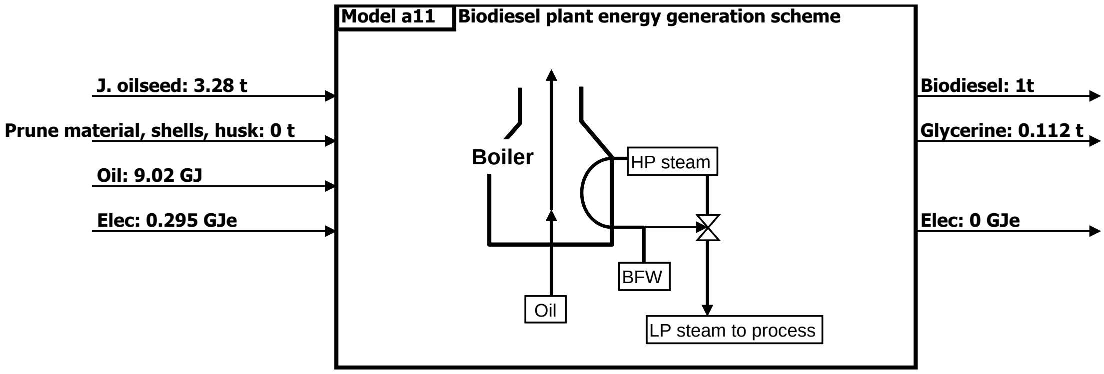
Model		**Basic Energy inputs**	**a11 Oil boiler + grid**	**a12 Coal boiler + grid**	**a21 NG boiler + grid**	**f11 Diesel genset with HUB**	**f12 NG genset with HUB**	**g NG CHP Microturbine**	**h11 Anaerobic digester + EFmGT with HUB**	**h12 Integtated biomass gasifier + Gas engine genset with HUB**
Overall net balance										
Credit for surplus electricity										
Primary energy credit	**GJp/ GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.01**	**-0.001**	**-0.002**	**-0.53**	**-0.18**
	GJp/ t biodiesel		0.0	0.0	0.0	-0.252	-0.044	-0.085	-19.74	-6.74
GHG credit	**kg CO_2eq/GJ biodiesel**		**0.0**	**0.0**	**0.0**	**-0.47**	**-0.08**	**-0.16**	**-36.46**	**-12.45**
	kg CO_2eq/t biodiesel		0.0	0.0	0.0	-17.345	-2.999	-5.829	-1358.99	-463.92
Credit for glycerine										
Primary energy credit	**GJp/ GJ biodiesel**		**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**	**-0.06**
	GJp/ t biodiesel		-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28	-2.28
GHG credit	**kg CO_2eq/GJ biodiesel**		**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**	**-2.46**
	kg CO_2eq/t biodiesel		-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85	-91.85
Net balance: Press-cake use as co-fuel for power plant (biogas production)										
Press-cake credit										
Primary energy from biogas (press-cake used for biogas production)	GJp/t biodiesel	0.02								
Electricity consumption for biogas production	GJe/t biodiesel	0.0063								
Primary energy credit	**GJp/GJ biodiesel**	**-0.356**								
	GJp/t biodiesel	-13.26								
Electricity generation	GJe/t biodiesel	5.86								
GHG credit	**kg CO_2eq/GJ biodiesel**	**-24.5**								
	kg CO_2/t biodiesel	-913.11								
Total fossil energy input	**GJf/GJ biodiesel**		**-0.176**	**-0.176**	**-0.176**	**-0.192**	**-0.190**	**-0.189**	**-0.807**	**-0.458**
Fossil energy saved		**%**	**115.2%**	**115.2%**	**115.2%**	**116.5%**	**116.4%**	**116.3%**	**169.5%**	**139.5%**
Primary Total Energy Input	**GJp/GJ biodiesel**		**-0.176**	**-0.176**	**-0.176**	**-0.192**	**-0.190**	**-0.189**	**0.717**	**1.066**
	GJp/t biodiesel		-6.6	-6.6	-6.5	-7.2	-7.1	-7.0	26.7	39.7
Farming			6.2559	6.2559	6.2559	6.2559	6.2559	6.2559	3.8165	3.8165
Harvesting + storage + drying + transportation			0.87	0.87	0.87	0.87	0.87	0.87	1.23	1.23
Manufacture			-13.87	-13.87	-13.85	-14.45	-14.39	-14.34	21.51	34.51
Distribution of biodiesel			0.167	0.167	0.167	0.167	0.167	0.167	0.167	0.167
GHG emissions	**kg CO_2eq/GJ biodiesel**		**30.09**	**32.25**	**29.57**	**29.18**	**28.56**	**28.62**	**-29.03**	**-5.01**
GHG avoided		**%**	**66.3%**	**63.9%**	**66.9%**	**67.3%**	**68.0%**	**68.0%**	**132.5%**	**105.6%**
	kg CO_2eq/t biodiesel		1121.3	1201.8	1102.1	1087.5	1064.4	1066.7	-1081.83	-186.8
Farming			1926.32	1926.32	1926.32	1926.32	1926.32	1926.32	1174.65	1174.65
Harvesting + storage + drying + transportation			67.36	67.36	67.36	67.36	67.36	67.36	94.60	94.60
Manufacture			-885.27	-804.71	-904.42	-919.04	-942.12	-939.84	-2363.94	-1468.87
Distribution of biodiesel			12.86	12.86	12.86	12.86	12.86	12.86	12.86	12.86

Appendix V: Biodiesel manufacturing plant: energy generation options

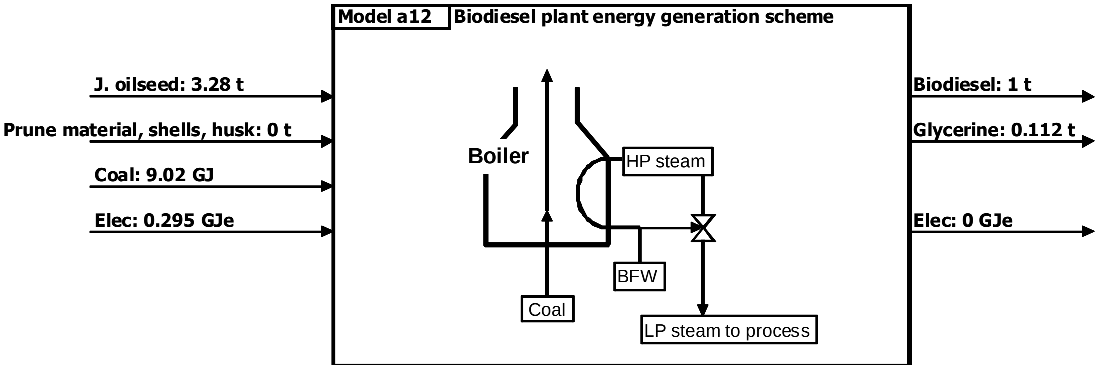
Scenario: IRR I

Table V. 1: Energy supply scenarios. Irrigated I.

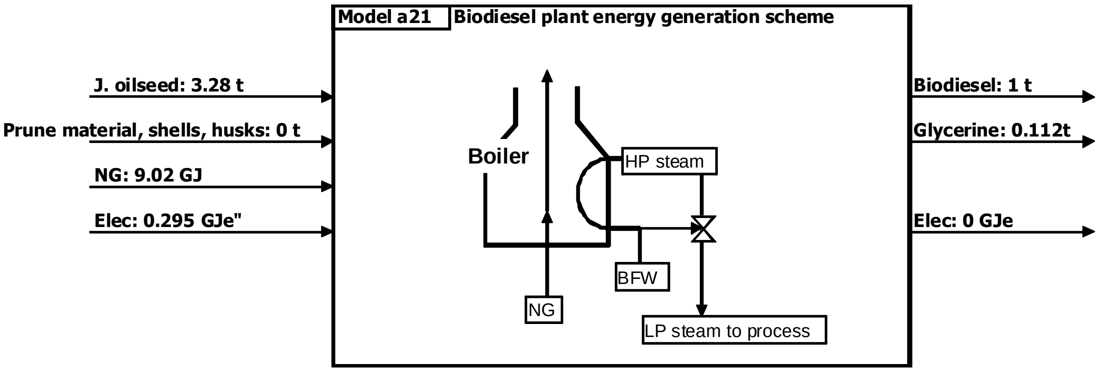
Fruit hulls and seed shells	**Energy generation scheme**			
Used as fertilizer	a11	Conventional oil boiler	**X**	**X**
	a12	Conventional coal boiler	**X**	**X**
	a21	Conventional NG boiler	**X**	**X**
	b11	Conventional oil boiler, backpressure turbogenerator	**X**	**X**
	b12	Conventional call boiler, backpressure turbogenerator	**X**	**X**
	b21	Conventional NG boiler, backpressure turbogenerator	**X**	**X**
	c11	NG GT + unfired HRSG	**X**	**X**
	c12	NG GT + co-firing HRSG	**X**	**X**
	c21	NG GT + unfired HRSG, backpressure turbogenerator	**X**	**X**
	c21	NG GT + co-fired HRSG, backpressure turbogenerator	**X**	**X**
Used as fuel	d1	Biomass boiler + CHP	**X**	**X**
	d2	Biomass boiler + CHP and combined cycle	**X**	**X**
	e	Biomass gasification + GT + unfired HRSG + BP/cond STG	**X**	**X**



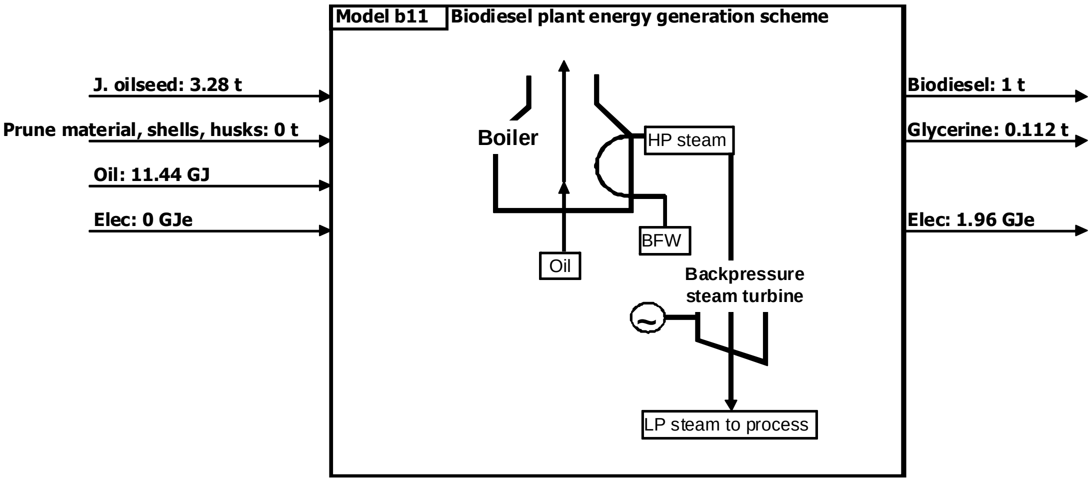
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	3.02
Duty	GJ/t biodiesel	7.66
Thermal efficiency		85%
Carbon oil consumption	GJ/t biodiesel	9.02
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Imported electricity	GJe/t biodiesel	0.295
Overall performance		
Total primary energy	GJp/t biodiesel	9.77
(including oil and imported electricity production)		
Overall efficiency		50%



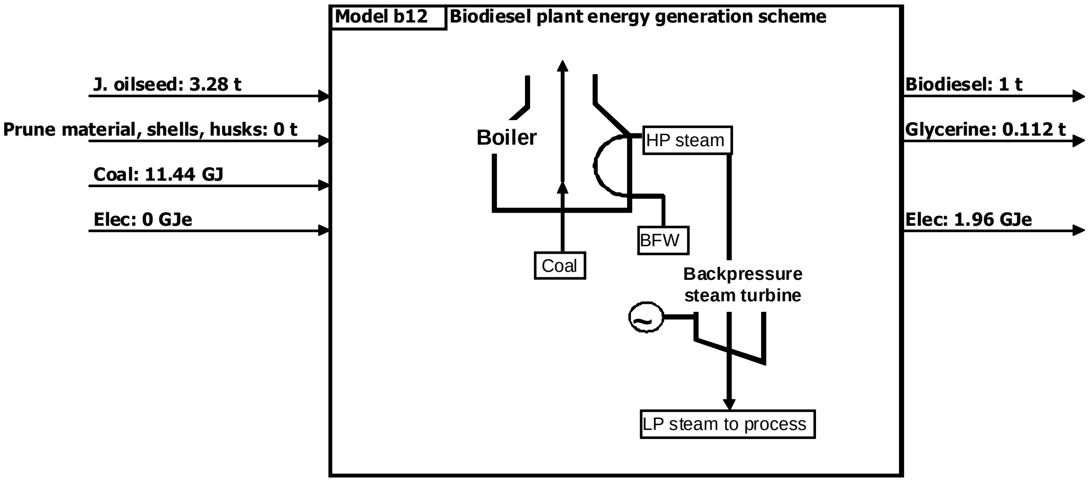
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	3.02
Duty	GJ/t biodiesel	7.66
Thermal efficiency		85%
Coal consumption		9.02
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Imported electricity	GJe/t biodiesel	0.295
Overall performance		
Total primary energy	GJp/t biodiesel	9.77
(including coal and imported electricity production)		
Overall efficiency		50%



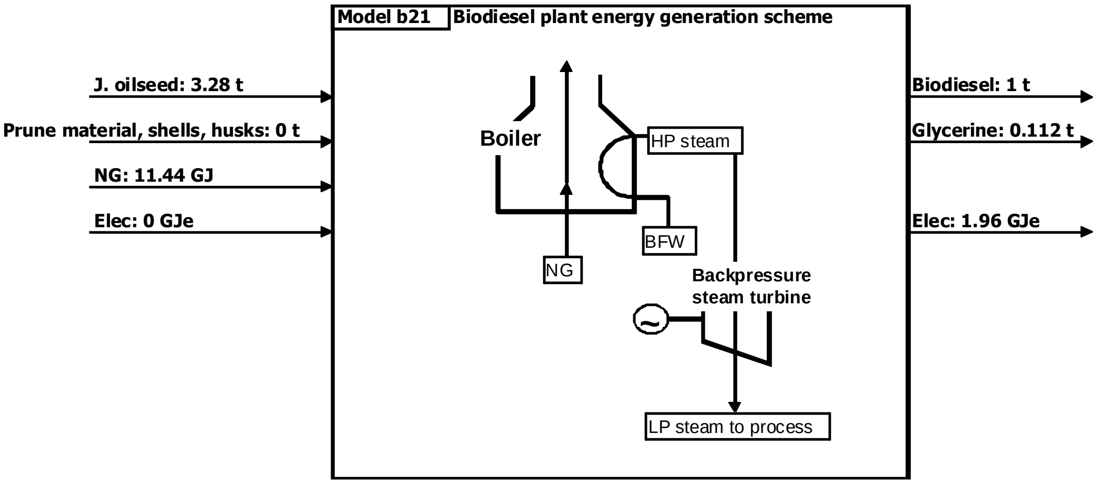
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	3.02
Duty	GJ/t biodiesel	7.66
Thermal efficiency		85%
NG consumption		9.02
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Imported electricity	GJe/t biodiesel	0.295
Overall performance		
Total primary energy	GJp/t biodiesel	9.96
(including NG and imported electricity production)		
Overall efficiency		49.1%



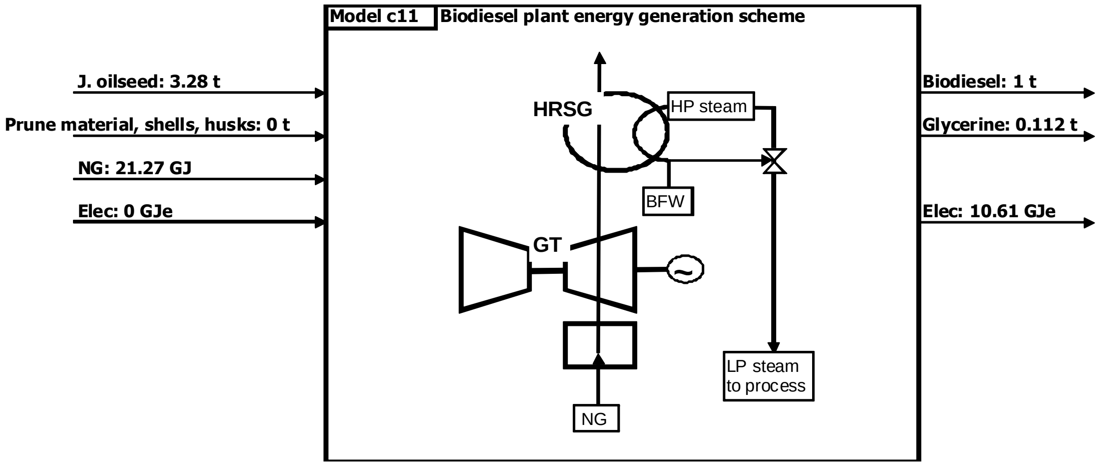
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Duty	GJ/tbiodiesel	9.73
Thermal efficiency		85%
Carbon oil consumption		11.4
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	2.26
Surplus electricity	GJe/t biodiesel	1.96
Overall performance		
Total primary energy	GJp/t biodiesel	11.56
(including oil and imported electricity production)		
Overall efficiency		59.3%



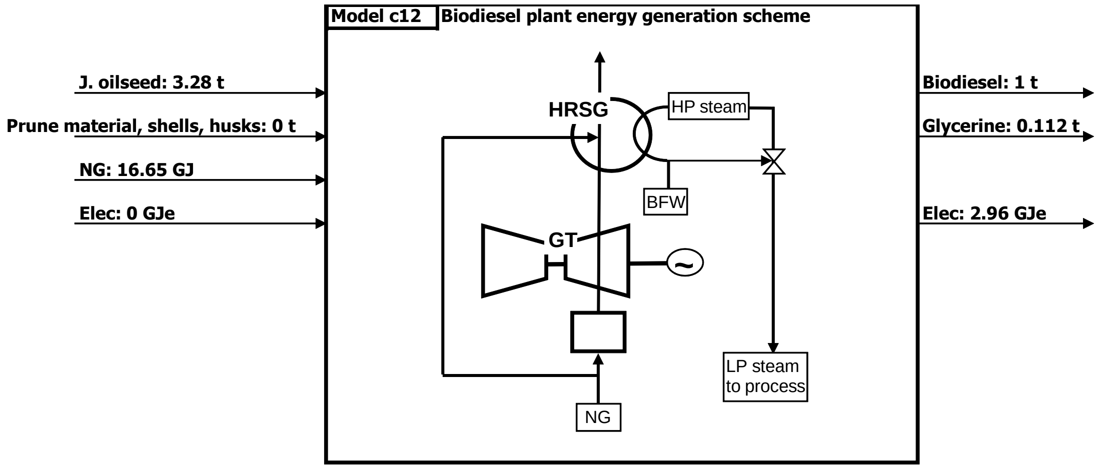
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Duty	GJ/tbiodiesel	9.73
Thermal efficiency		85%
Coal consumption		11.4
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	2.26
Surplus electricity	GJe/t biodiesel	1.96
Overall performance		
Total primary energy	GJp/t biodiesel	11.56
(including coal and imported electricity production)		
Overall efficiency		59.3%



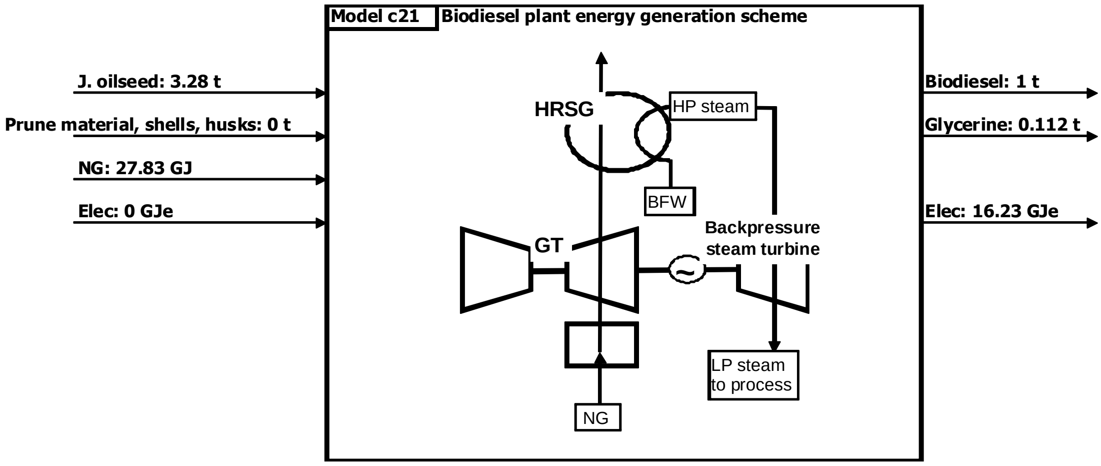
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Duty	GJ/tbiodiesel	9.73
Thermal efficiency		85%
NG consumption		11.44
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	2.26
Surplus electricity	GJe/t biodiesel	1.96
Overall performance		
Total primary energy	GJp/t biodiesel	11.78
(including NG and imported electricity production)		
Overall efficiency		58.1%



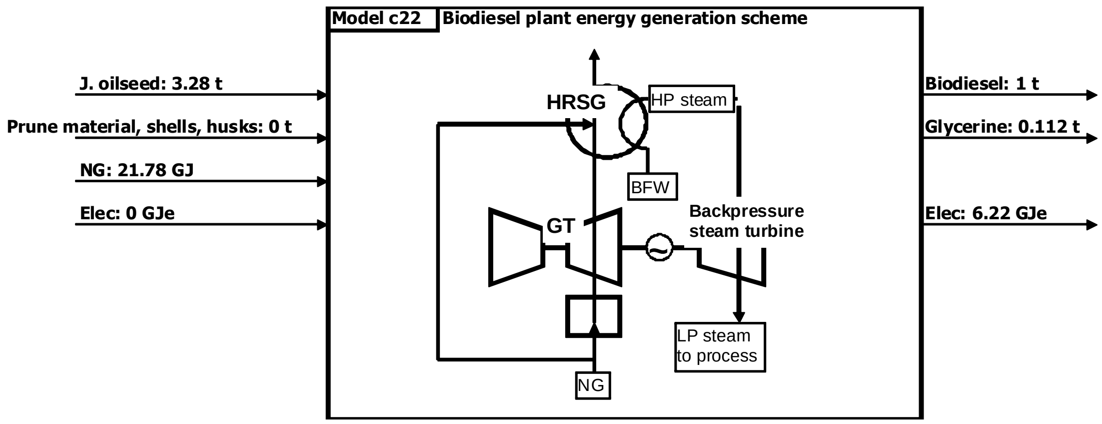
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	10.9
NG consumption	GJ/t biodiesel	21.27
Efficiency		51%
HRSG		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	3.0
Thermal duty	GJ/t biodiesel	7.66
Co-firing NG consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Thermal efficiency		87%
NG consumption		21.27
Surplus electricity	GJe/t biodiesel	10.61
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Overall performance		
Total primary energy	GJp/t biodiesel	21.9
(including NG and imported electricity production)		
Overall efficiency		70.7%



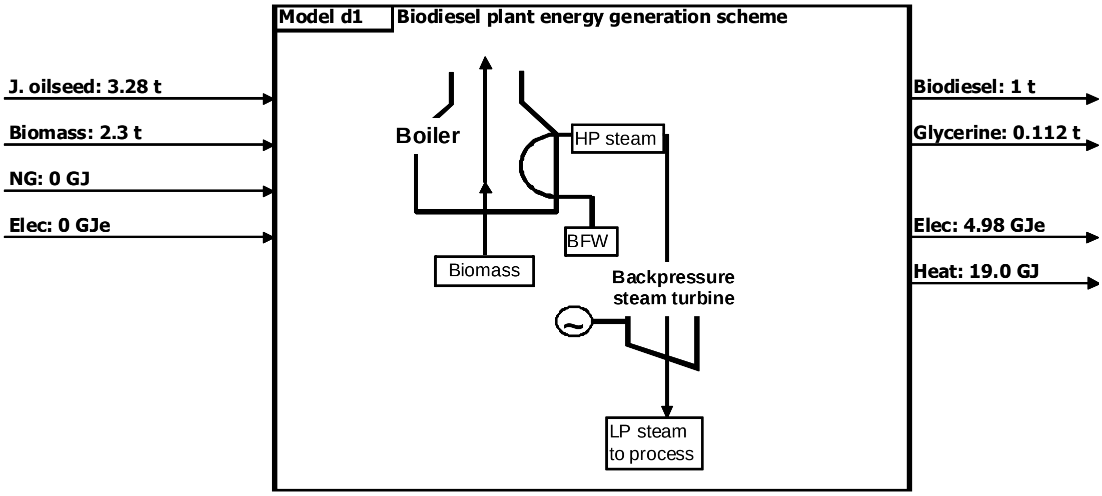
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	3.26
NG consumption	GJ/t biodiesel	6.36
Efficiency		51%
HRSG		
Steam outlet conditions	bara	60
	°C	450
Steam production	GJ/t biodiesel	3.0
Thermal duty	GJ/t biodiesel	7.66
Co-firing NG consumption	GJ/t biodiesel	10.3
Gas turbine + HRSG		
Thermal efficiency		66%
NG consumption		16.65
Surplus electricity	GJe/t biodiesel	2.96
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Overall performance		
Total primary energy	GJp/t biodiesel	17.15
(including NG, biomass and imported electricity production)		
Overall efficiency		45.8%



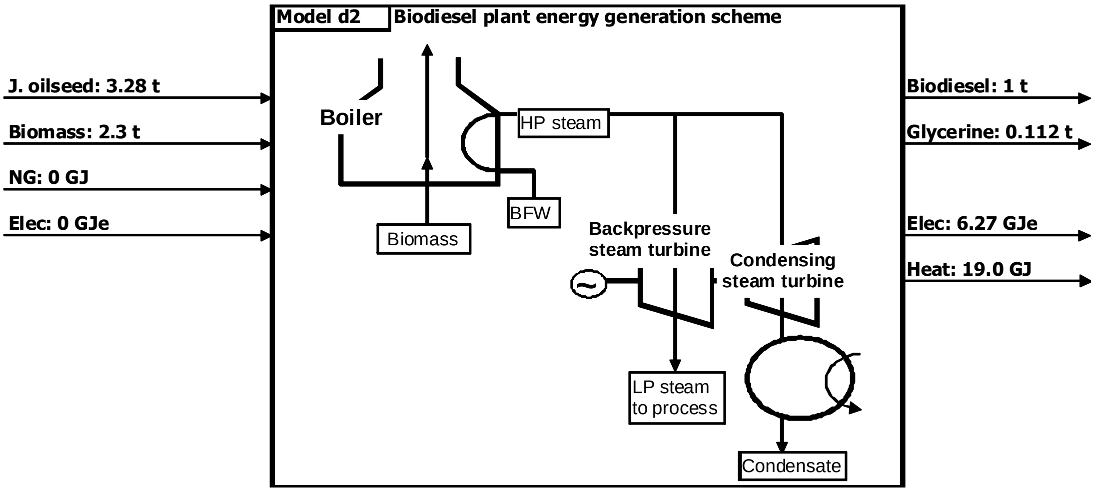
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	14.27
NG consumption	GJ/t biodiesel	27.83
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Thermal duty	GJ/t biodiesel	9.73
Co-firing NG consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Thermal efficiency		87%
NG consumption		27.83
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	16.5
Surplus electricity	GJe/t biodiesel	16.23
Overall performance		
Total primary energy	GJp/t biodiesel	28.66
(including NG and imported electricity production)		
Overall efficiency		73.7%



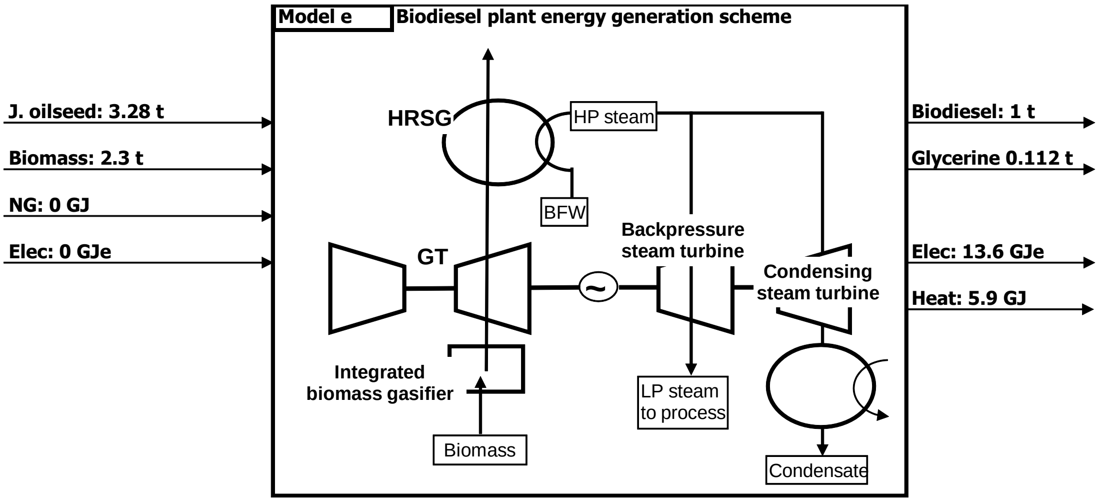
Main process conditions		
Gas turbine		
Electricity production	GJe/t biodiesel	4.26
NG consumption	GJ/t biodiesel	8.31
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Thermal duty	GJ/t biodiesel	9.73
Co-firing NG consumption	GJ/t biodiesel	13.47
Gas turbine + HRSG		
Thermal efficiency		66%
NG consumption		21.78
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	6.52
Surplus electricity	GJe/t biodiesel	6.22
Overall performance		
Total primary energy	GJp/t biodiesel	22.44
(including NG and imported electricity production)		
Overall efficiency		49.5%



Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Duty	GJ/t biodiesel	9.73
Thermal efficiency		78%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Excess steam	t/t biodiesel	5.0
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	5.28
Surplus electricity	GJe/t biodiesel	4.98
Overall performance		
Total primary energy	GJp/t biodiesel	36.82
(including biomass and imported electricity production)		
Overall efficiency		26.8%



Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	3.8
Duty	GJ/t biodiesel	9.73
Thermal efficiency		78%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Steam to process	bara	90
	°C	240
	t/t biodiesel	3.8
Excess steam	t/t biodiesel	5.0
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	2.26
Condensing STG		
Efficiency	MWe/t steam	0.24
Electricity generation	GJe/t biodiesel	4.31
Surplus electricity	GJe/t biodiesel	6.27
Overall performance		
Total primary energy	GJp/t biodiesel	36.82
(including biomass and imported electricity production)		
Overall efficiency		30.3%



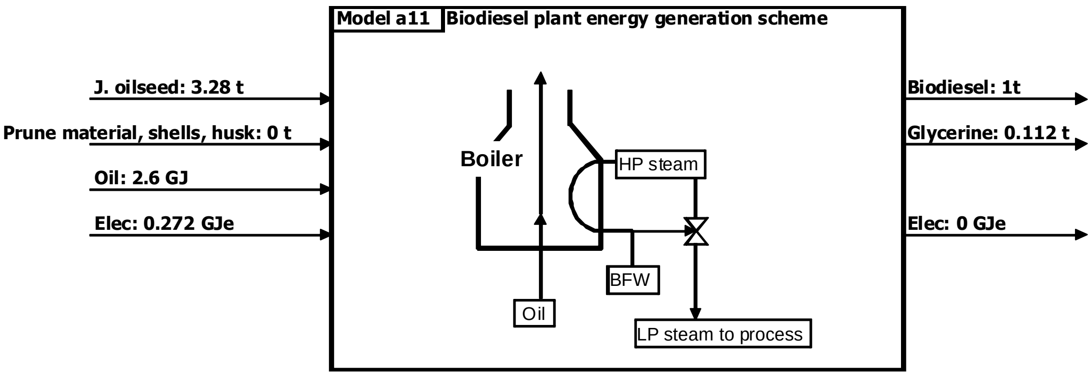
Main process conditions		
Gasifier		
Syngas production	t/t biodiesel	12.1
Gasifier efficiency		37%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Gas turbine		
Electricity production	GJe/t biodiesel	11.3
Producer gas consumption	GJ/t biodiesel	22.02
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	2.98
Thermal duty	GJ/t biodiesel	7.69
Co-firing syngas consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Producer gas consumption	GJ/t biodiesel	62.9
Efficiency		87%
Steam to process		
	bara	90
	°C	240
	t/t biodiesel	3.8
Excess steam	t/t biodiesel	1.2
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	2.26
Condensing STG		
Efficiency	MWe/t steam	0.24
Electricity generation	GJe/t biodiesel	0.35

Main process conditions. Model e. (cont.)		
Overall performance		
Total primary energy	GJp/t biodiesel	36.82
(including biomass and imported electricity production)		
Overall efficiency		50.2%
Surplus electricity	GJe/t biodiesel	13.6

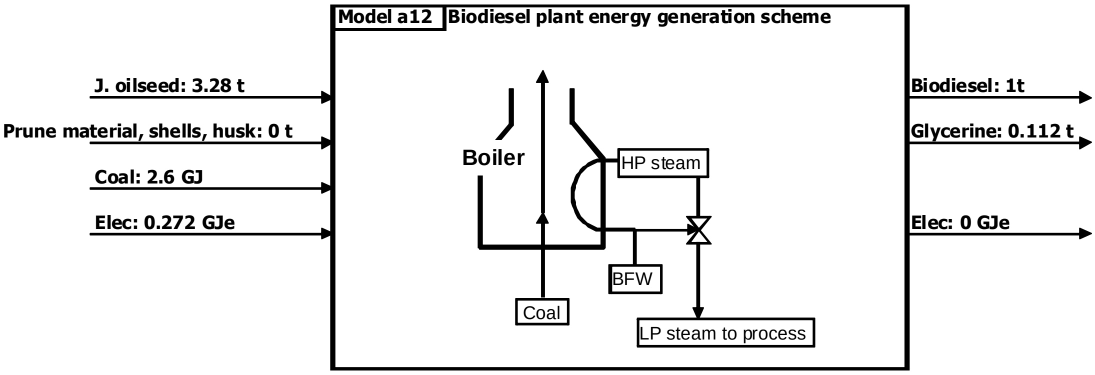
Scenario: IRR II

Table V. 2: Energy supply scenarios. Irrigated II.

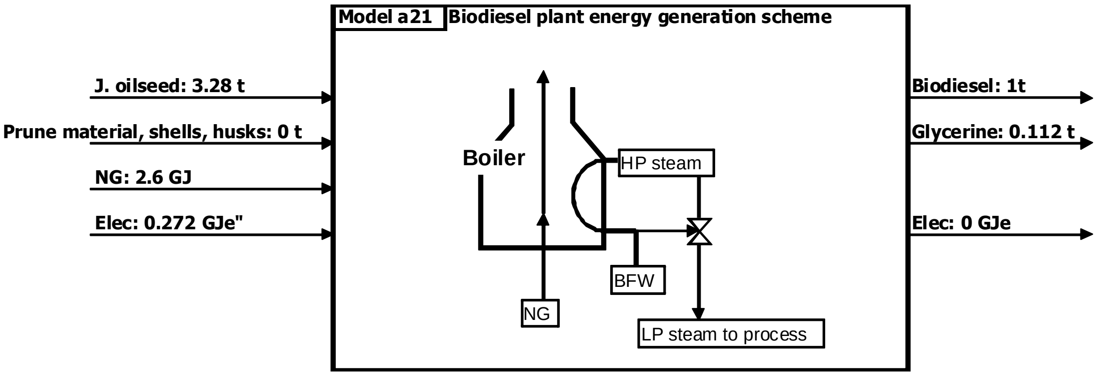
Fruit hulls and seed shells	**Energy generation scheme**			
Used as fertilizer	a11	Conventional oil boiler	**X**	**X**
	a12	Conventional coal boiler	**X**	**X**
	a21	Conventional NG boiler	**X**	**X**
	b11	Conventional oil boiler, backpressure turbogenerator	**X**	**X**
	b12	Conventional coal boiler, backpressure turbogenerator	**X**	**X**
	b21	Conventional NG boiler, backpressure turbogenerator	**X**	**X**
	c11	NG GT + unfired HRSG	**X**	**X**
	c12	NG GT + co-firing HRSG	**X**	**X**
	c21	NG GT + unfired HRSG, backpressure turbogenerator	**X**	**X**
	c21	NG GT + co-fired HRSG, backpressure turbogenerator	**X**	**X**
Used as fuel	d1	Biomass boiler + CHP	**X**	**X**
	d2	Biomass boiler + CHP and combined cycle	**X**	**X**
	e	Biomass gasification + GT + unfired HRSG + BP/cond STG	**X**	**X**



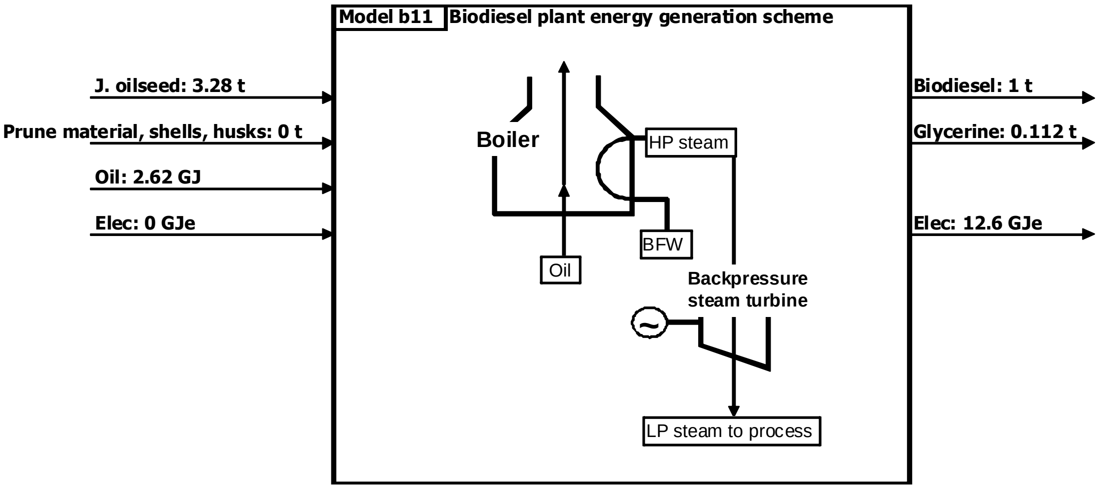
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	0.99
Duty	GJ/t biodiesel	2.21
Thermal efficiency		85%
Carbon oil consumption	GJ/t biodiesel	2.6
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Imported electricity	GJe/t biodiesel	0.272
Overall performance		
Total primary energy	GJp/t biodiesel	3.24
(including oil and imported electricity production)		
Overall efficiency		66%



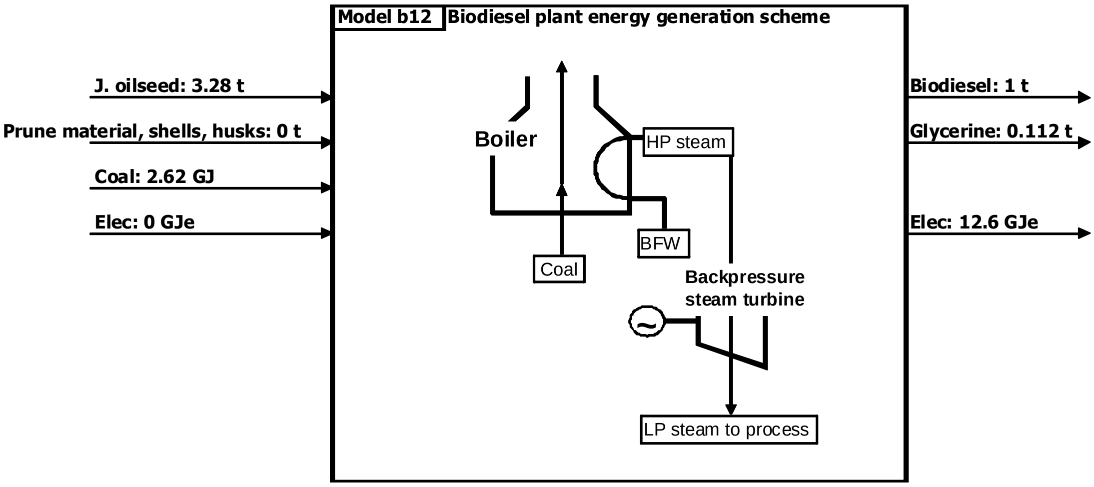
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	0.99
Duty	GJ/t biodiesel	2.21
Thermal efficiency		85%
Coal consumption		2.6
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Imported electricity	GJe/t biodiesel	0.272
Overall performance		
Total primary energy	GJp/t biodiesel	3.24
(including coal and imported electricity production)		
Overall efficiency		66%



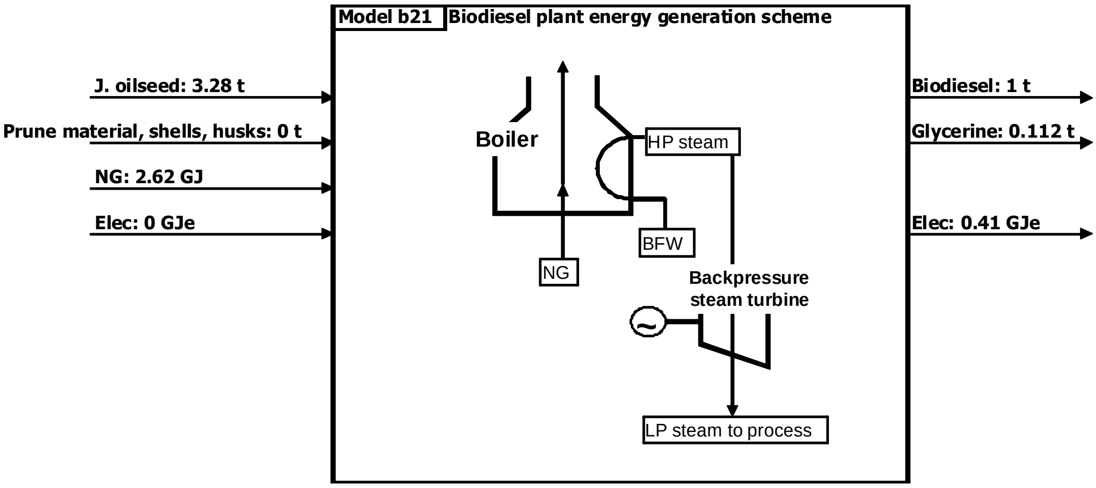
Main process conditions		
Boiler		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	0.99
Duty	GJ/t biodiesel	2.21
Thermal efficiency		85%
NG consumption		2.6
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Imported electricity	GJe/t biodiesel	0.272
Overall performance		
Total primary energy	GJp/t biodiesel	3.29
(including NG and imported electricity production)		
Overall efficiency		65%



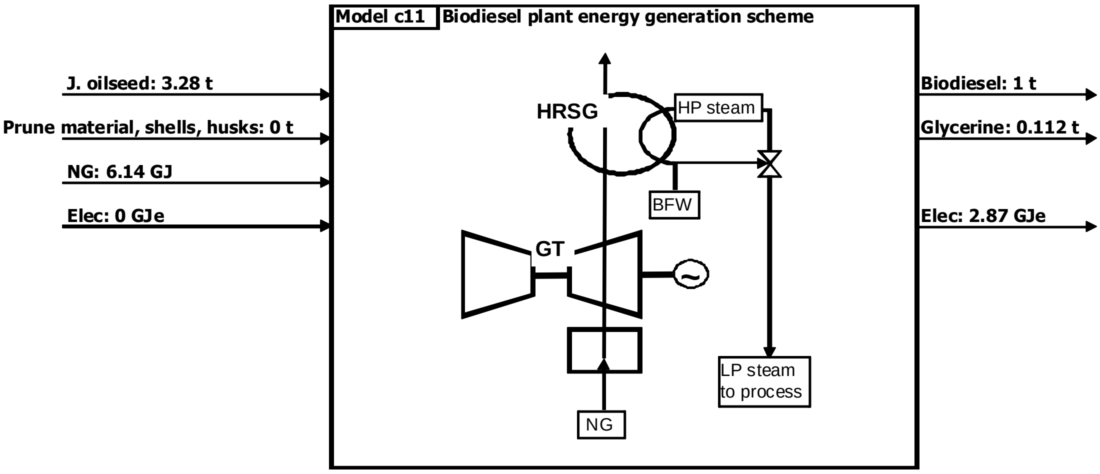
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Duty	GJ/tbiodiesel	2.23
Thermal efficiency		85%
Carbon oil consumption		2.62
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.42
Surplus electricity	GJe/t biodiesel	12.6
Overall performance		
Total primary energy	GJp/t biodiesel	2.64
(including oil and imported electricity production)		
Overall efficiency		96%



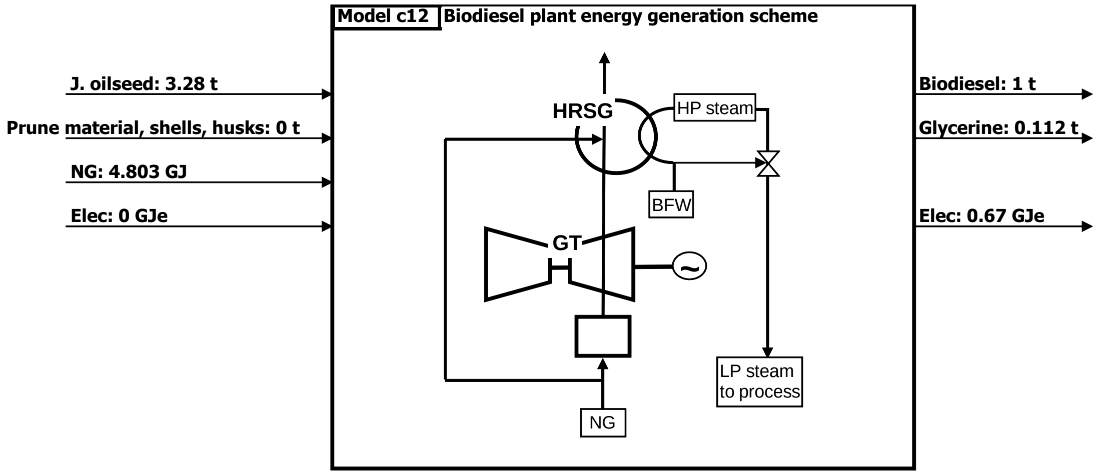
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Duty	GJ/tbiodiesel	2.23
Thermal efficiency		85%
Coal consumption		2.62
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.42
Surplus electricity	GJe/t biodiesel	12.6
Overall performance		
Total primary energy	GJp/t biodiesel	2.64
(including coal and imported electricity production)		
Overall efficiency		96%



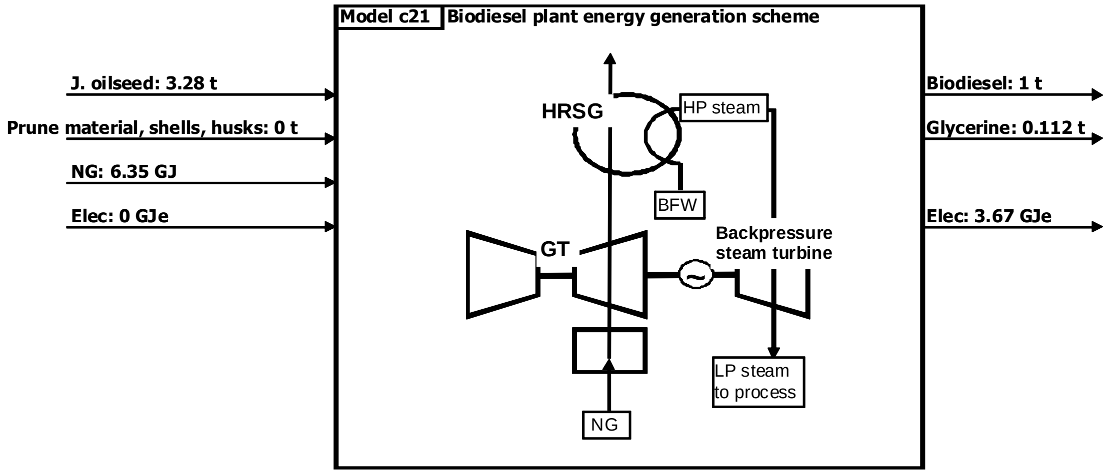
Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Duty	GJ/tbiodiesel	2.23
Thermal efficiency		85%
NG consumption		2.62
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.42
Surplus electricity	GJe/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	2.70
(including NG and imported electricity production)		
Overall efficiency		94.4%



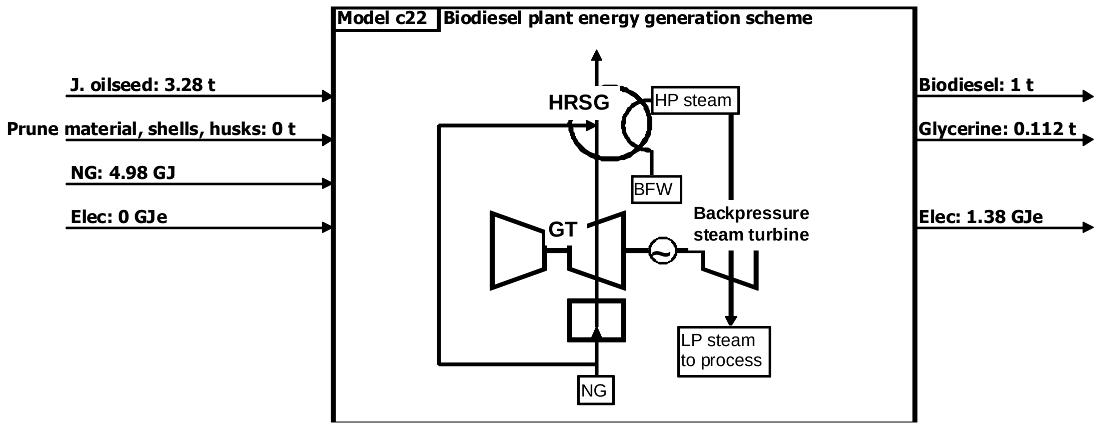
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	3.15
NG consumption	GJ/t biodiesel	6.14
Efficiency		51%
HRSG		
Steam outlet conditions	bara	60
	°C	450
Steam production	t/t biodiesel	0.99
Thermal duty	GJ/t biodiesel	2.21
Co-firing NG consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Thermal efficiency		87%
NG consumption		6.14
Surplus electricity	GJe/t biodiesel	2.87
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Overall performance		
Total primary energy	GJp/t biodiesel	6.3
(including NG and imported electricity production)		
Overall efficiency		79.3%



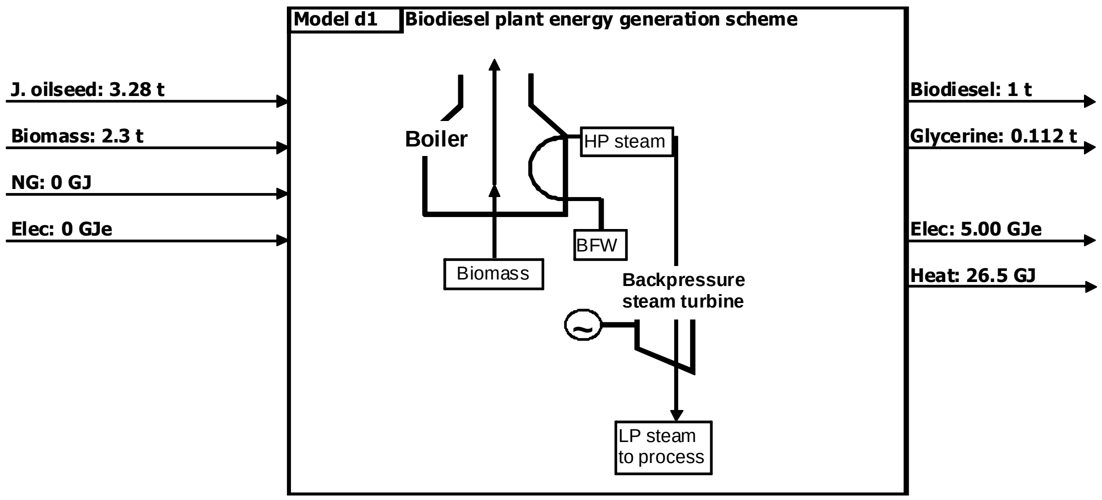
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	0.94
NG consumption	GJ/t biodiesel	1.83
Efficiency		51%
HRSG		
Steam outlet conditions	bara	60
	°C	450
Steam production	GJ/t biodiesel	0.99
Thermal duty	GJ/t biodiesel	2.21
Co-firing NG consumption	GJ/t biodiesel	2.97
Gas turbine + HRSG		
Thermal efficiency		66%
NG consumption		4.803
Surplus electricity	GJe/t biodiesel	0.67
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Overall performance		
Total primary energy	GJp/t biodiesel	4.947
(including NG, biomass and imported electricity production)		
Overall efficiency		56.7%



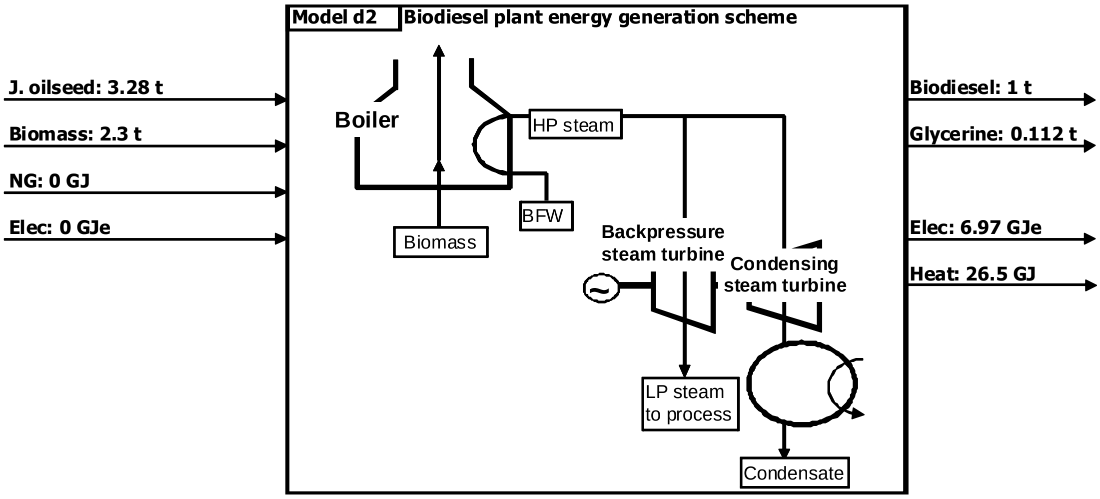
Main process conditions		
Gas turbine		
Electricity production	GJ/t biodiesel	3.26
NG consumption	GJ/t biodiesel	6.35
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Thermal duty	GJ/t biodiesel	2.23
Co-firing NG consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Thermal efficiency		87%
NG consumption		6.35
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.51
Surplus electricity	GJe/t biodiesel	3.67
Overall performance		
Total primary energy	GJp/t biodiesel	6.56
(including NG and imported electricity production)		
Overall efficiency		88.6%



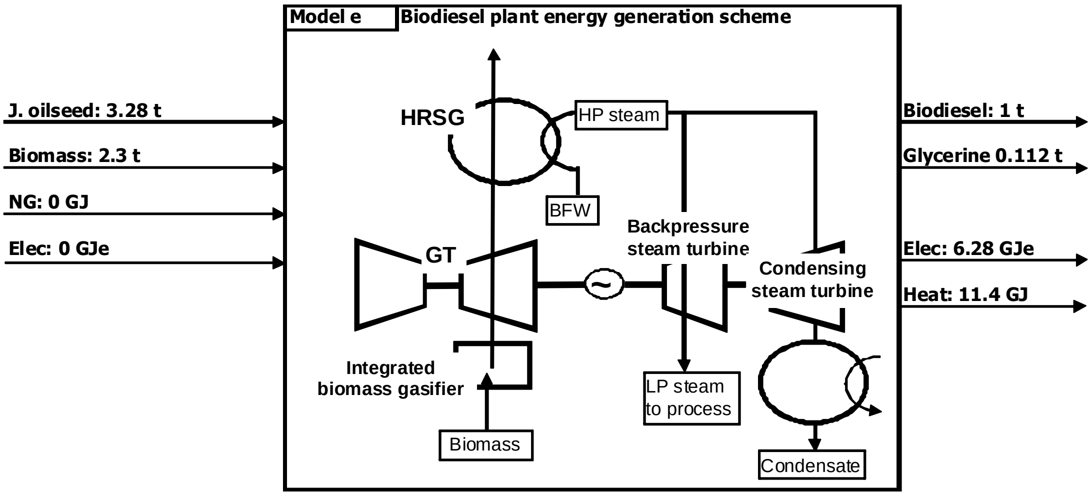
Main process conditions		
Gas turbine		
Electricity production	GJe/t biodiesel	0.975
NG consumption	GJ/t biodiesel	1.90
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Thermal duty	GJ/t biodiesel	2.23
Co-firing NG consumption	GJ/t biodiesel	3.08
Gas turbine + HRSG		
Thermal efficiency		66%
NG consumption		4.98
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.45
Surplus electricity	GJe/t biodiesel	1.38
Overall performance		
Total primary energy	GJp/t biodiesel	5.13
(including NG and imported electricity production)		
Overall efficiency		68.6%



Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Duty	GJ/t biodiesel	2.23
Thermal efficiency		78%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Excess steam	t/t biodiesel	7.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.55
Surplus electricity	GJe/t biodiesel	5.00
Overall performance		
Total primary energy	GJp/t biodiesel	36.8
(including biomass and imported electricity production)		
Overall efficiency		19.4%



Main process conditions		
Boiler		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Duty	GJ/t biodiesel	2.23
Thermal efficiency		78%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Excess steam	t/t biodiesel	7.8
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.68
Condensing STG		
Efficiency	MWe/t steam	0.24
Electricity generation	GJe/t biodiesel	6.6
Surplus electricity	GJe/t biodiesel	6.97
Overall performance		
Total primary energy	GJp/t biodiesel	36.8
(including biomass and imported electricity production)		
Overall efficiency		24.7%



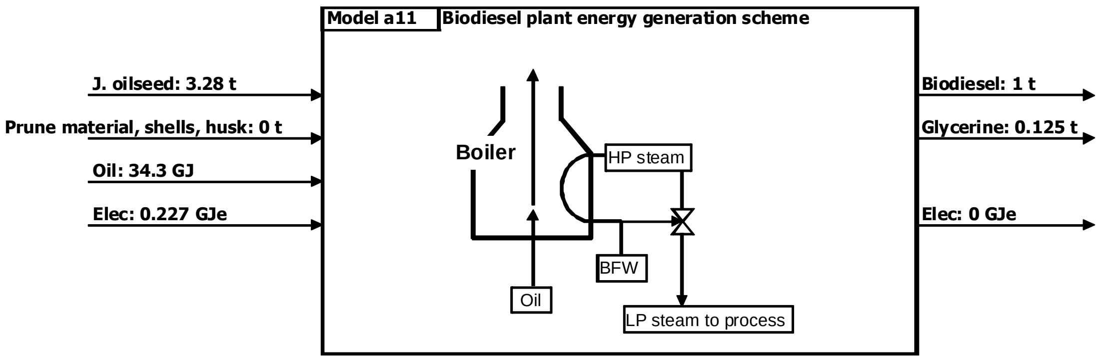
Main process conditions		
Gasifier		
Syngas production	t/t biodiesel	12.1
Gasifier efficiency		37%
Biomass consumption	t/t biodiesel	2.3
	GJ/t biodiesel	36.8
Gas turbine		
Electricity production	GJe/t biodiesel	3.26
Producer gas consumption	GJ/t biodiesel	6.37
Efficiency		51%
HRSG		
Steam outlet conditions	bara	125
	°C	535
Steam production	t/t biodiesel	0.976
Thermal duty	GJ/t biodiesel	2.23
Co-firing syngas consumption	GJ/t biodiesel	0.0
Gas turbine + HRSG		
Producer gas consumption	GJ/t biodiesel	62.9
Efficiency		87%
Steam to process		
Fat splitting		
	bara	60
	°C	260
	t/t biodiesel	0.62
Esterification		
	bara	10
	°C	240
	t/t biodiesel	0.5
Excess steam	t/t biodiesel	3.2
Backpressure STG		
Efficiency	MWe/t steam	0.17
Electricity generation	GJe/t biodiesel	0.68
Condensing STG		
Efficiency	MWe/t steam	0.24
Electricity generation	GJe/t biodiesel	2.6

Main process conditions. Model e. (cont.)		
Overall performance		
Total primary energy	GJp/t biodiesel	36.82
(including biomass and imported electricity production)		
Overall efficiency		50.2%
Surplus electricity	GJe/t biodiesel	6.28

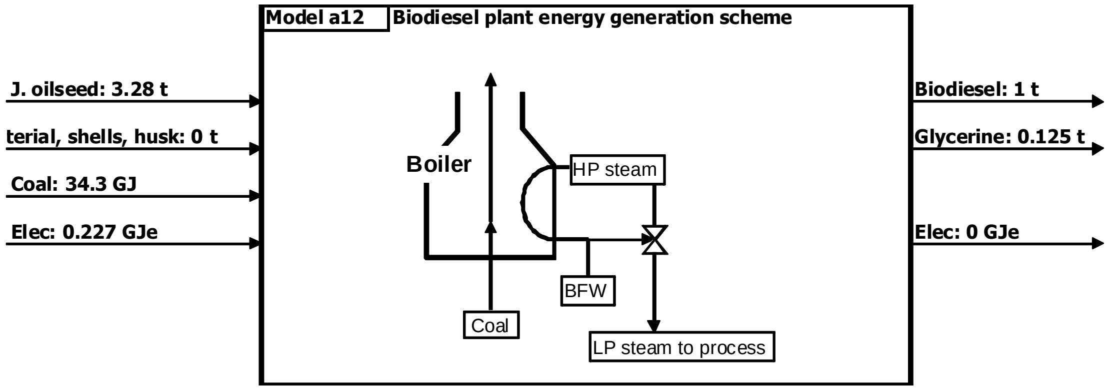
Scenario: RAIN

Table V. 3: Energy supply scenarios. Rainfed.

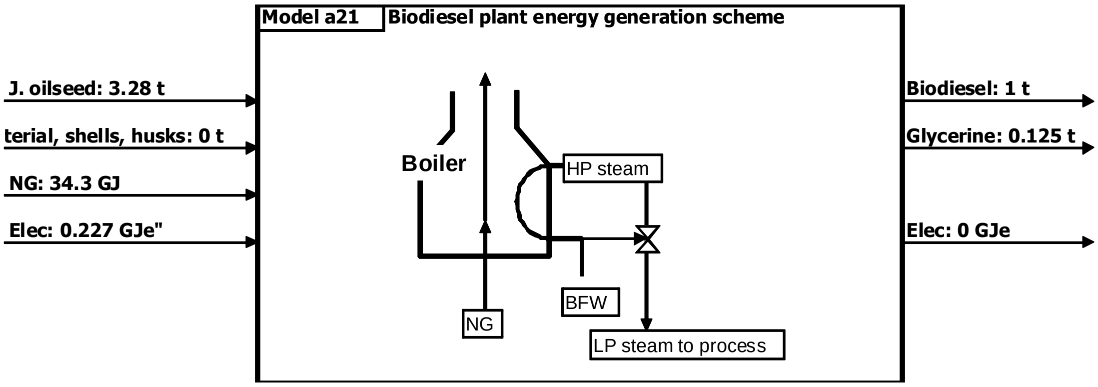
Fruit hulls and seed shells	Energy generation scheme		
Used as fertilizer	a11 Conventional oil boiler	X	X
	a12 Conventional coal boiler	X	X
	a21 Conventional NG boiler	X	X
	f11 Diesel genset with heat utilization block	X	X
	f12 NG genset with heat utilization block	X	X
	g NG CHP Microturbine	X	X
Used as fuel	h11 Anaerobic digester + CHP externally fired micro gas turbine	X	X
	h12 Integrated biomass gasifier + CHP gas engine genset	X	X



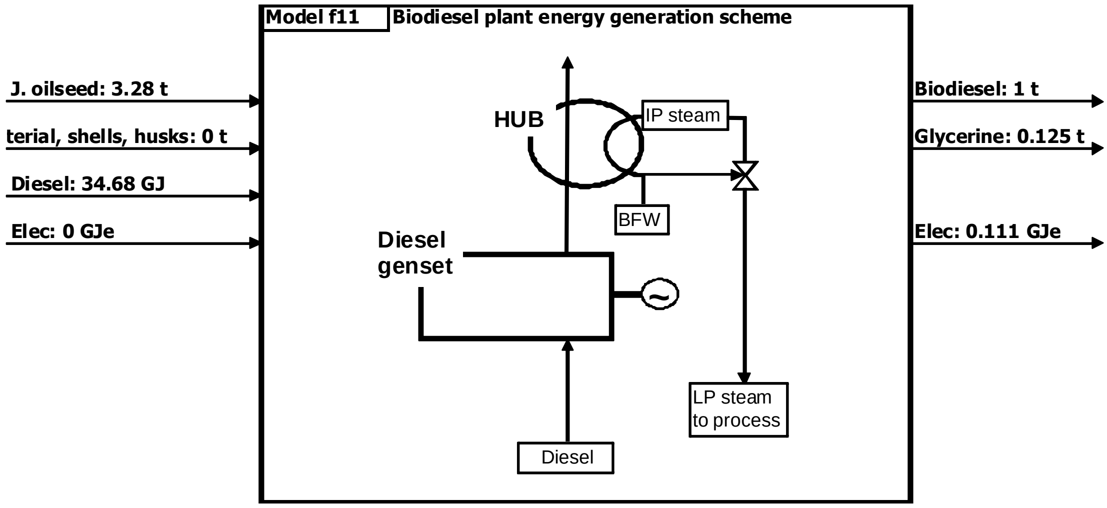
Main process conditions		
Boiler		
Steam outlet conditions	bara	4.0
	°C	95
Steam production	t/t biodiesel	0.405
Duty	GJ/t biodiesel	0.9715
Thermal efficiency		85%
Carbon oil consumption	GJ/t biodiesel	34.3
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Imported electricity	GJe/t biodiesel	0.227
Overall performance		
Total primary energy	GJp/t biodiesel	1.67
(including oil and imported electricity production)		
Overall efficiency		66%



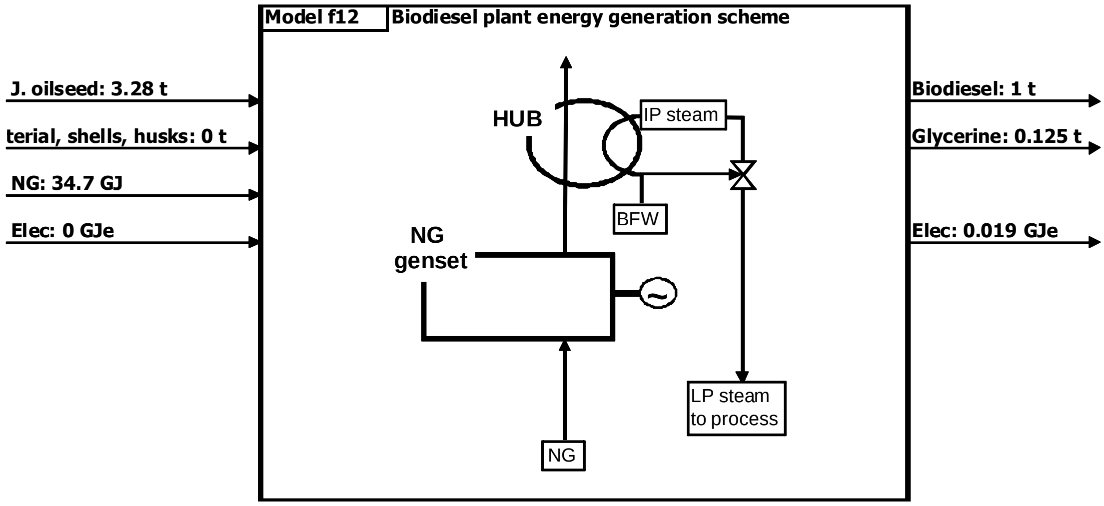
Main process conditions		
Boiler		
Steam outlet conditions	bara	4.0
	°C	95
Steam production	t/t biodiesel	0.405
Duty	GJ/t biodiesel	0.9715
Thermal efficiency		85%
Coal consumption		34.3
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Imported electricity	GJe/t biodiesel	0.227
Overall performance		
Total primary energy	GJp/t biodiesel	1.67
(including coal and imported electricity production)		
Overall efficiency		66%



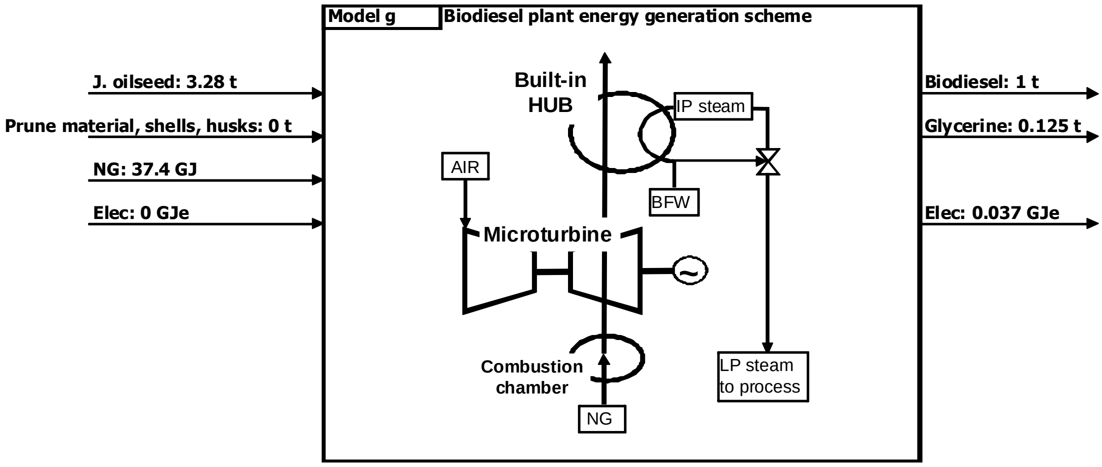
Main process conditions		
Boiler		
Steam outlet conditions	bara	4.0
	°C	95
Steam production	t/t biodiesel	0.405
Duty	GJ/t biodiesel	0.9715
Thermal efficiency		85%
NG consumption		34.3
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Imported electricity	GJe/t biodiesel	0.227
Overall performance		
Total primary energy	GJp/t biodiesel	1.67
(including NG and imported electricity production)		
Overall efficiency		65%



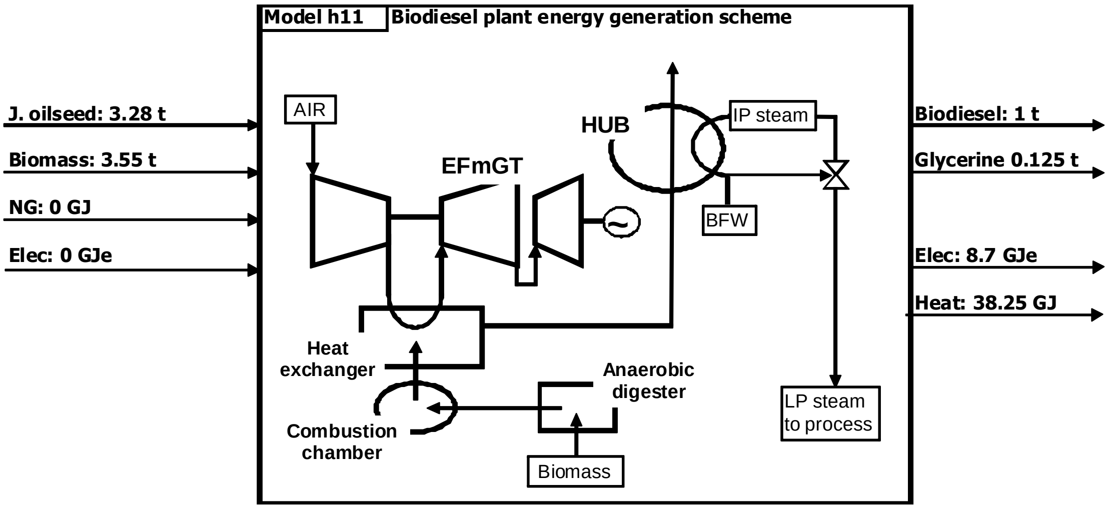
Main process conditions		
Diesel genset		
Electricity production	GJ/t biodiesel	0.34
Diesel consumption	GJ/t biodiesel	34.68
Electrical efficiency		40%
HUB		
Steam outlet conditions	bara	6.0
	°C	95
Steam production	GJ/t biodiesel	0.407
Thermal duty	GJ/t biodiesel	0.971
Co-firing diesel consumption	GJ/t biodiesel	0.0
Diesel genset + HUB		
Genset total efficiency		84%
Diesel consumption		34.68
Surplus electricity	GJe/t biodiesel	0.111
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	1.34
Overall efficiency		91%



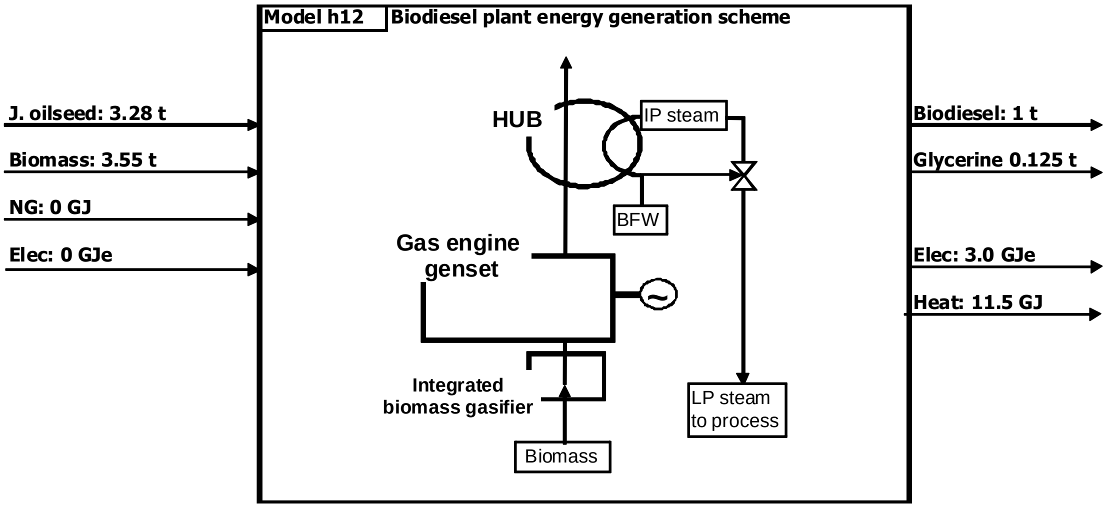
Main process conditions		
NG genset		
Electricity production	GJ/t biodiesel	0.25
NG consumption	GJ/t biodiesel	34.68
Electrical efficiency		34%
HUB		
Steam outlet conditions	bara	6.0
	°C	95
Steam production	GJ/t biodiesel	0.407
Thermal duty	GJ/t biodiesel	0.971
Co-firing NG consumption	GJ/t biodiesel	0.0
NG genset + HUB		
Genset total efficiency		84%
NG consumption		34.68
Surplus electricity	GJe/t biodiesel	0.019
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	1.19
Overall efficiency		94%



Main process conditions		
NG CHP Microturbine		
Electricity production	GJ/t biodiesel	0.26
NG consumption	GJ/t biodiesel	37.37
Electrical efficiency		30%
Built-in HUB		
Steam outlet conditions	bara	4.0
	°C	95
Steam production	GJ/t biodiesel	0.405
Thermal duty	GJ/t biodiesel	0.9715
Co-firing NG consumption	GJ/t biodiesel	0.0
NG Microturbine + HUB		
Total efficiency		78%
NG consumption		37.37
Surplus electricity	GJe/t biodiesel	0.037
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	1.28
Overall efficiency		89%



Main process conditions		
Anaerobic digester		
Biogas production	t/t biodiesel	0.99
Digester efficiency		60%
Biomass consumption	t/t biodiesel	3.55
	GJ/t biodiesel	56.78
EFmGT		
Electricity production	GJ/t biodiesel	8.94
Biogas consumption	GJ/t biodiesel	23.36
Electrical efficiency		30%
HUB		
Steam outlet conditions	bara	6.0
	°C	95
Steam production	GJ/t biodiesel	0.407
Thermal duty	GJ/t biodiesel	0.971
Co-firing biogas consumption	GJ/t biodiesel	0.0
EFmGT + HUB		
Total efficiency		69%
Biomass consumption		56.80
Surplus electricity	GJe/t biodiesel	8.7
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	56.78
Overall efficiency		17.3%



Main process conditions		
Gasifier		
Syngas production	t/t biodiesel	8.4
Gasifier efficiency		22%
Biomass consumption	t/t biodiesel	3.55
	GJ/t biodiesel	56.8
Gas engine genset		
Electricity production	GJ/t biodiesel	3.2
Syngas consumption	GJ/t biodiesel	43.5
Electrical efficiency		34%
HUB		
Steam outlet conditions	bara	6.0
	°C	95
Steam production	GJ/t biodiesel	0.407
Thermal duty	GJ/t biodiesel	0.971
Co-firing syngas consumption	GJ/t biodiesel	0.0
Gas engine genset + HUB		
Total efficiency		84%
Biomass consumption		56.80
Surplus electricity	GJe/t biodiesel	3.0
Steam to process	bara	1.4
	°C	60
	t/t biodiesel	0.41
Overall performance		
Total primary energy	GJp/t biodiesel	56.78
Overall efficiency		7.2%

Appendix VI: GHG emissions (kg CO_2eq/GJ biodiesel/a) and GHG reduction ratio (%).

$$GHG\ reduction\ ratio\ (\%) = \frac{GHG\ emissions_{test\ case} - GHG\ emissions_{base\ case}}{GHG\ emissions_{base\ case}}$$

Chart VI. 1: GHG emissions (kgCO_2eq/$GJ_{biodiesel}$/a) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). **Net balance: Press-cake as fertilizer (green manure)**

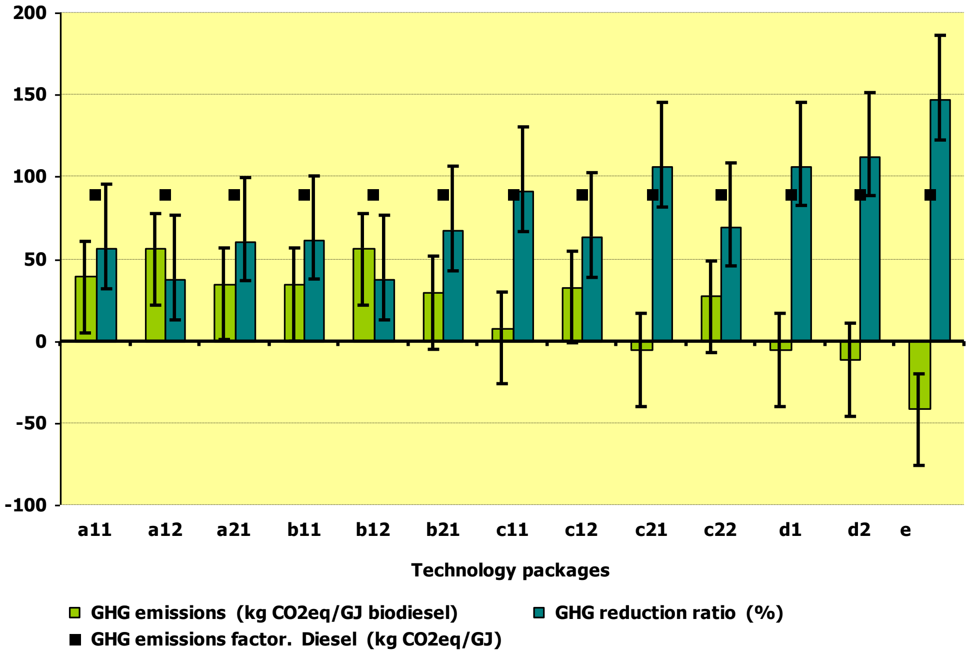


Chart VI. 2: GHG emissions (kgCO_2eq/$GJ_{biodiesel}$/a) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). One-stage Henkel Transesterification Process (90 bar, 240°C). **Net balance: Press-cake use as co-fuel for power plant**

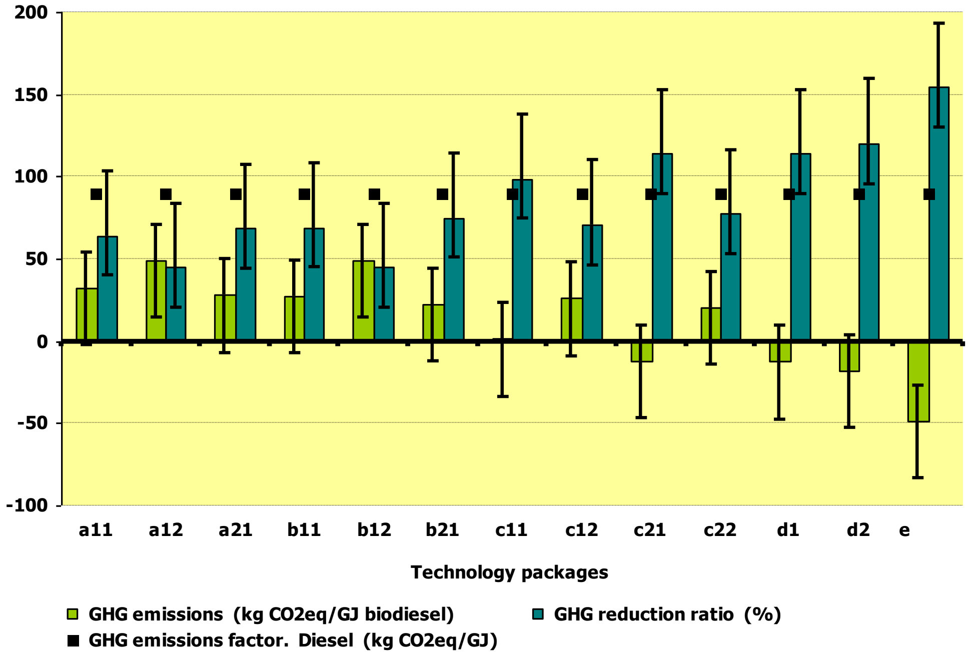


Chart VI. 3: GHG emissions GHG emissions (kgCO_2eq/$GJ_{biodiesel}$/a) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). **Net balance: Press-cake as fertilizer (green manure)**

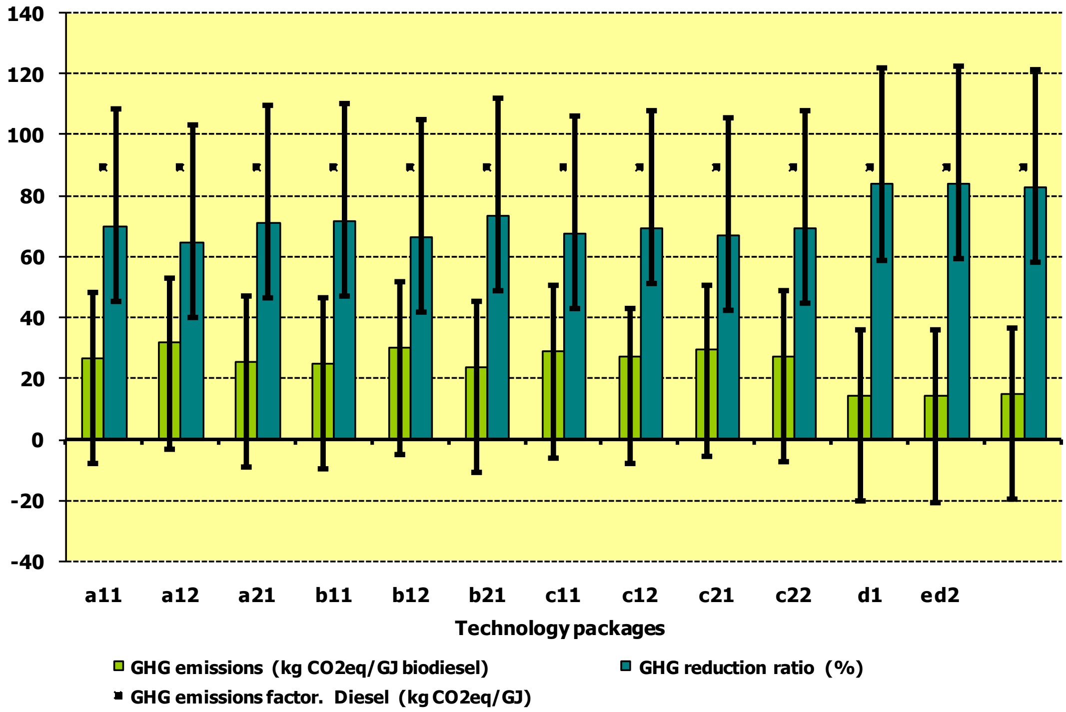


Chart VI. 4: GHG emissions GHG emissions (kgCO_2eq/$GJ_{biodiesel}$/a) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Irrigated. Spacing 3x3 m. 1,111 trees/ha). Two-stage process. Fat-Splitting (60 bar, 260°C) and Esterification (10 bar, 240°C). **Net balance: Press-cake use as co-fuel for power plant**

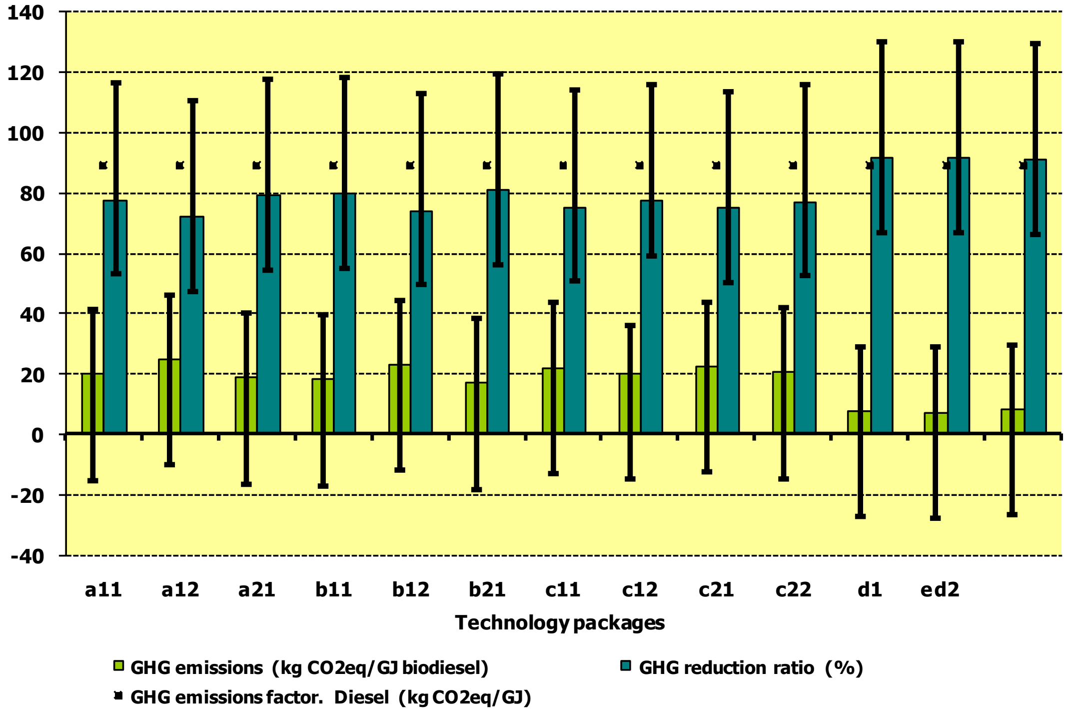


Chart VI. 5: GHG emissions GHG emissions (kgCO_2eq/$GJ_{biodiesel}$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). **Net balance: Press-cake as fertilizer (green manure)**

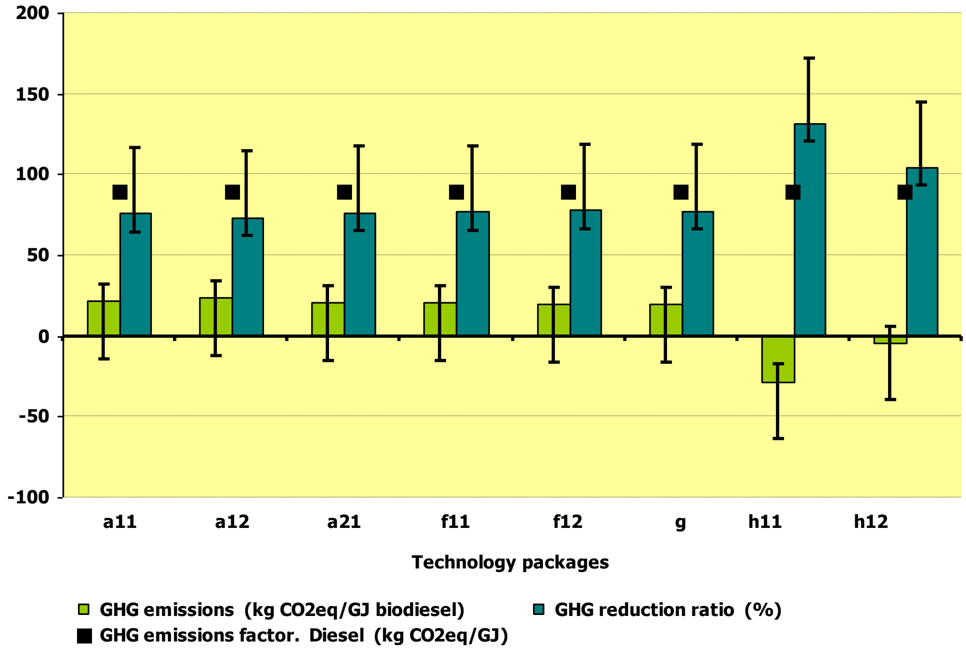


Chart VI. 6: GHG emissions GHG emissions ($kgCO_2eq/GJ_{biodiesel}/a$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. Organic, chemical fertilizers and agro-chemicals applied). Transesterification Process (1.4 bar, 60°C). **Net balance: Press-cake use as co-fuel for power plant**

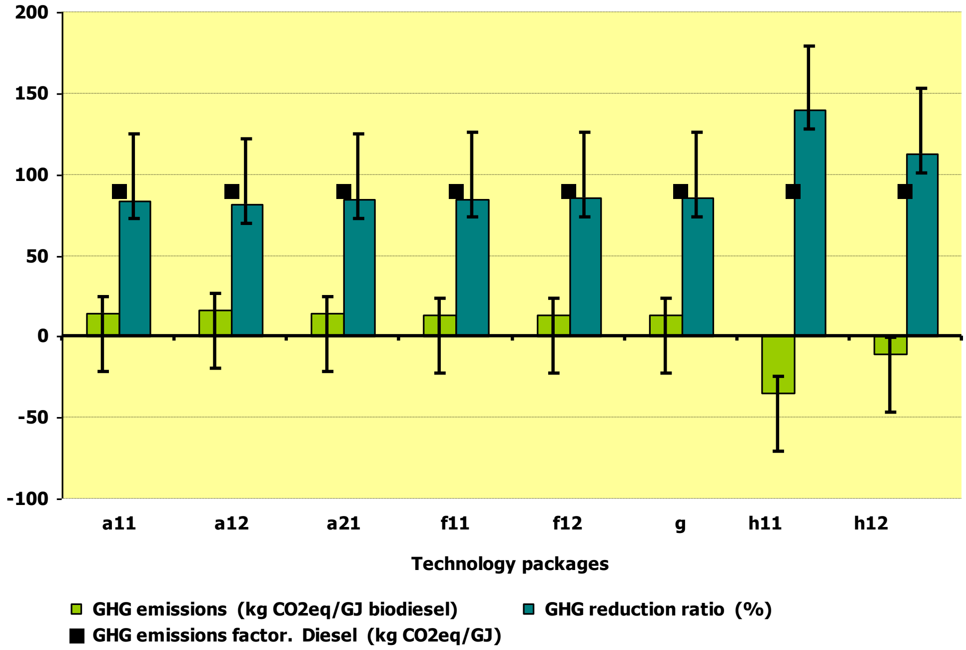


Chart VI. 7: GHG emissions GHG emissions ($kgCO_2eq/GJ_{biodiesel}/a$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). **Net balance: Press-cake as fertilizer (green manure)**

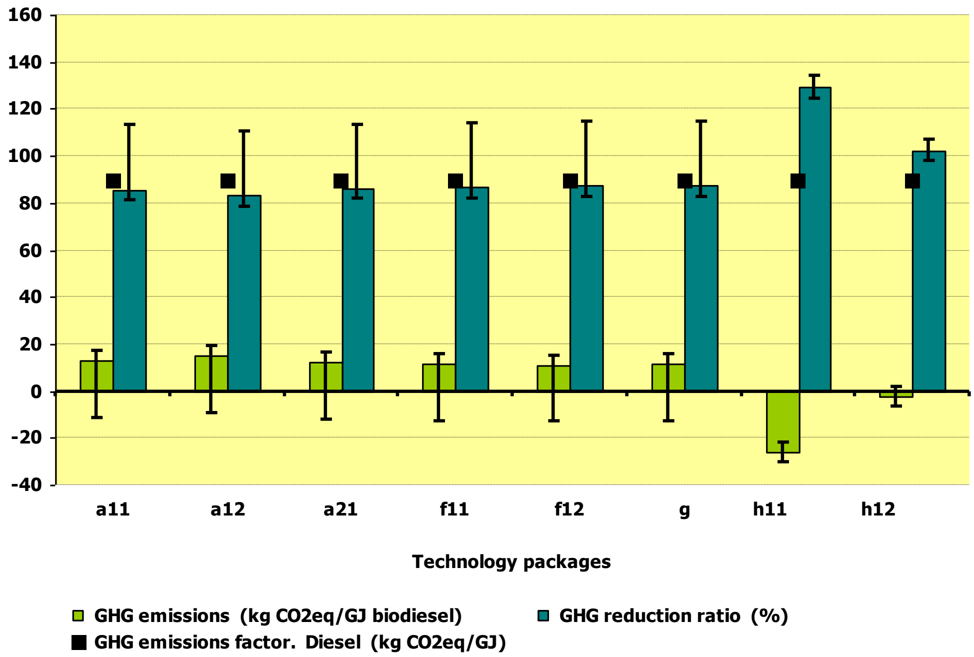
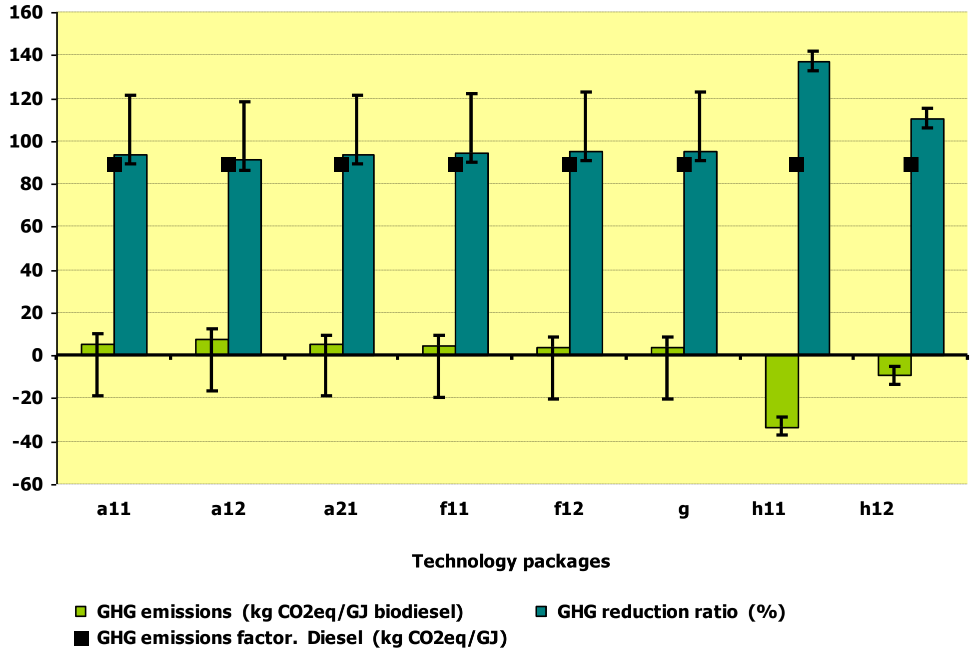


Chart VI. 8: GHG emissions GHG emissions ($kgCO_2eq/GJ_{biodiesel}/a$) and GHG reduction ratio (%). *Jatropha* to biodiesel pathway (Rainfed. Spacing 2x2 m. 2,500 trees/ha. No fertilizers and agro-chemicals used). Transesterification Process (1.4 bar, 60°C). **Net balance: Press-cake use as co-fuel for power plant**



Appendix VII: Visual Basic code for stochastic sensitivity analysis

```
Const C_nCycles = 2000
Const C_InputTableName = "InputTable"
Const C_OutputTableName = "OutputTable"
Const C_SensitivitySheetName = "Sensitivity"
Const SaveAfter = 501

Function CreateInputNames(Optional ByRef P_ReturnLastName As String = "")

   Dim RowCount As Long, _
      cCount As Long, _
      cName As String

   If P_ReturnLastName = "" Then _
      Sheets(C_SensitivitySheetName).Columns("A:A").Insert Shift:=xlToRight,
CopyOrigin:=xlFormatFromLeftOrAbove

   RowCount = 1
   For Each cRow In Range(Names(C_InputTableName).RefersTo).Rows
      cName = Replace(Replace(Replace(Replace(cRow.Cells(1, 1).Value, "_", ""),
" ", "_"), "(", ""), ")", "")

      If P_ReturnLastName = "" Then
         Sheets(C_SensitivitySheetName).Columns("A:A").Insert Shift:=xlToRight,
CopyOrigin:=xlFormatFromLeftOrAbove
         Sheets(C_SensitivitySheetName).Cells(1, 1).Value = cName

         On Error Resume Next
            ActiveWorkbook.Names(cName).Delete
         On Error GoTo 0

         ActiveWorkbook.Names.Add Name:=cName, _
                        RefersToR1C1:=Left(Names(C_InputTableName).RefersTo,
InStr(Names(C_InputTableName).RefersTo, "!")) _
                                    & cRow.Cells(1,
2).Address(ReferenceStyle:=xlR1C1)

         Application.Run "ATPVBAEN.XLAM!Random", _
               Sheets(C_SensitivitySheetName).Cells(2, 1), 1, _
               C_nCycles, 1, , _
               cRow.Cells(1, 3).Value, _
               cRow.Cells(1, 4).Value

         For i = 1 To C_nCycles
            Sheets(C_SensitivitySheetName).Cells(i + 1, 1).Value =
Round(Sheets(C_SensitivitySheetName).Cells(i + 1, 1).Value, cRow.Cells(1,
5).Value)
         Next i
```

```
        Else
            P_ReturnLastName = cName
        End If
    Next cRow

End Function


Function CreateOutputNames() As Long

    CreateOutputNames = 0

    Dim RowCount As Long, _
        cCount As Long, _
        cName As String

    RowCount = 1
    For Each cRow In Range(Names(C_OutputTableName).RefersTo).Rows
        If RowCount = 1 Then
            Set fRow = cRow
        Else
            cCount = 1
            For Each cCell In fRow.Cells
                If cCount > 1 Then
                    cName = Replace(Replace(cCell.Value & cRow.Cells(1, 1).Value, "_",
""), " ", "_")
                    Sheets(C_SensitivitySheetName).Columns("A:A").Insert
Shift:=xlToRight, CopyOrigin:=xlFormatFromLeftOrAbove
                    Sheets(C_SensitivitySheetName).Cells(1, 1).Value = cName
                    'MsgBox cRow.Cells(1, cCount).Address(ReferenceStyle:=xlR1C1)
                    ActiveWorkbook.Names.Add Name:=cName, _

RefersToR1C1:=Left(Names(C_OutputTableName).RefersTo,
InStr(Names(C_InputTableName).RefersTo, "!")) _
                                              & cRow.Cells(1,
cCount).Address(ReferenceStyle:=xlR1C1)
                    CreateOutputNames = CreateOutputNames + 1
                End If
                cCount = cCount + 1
            Next cCell
        End If
        RowCount = RowCount + 1
    Next cRow

End Function

Function RunCalculations_AE(FirstDataColumn As Long)
    HasChanged = False
```

```
    For Each cRow In Sheets(C_SensitivitySheetName).Rows
        If cRow.Cells(1, FirstDataColumn).Value = "" Then Exit For
        If cRow.Row > 1 Then
            IsRecord = False
            For Each cCell In cRow.Cells
                If cCell.Column < FirstDataColumn Then
                    If cCell.Value = "" And Not IsRecord Then
                        IsRecord = True
                    End If
                Else
                    If cCell.Value = "" Then Exit For
                    If IsRecord Then Range(Names(Cells(1,
cCell.Column).Value).RefersTo).Cells(1, 1).Value = cCell.Value
                End If
            Next cCell

            If IsRecord Then
                For i = 1 To FirstDataColumn - 1
                    cRow.Cells(1, i) = Range(Names(Cells(1, i).Value).RefersTo).Value
                Next i
                HasChanged = True
            End If

            If HasChanged And cRow.Row / SaveAfter = Int(cRow.Row / SaveAfter)
Then
                ActiveWorkbook.Save
                HasChanged = False
            End If
        End If
        DoEvents
    Next cRow
    On Error Resume Next
        Sheets(C_SensitivitySheetName).Name =
Replace(Left(Names(C_OutputTableName).RefersTo,
InStr(Names(C_InputTableName).RefersTo, "!") - 1), "=", "") & "_" &
Sheets(C_SensitivitySheetName).Name
    On Error GoTo 0
    ActiveWorkbook.Save
End Function

Sub A00_start()
    'MsgBox Range("A1").Address(ReferenceStyle:=xlR1C1)
    sSheetExists = False
    For Each cSheet In ActiveWorkbook.Sheets
        If cSheet.Name = C_SensitivitySheetName Then
            sSheetExists = True
            Exit For
        End If
    Next cSheet
```

```
    If sSheetExists Then
        Dim fName As String, fDataColumn As Long
        fName = "findName#)*"
        fDataColumn = 0

        CreateInputNames fName
        For Each cCell In Sheets(C_SensitivitySheetName).Rows(1).Cells
            If cCell.Value = fName Then
                fDataColumn = cCell.Column
                Exit For
            End If
        Next cCell
        If fDataColumn > 0 Then RunCalculations_AE fDataColumn

    Else
        ActiveWorkbook.Sheets.Add
        ActiveSheet.Name = C_SensitivitySheetName
        CreateInputNames
        RunCalculations_AE CreateOutputNames() + 1
    End If

End Sub
Function FindFirstDataColumn(Optional ByVal sSheetName =
C_SensitivitySheetName) As Long
        Dim fName As String
        fName = "findName#)*"
        FindFirstDataColumn = 0
        CreateInputNames fName
        For Each cCell In Sheets(sSheetName).Rows(1).Cells
            If cCell.Value = fName Then
                FindFirstDataColumn = cCell.Column
                Exit For
            End If
        Next cCell

End Function
```

Appendix VIII: Sensitivity analysis

Chart VIII. 1: Sensitivity analysis results. IRR_Agro scenario

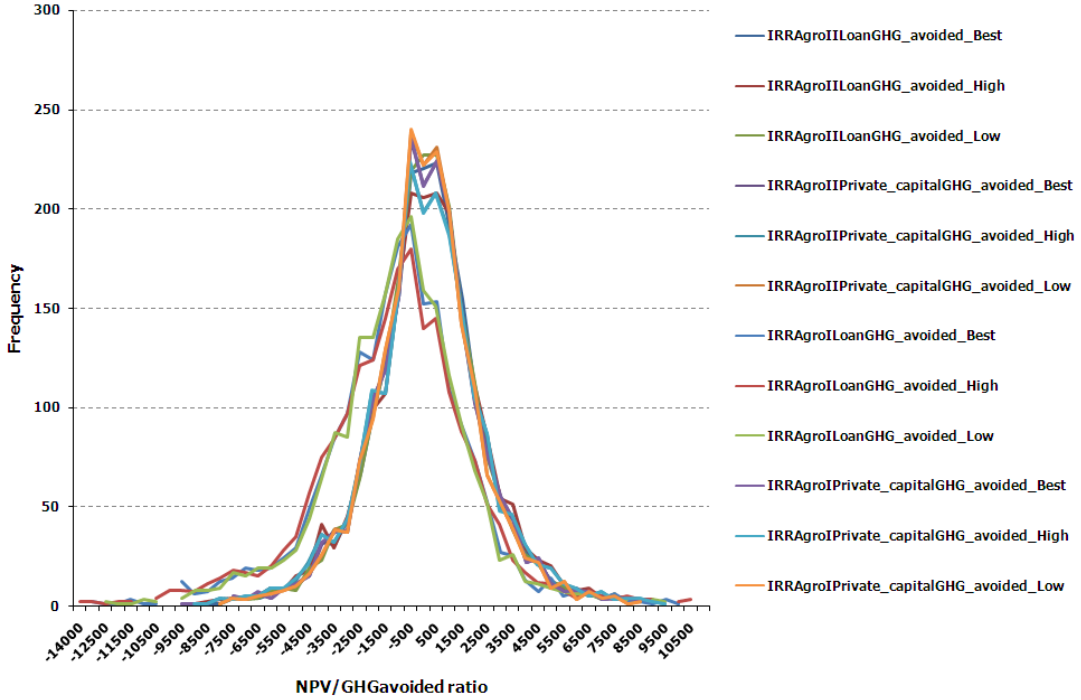
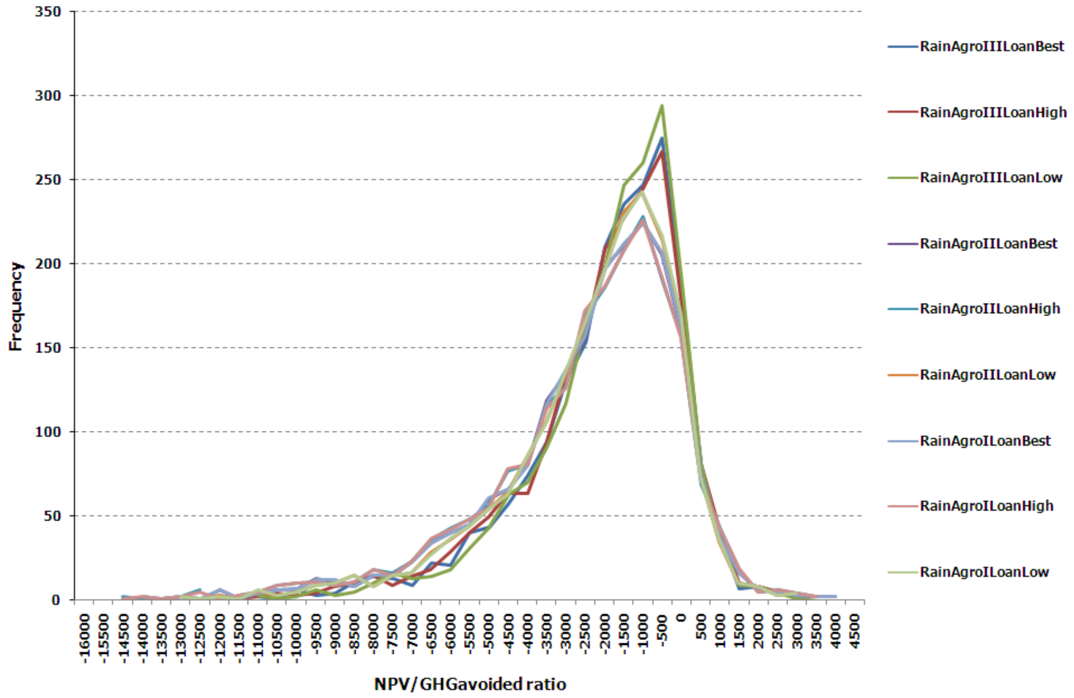


Chart VIII. 2: Sensitivity analysis results. RAIN_Agro scenario



Scenario_IRR_Production

Chart VIII. 3: Sensitivity analysis results. IRR_Production scenario. CAPEX 8.0 MGBP

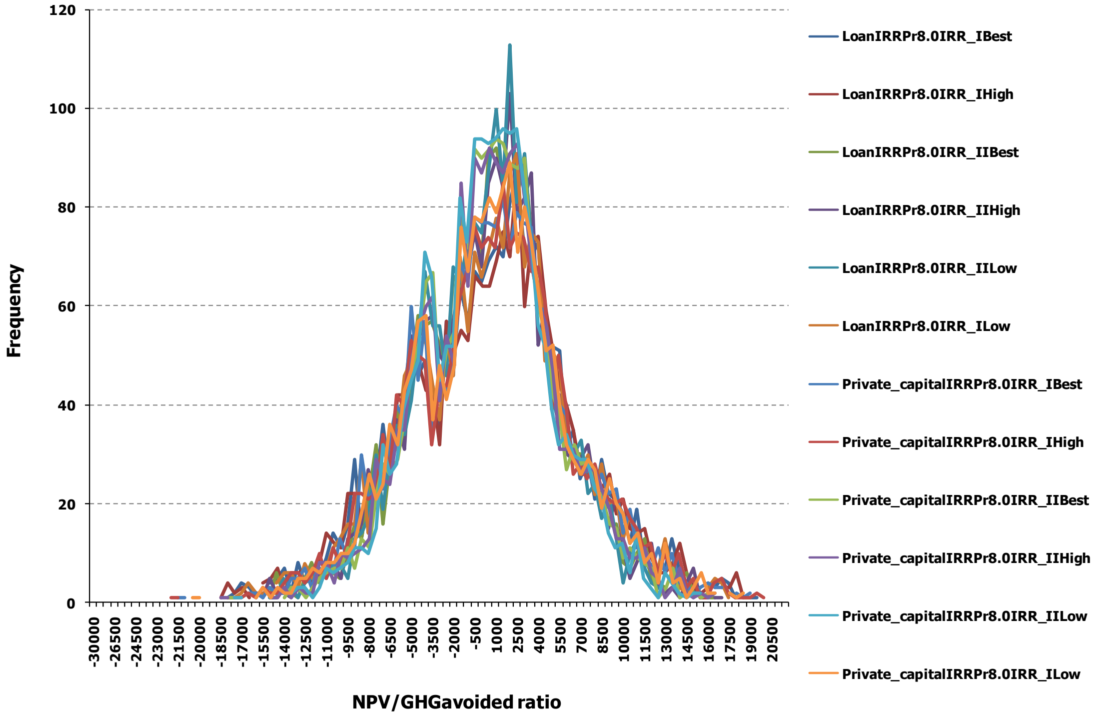


Chart VIII. 3: Sensitivity analysis results. IRR_Production scenario. CAPEX 11.5 MGBP

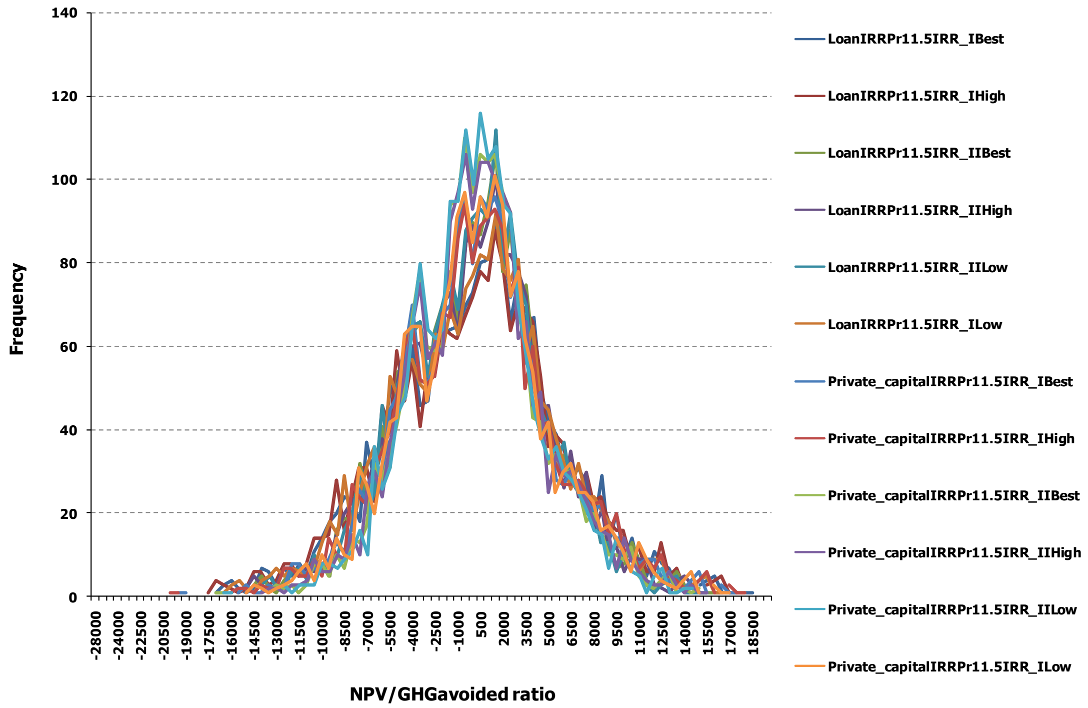


Chart VIII. 4: Sensitivity analysis results. IRR_Production scenario. CAPEX 15.0 MGBP

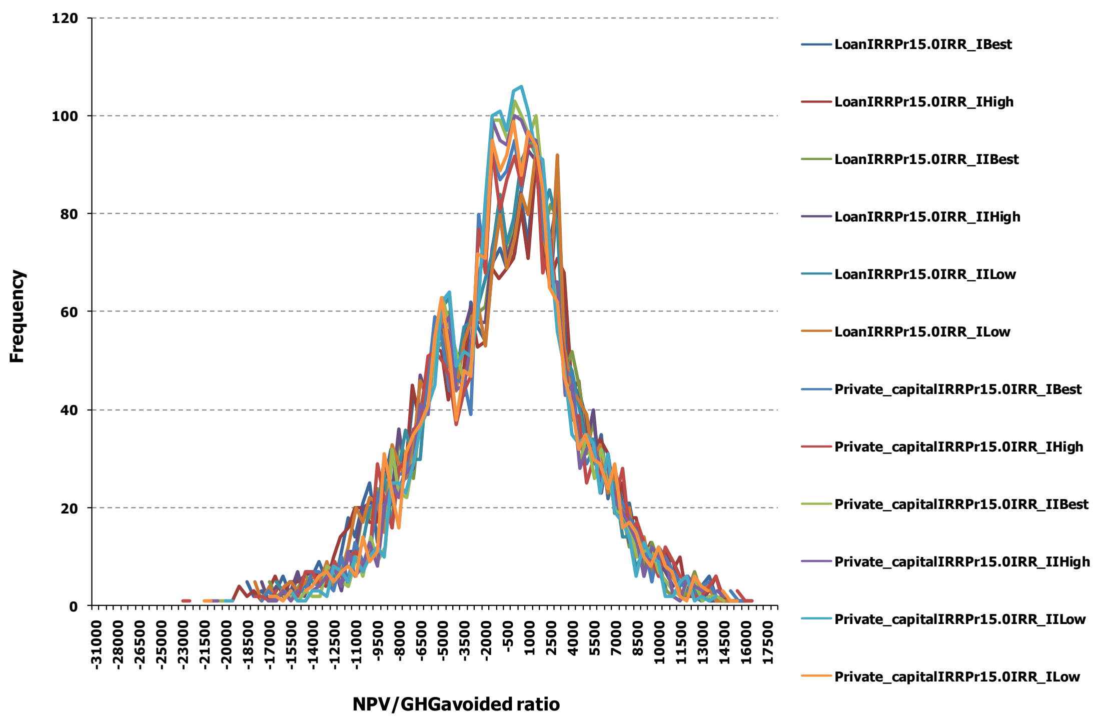


Chart VIII. 5: Sensitivity analysis results. IRR_Production scenario. CAPEX 18.5 MGBP

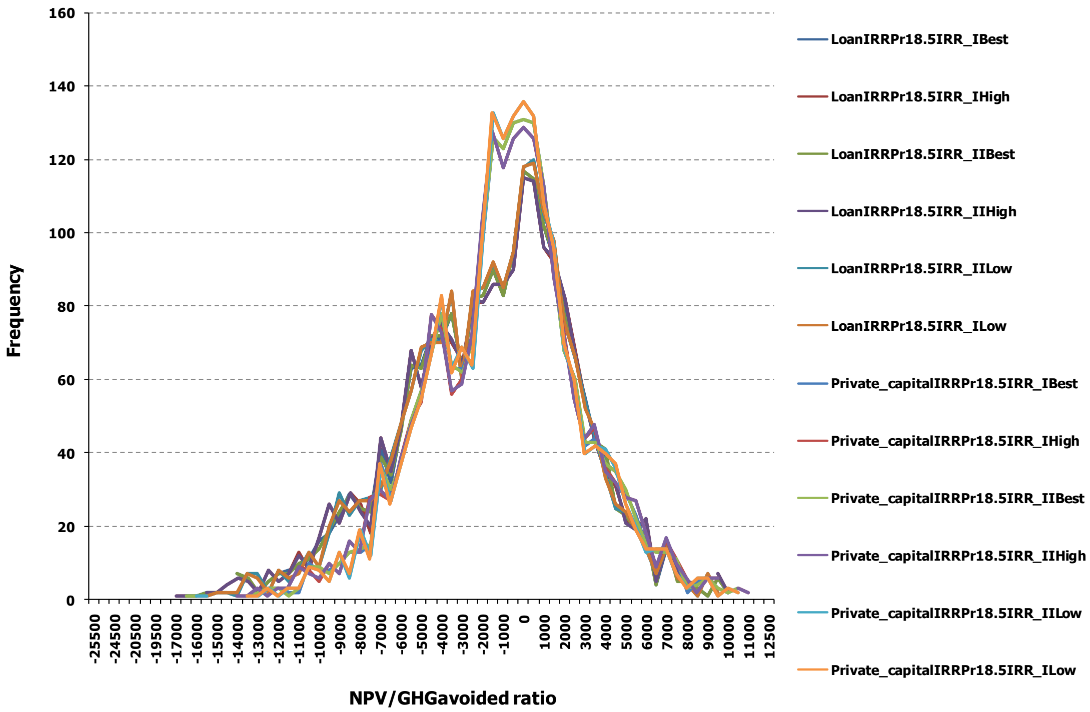
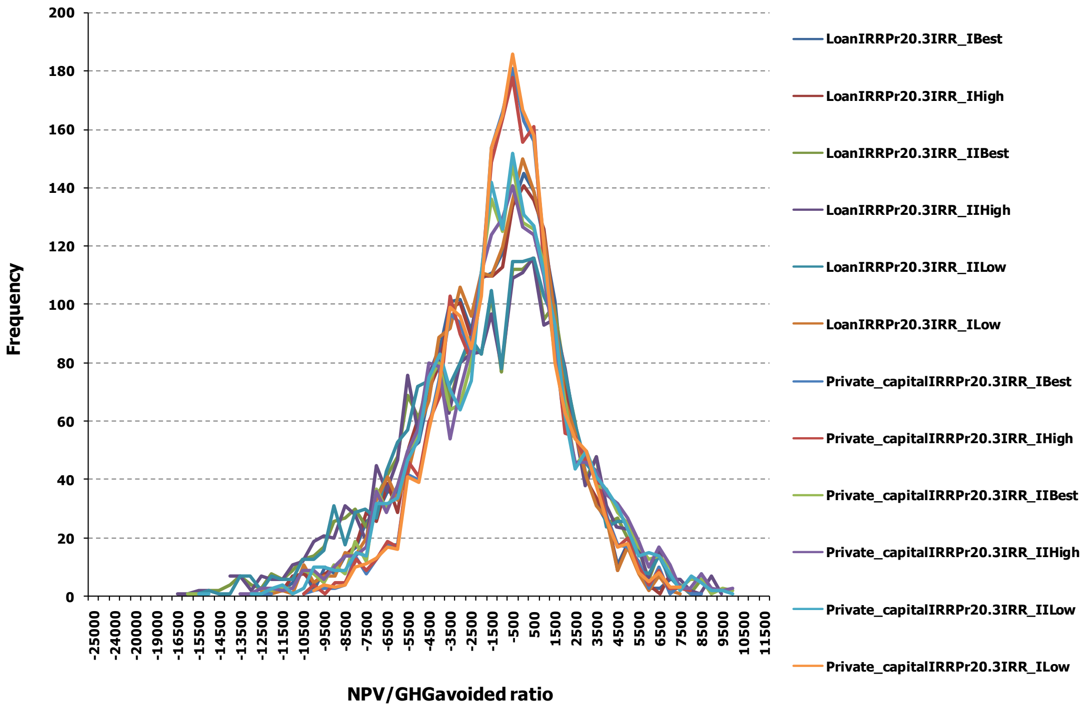


Chart VIII. 6: Sensitivity analysis results. IRR_Production scenario. CAPEX 20.3 MGBP



Scenario_RAIN_Production

Chart VIII. 7: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.11 MGBP

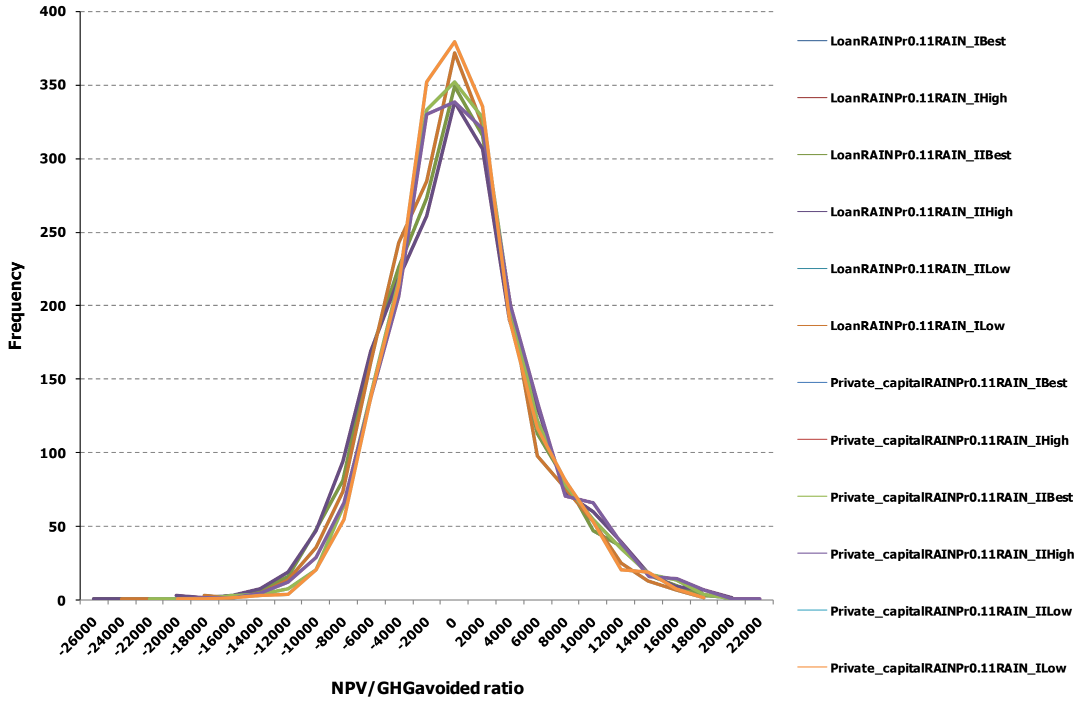


Chart VIII. 8: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.16 MGBP

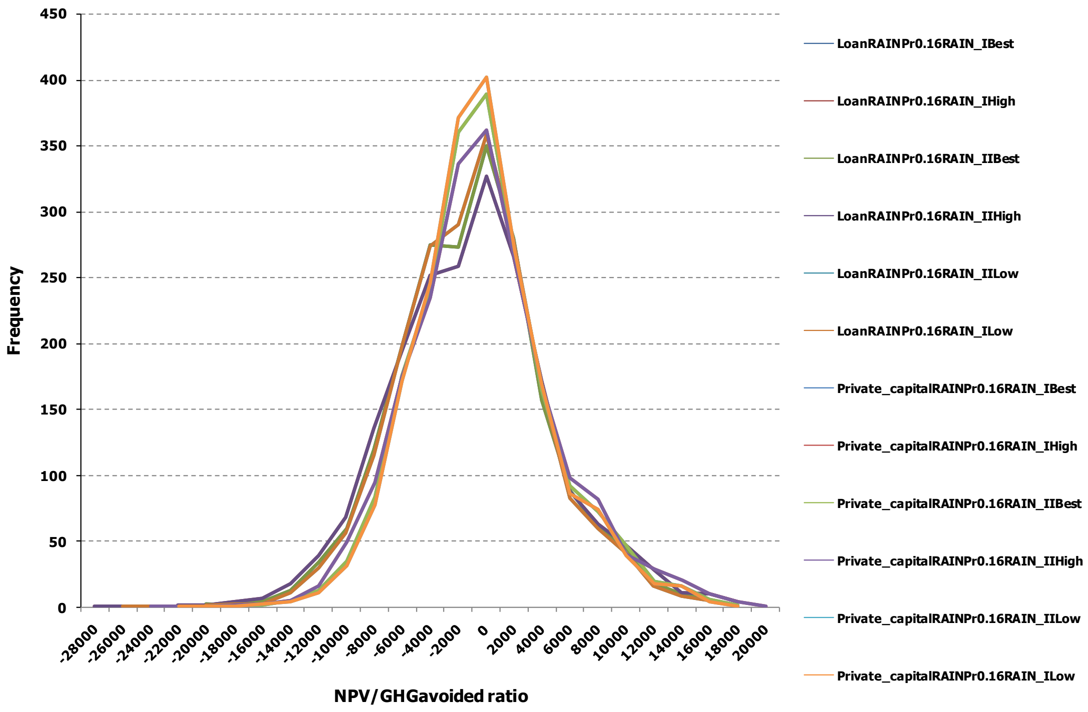


Chart VIII. 9: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.21 MGBP

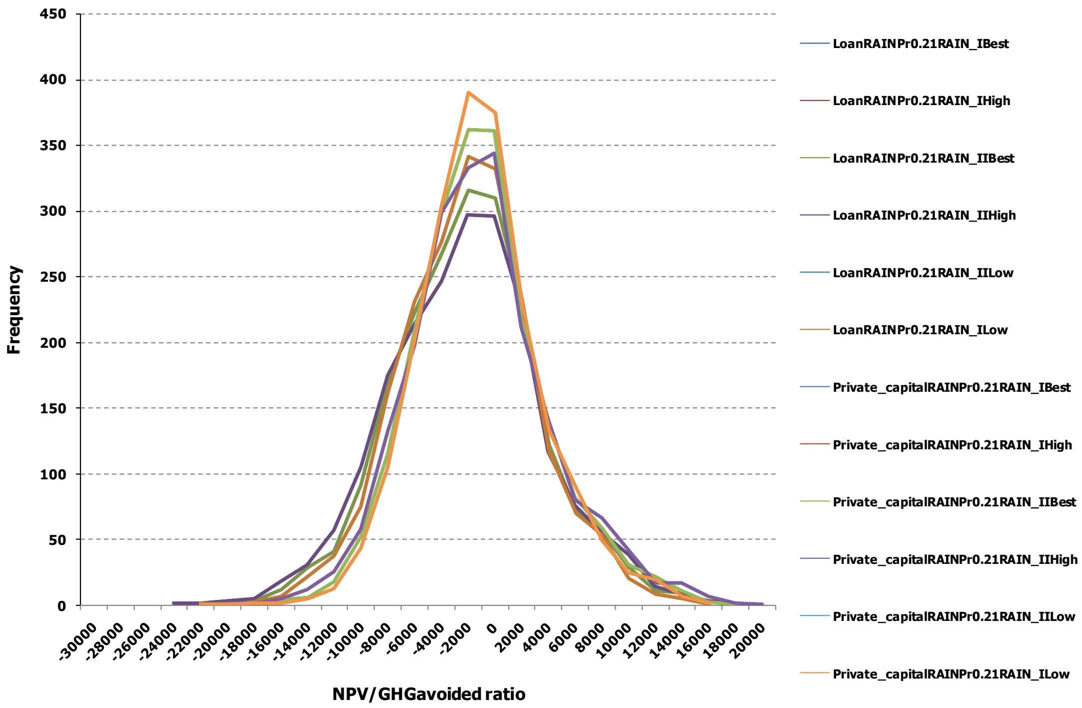


Chart VIII. 10: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.26 MGBP

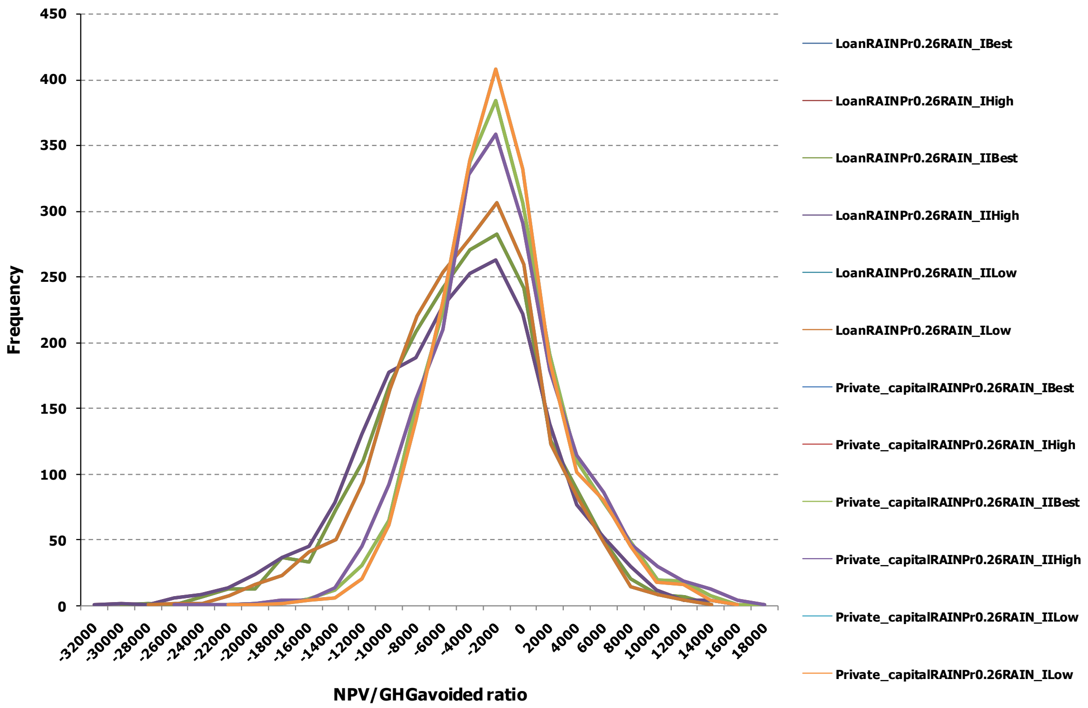
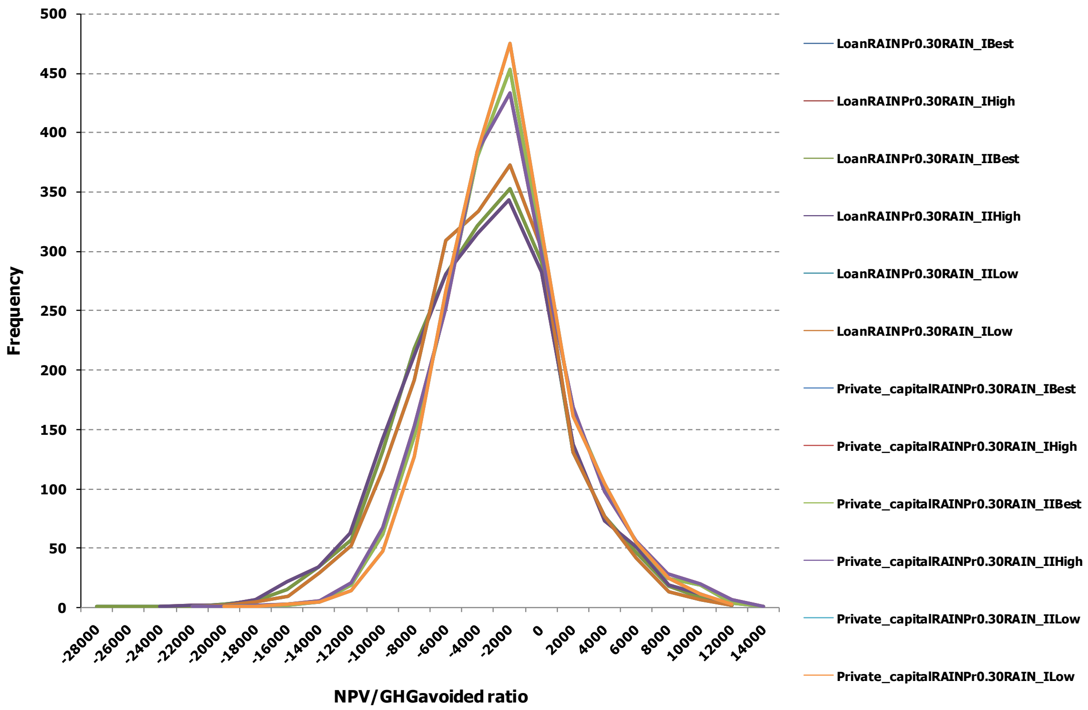


Chart VIII. 11: Sensitivity analysis results. RAIN_Production scenario. CAPEX 0.30 MGBP



Appendix IX: Correlation charts

Chart IX. 1: Correlation. Agriculture. Irrigated I scenario (IRR I_Agro_Correlation)

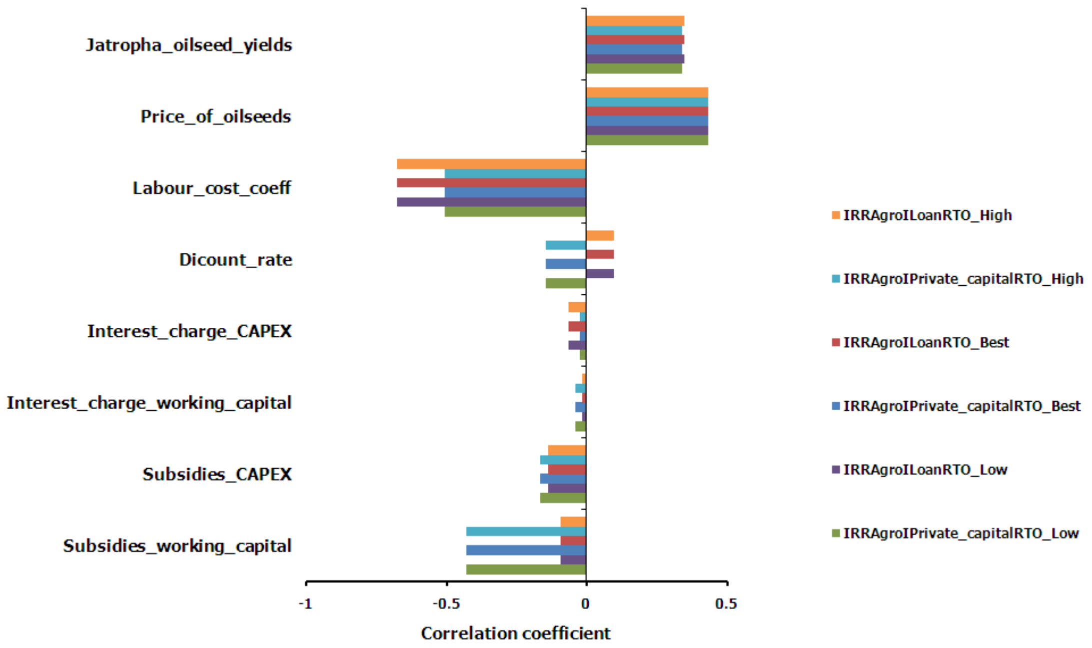


Chart IX. 2: Correlation. Agriculture. Irrigated I scenario (IRR II_Agro_Correlation)

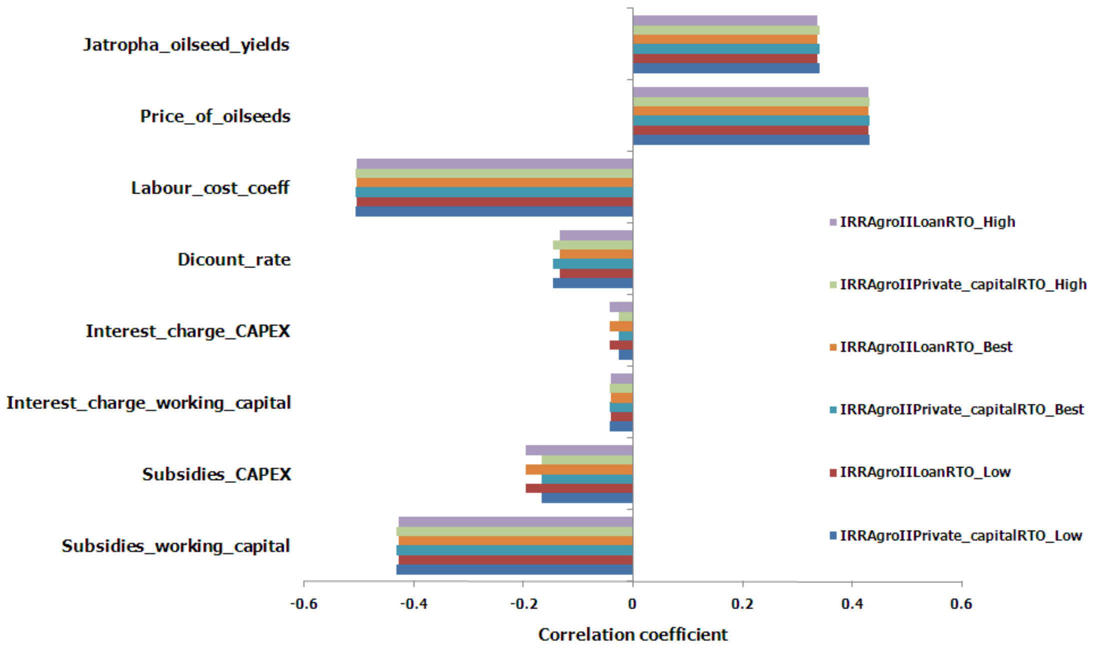
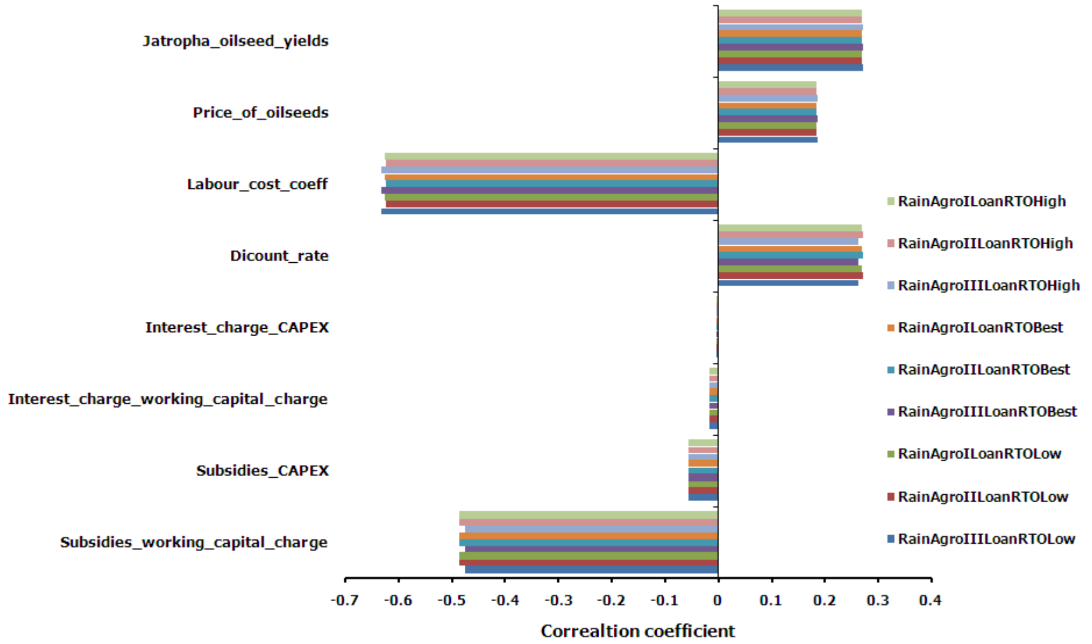


Chart IX. 3: Correlation. Agriculture. Small-scale scenario (RAIN_Agro_Correlation).



IRR_Production_Correlation

Chart IX. 4: Correlation. Production. Large scale scenario. (IRR_Production_Correlation). CAPEX 8.0 MGBP

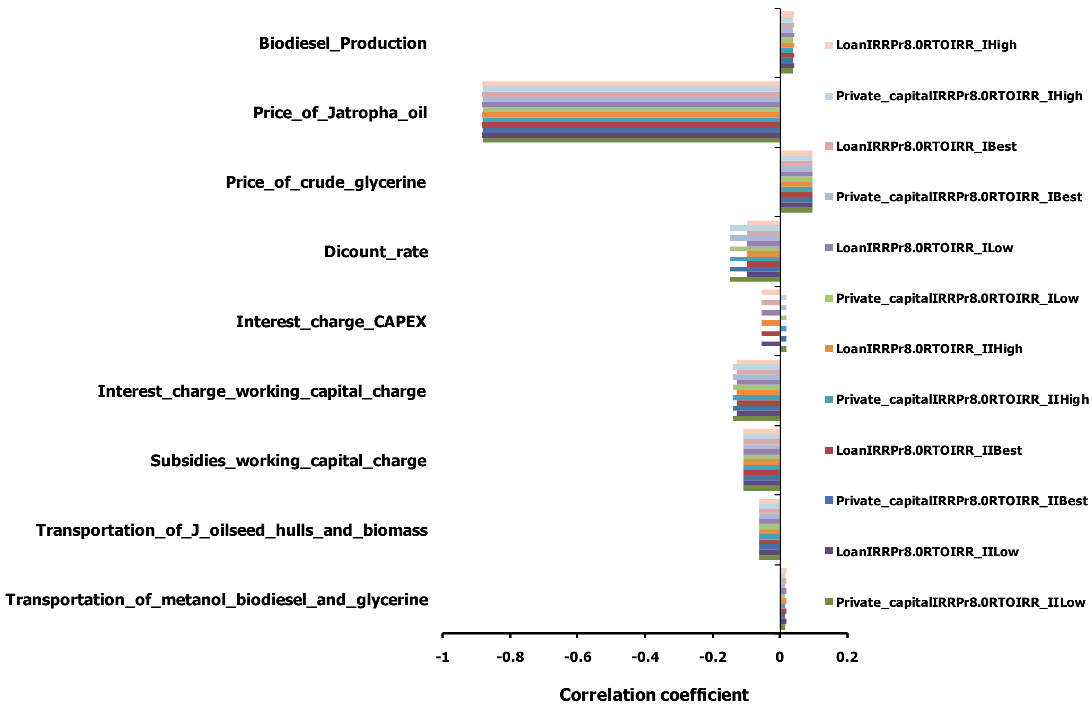


Chart IX. 5: Correlation. Production. Large scale scenario. (IRR_Production_Correlation). CAPEX 11.5 MGBP

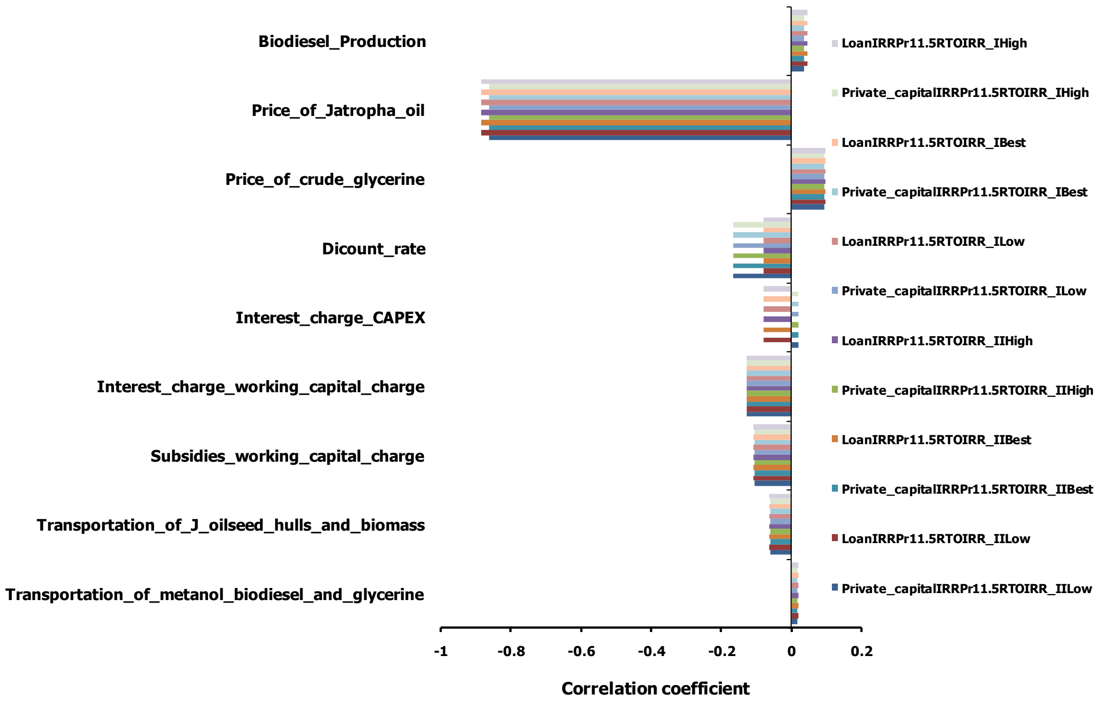


Chart IX. 6: Correlation. Production. Large scale scenario. (IRR_Production_Correlation). CAPEX 15.0 MGBP

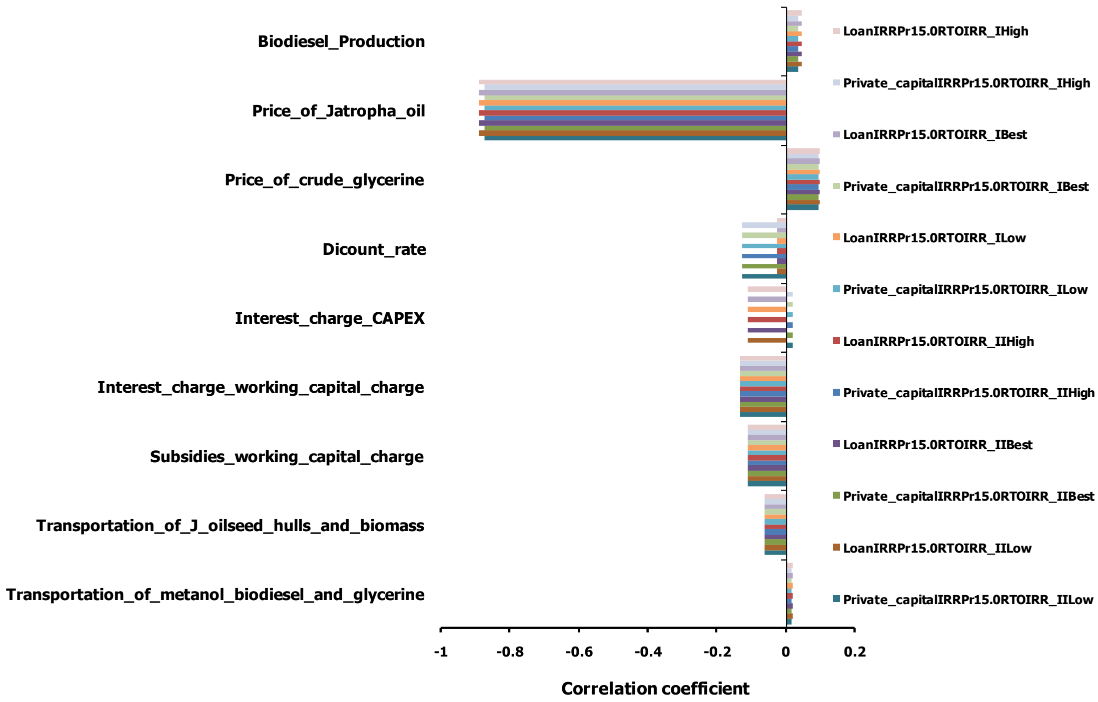


Chart IX. 7: Correlation. Production. Large scale scenario. (IRR_Production_Correlation). CAPEX 18.5 MGBP

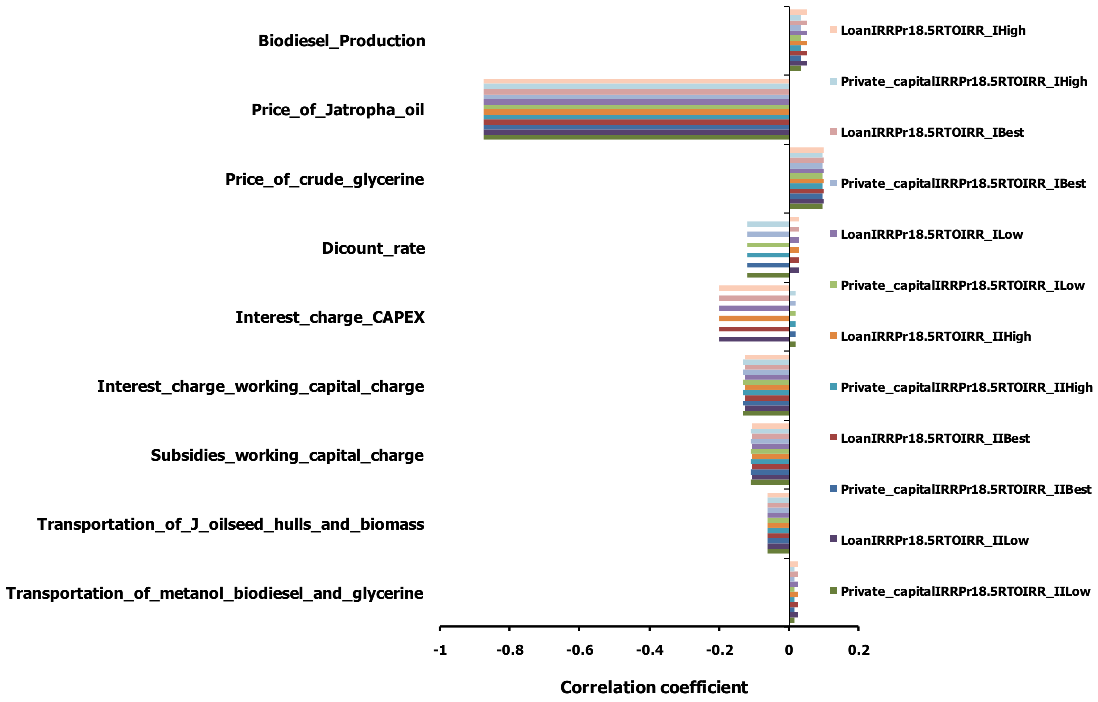
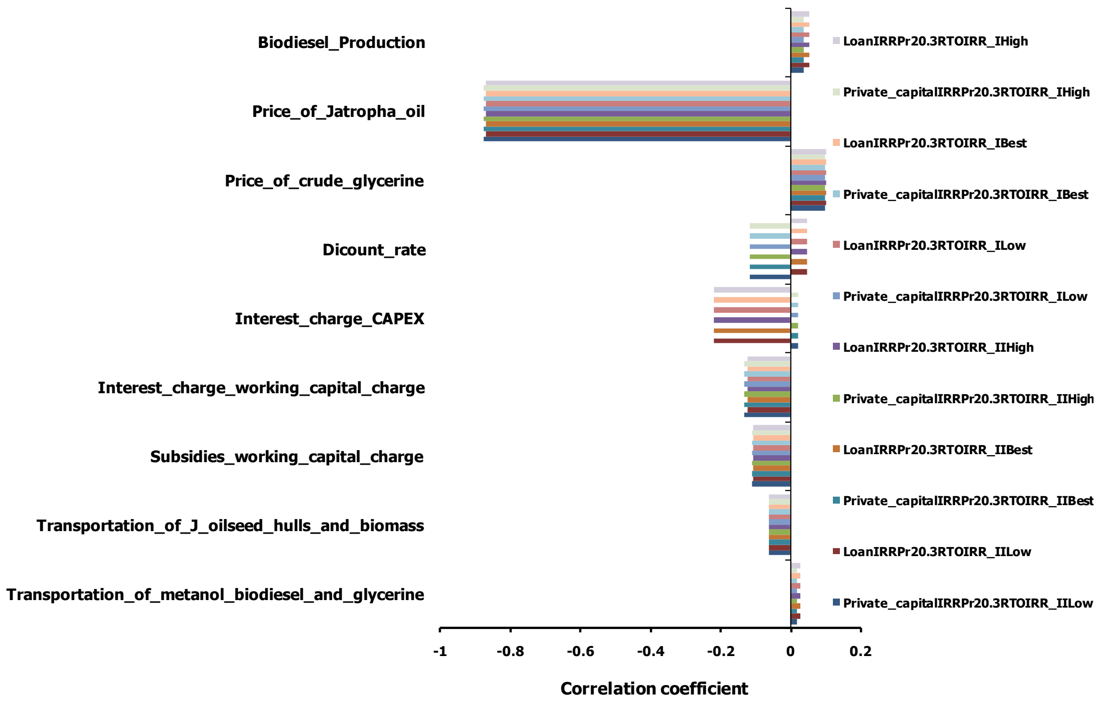


Chart IX. 8: Correlation. Production. Large scale scenario. (IRR_Production_Correlation). CAPEX 20.3 MGBP



RAIN_Production_Correlation

Chart IX. 9: Correlation. Production. Small- scale scenario. (RAIN_Production_Correlation). CAPEX 0.11 MGBP

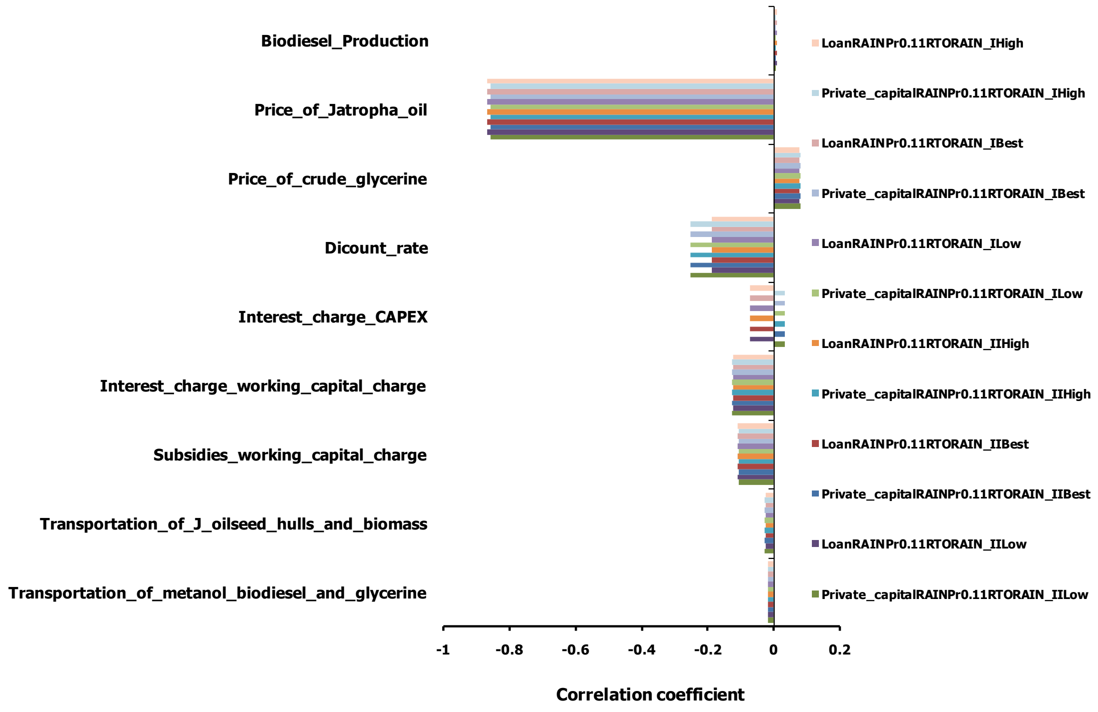


Chart IX. 10: Correlation. Production. Small- scale scenario. (RAIN_Production_Correlation). CAPEX 0.16 MGBP

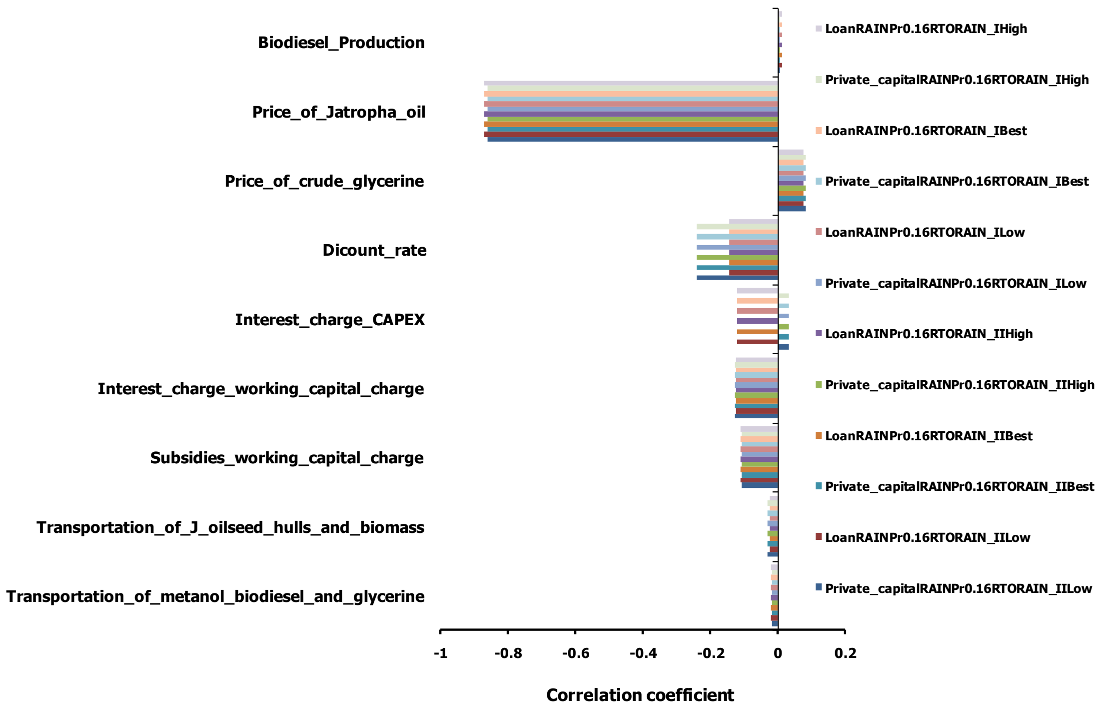


Chart IX. 11: Correlation. Production. Small- scale scenario. (RAIN_Production_Correlation). CAPEX 0.21 MGBP

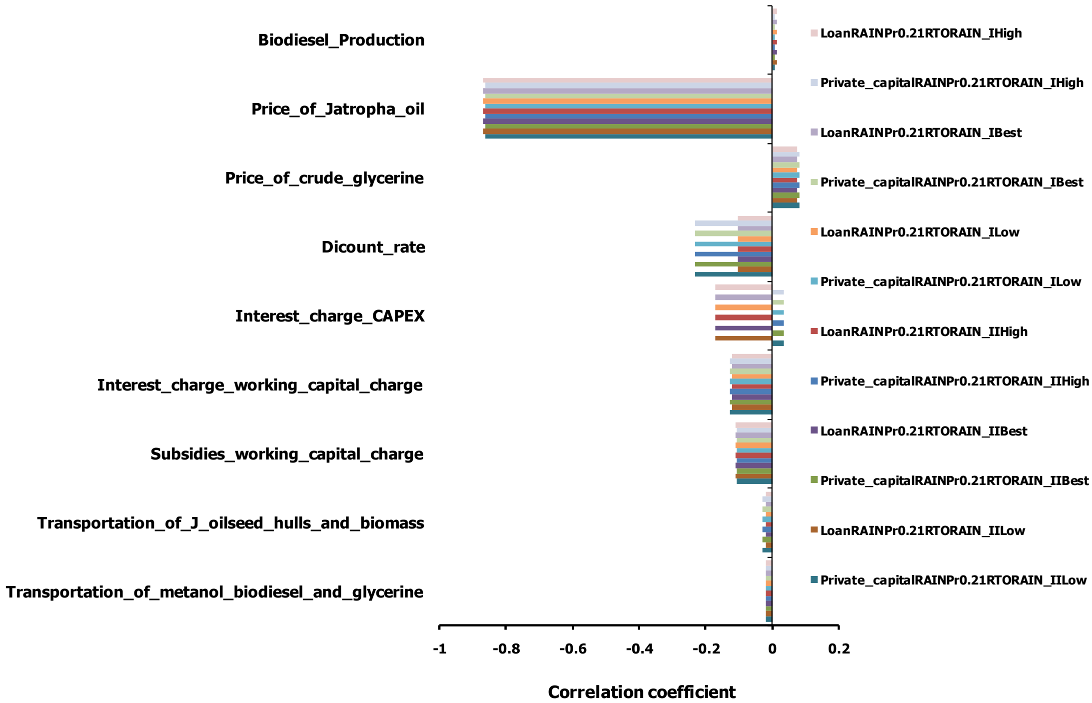


Chart IX. 12: Correlation. Production. Small- scale scenario. (RAIN_Production_Correlation). CAPEX 0.26 MGBP

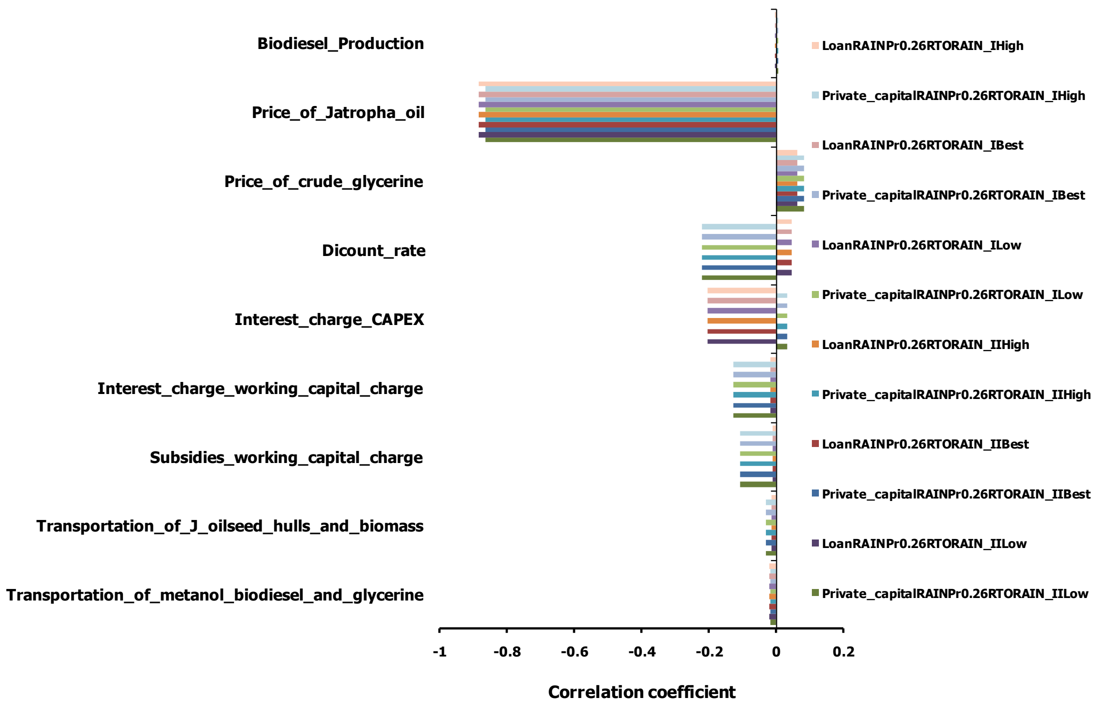
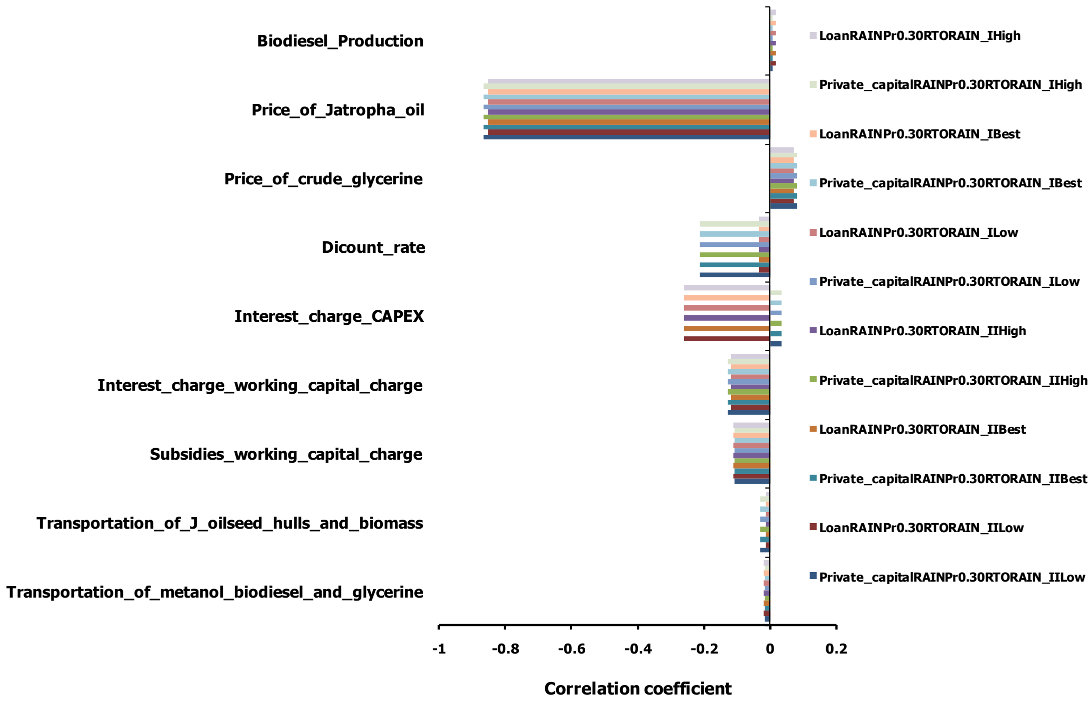


Chart IX. 13: Correlation. Production. Small- scale scenario. (RAIN_Production_Correlation). CAPEX 0.30 MGBP



Appendix X: Effect of seasonality and stage of maturity on the fatty acid composition of *Jatropha curcas* Linn. (%)

Major fatty acids (as % of total fatty acid profile)	**Summer Harvest**		**Winter Harvest**	
	Slightly immature seeds	**Mature sundried seeds**	**Slightly immature seeds**	**Mature sundried seeds**
Palmitic	13.493	16.221	13.648	15.392
Palmitoleic	0.913	1.487	1.065	1.251
Stearic	10.902	5.255	10.429	6.409
Oleic	49.364	35.972	47.441	36.601
Linoleic	24.541	40.577	25.746	38.456

Source: Raina & Gaikwad: 1987

Appendix XI: Water filled pore space (WFPS)

According to Grundmann, *et. al*. (1995) cited by Ilstedt, *et. al.* (2000), water filled pore space (WFPS) or water filled porosity (WPS), which is synonymous with relative saturation is the water unit that is easiest to compare between soils, and also takes air filled pore space into account.

WFPS could be calculated following Weirer, *et. al.* (1993) recited in Padney and Srivastava (2009) and Aulakh, *et. al*. (2000) as:

$$WFPS = [(gravimetric\ water\ context\ x\ soil\ bulk\ density)/\ total\ soil\ porosity], \quad (1)$$

where

$$Soil\ porosity = [(1-\ (soil\ bulk\ density/2.65)] \quad (2)$$

Gravimetric water content could be measured as:

$$W_g = (W_{fw} - W_{dw})/W_{dw}, \quad (3)$$

where

W_{fw} - the mass of the moist soil, and
W_{dw} - the mass of the soil dried at 105^{o}C for 12 hours.

Finally, water filled porosity (Ilstedt, *et. al*.: 2000), could be calculated as:

$$WFP = ((W_{fw} - W_{dw})/\rho_w)/V_{p.} \quad (4)$$

where

W_{dw} - the mass of the soil dried at 105^{o}C for 12 hours (as above), and

$$V_p = W_{fw}/\rho_b - W_{dw}/(LOI \times 1.3 + (1 - LOI) \times 2.65) \quad (5)$$

2.65 equals the assumed practice density of mineral solids (t/m^3 or kg/l), and the density of organic solids 1.3 (t/m^3 or kg/l), which is represented by LOI, i.e. ratio lost after 4 hours in 500^{o}C to the dry weight before ignition. According to Malmer, *et. al.* (1998) recited by Ilstedt, *et. al*. (2000), the loss of ignition (LOI, %w/w) in the topsoil has the range of 2.5-20%.

W_{fw} - the mass of the soil in question,

ρ_b - the bulk density of the soil sample, t/m^3 or kg/l,

ρ_w - the density of water, t/m^3 or kg/l.

Appendix XII: Biogas data used for calculations

- Biogas energy value: 32.64 MJ/m^3; LHV: 5.96 kWh/m^3, 5.4 kcal/l; 4713 kcal/m^3. Density: 0.940 kg/m^3 (Srivastava, *et. al.*: no date);
- Agricultural biogas: Density: 0.00113 kg/l (Althause, *et. al.*: 2004. Swiss Centre for Life Cycle Inventories. Ecoinvent Report No. 1);
- Biogas: 60% CH_4, 40% CO_2, traces of H_2 and H_2S; LHV: 17.8 GJ/t, 21.6 MJ/m^3 (Nigaguna: no date);
- Biogas energy content: 600-800 Btu per standard cubic foot (22.36-29.81MJ/m^3) (www.cospp.com);
- Methane (CH_4) heat value: 34 MJ/m^3 (www.cospp.com);
- 500-600 l (0.5-0.6 m^3) per 1-1.5 kg of wet *Jatropha* oil-seed cake (10-15% of oil). Biogas: 1,000.0 l per 1 m^3 (Siddheshwas and Karve: pers. comm., 2005), 0.380 m^3/kg cake (Khandelwal, *et. al.*: 1980);
- Production: 300-400 m^3 per kg of dry oil-cake (max. 500 m^3/kg) (Patil: pers. comm.);
- Biogas produced from oil cake contains 70-75% methane.
  Its degradation rate is 70-80%. Daily output per unit volume of digester: 2.0-2.5 (Patil: pers. comm.);
- 1 kWh (electricity) rose from a genset equal to 0.75 m^3 biogas hr^{-1} (60% methane) (Ravindranath & Chanakya: 1986);
- Electricity consumption for biogas production is 0.002 kWh/m^3 biogas (WII Conference: 2006);
- In case of biogas production (based on maize silage) using a biogas plant with covered storage tank - methane loses is 1.0% of the biogas produced (COSPP: July-August 2009).