Integration of Greenhouse Gas Control technologies within the Energy, Water and Food Nexus to enhance the environmental performance of food production systems

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Abstract:

The sustainability of food production systems is inherently linked with energy, water and food (EWF) resources directly and in-directly throughout their lifecycle. The understanding of the interdependencies between the three resource sectors in the context of food production can provide a measurable account for resource requirements, while meeting food security objectives. The energy, water and food Nexus tool developed by the authors has been designed to model the inter-dependency between energy, water and food resources, whilst conducting an environmental assessment of product systems. With emphasis on the inter-linkages between EWF resources, the tool quantifies material flows, natural resource and energy consumption at component unit process level. This work integrates greenhouse gas control and waste to power technologies within the energy, water and food Nexus tool and evaluates the environmental impact of a hypothetical food product system designed to deliver a perceived level of food self-sufficiency (40%) for the State of Qatar. Multiple system configurations, representative of different pathways for the delivery of consistent food products are evaluated, transforming a once linear product system into a circular design. The sub-systems added consist of a biomass integrated gasification combined cycle which recycles solid waste into useful forms of energy that can be re-used within the nexus. In addition, a carbon capture sub-system is integrated to capture and recycle CO_2 from both the fossil fuel powered and the biomass integrated gasification combined cycle energy sub-systems. The integration of carbon capture with the biomass integrated gasification combined cycle transforms the carbon neutral biomass integrated gasification combined cycle process to a negative greenhouse gas emission technology known as bio-energy with carbon capture and storage. For the different scenarios and sub-system configurations considered, the global warming potential can be theoretically balanced (reduced by ~98 %) through the integration of photovoltaics, biomass integrated gasification combined cycle and carbon capture technologies. The peak global warming potential, i.e. a fully fossil fuel dependent system, is recorded at 1.73×10^9 kg CO_2 eq. /year whilst the lowest achievable global warming potential is 2.18×10^7 kg CO_2 eq. /year when utilising a combination of photovoltaics, carbon capture integrated with combined cycle gas turbine in addition to the integrated negative emission achieving system. The natural gas consumption is reduced by 7.8×10^7 kg/year in the best case configuration, achieving a credit. In the same scenario, the photovoltaics land footprint required is calculated to a maximum of 660 ha. The maximum theoretically achievable negative emission is 1.09×10^9 kg CO_2/year.

1. Introduction:

Since the mid nineteenth century, the cumulative emission of greenhouse gasses (GHG) has reached approximately 1,200 Gt CO_2eq. raising concentrations of atmospheric CO_2 to a record 430 ppm. It is stated that even if the concentration of atmospheric CO_2 remained below 500 – 550 ppm, the probability of a 2-3 ^{o}C increase in global temperatures remains high, while any higher increase would be dangerous (Stern, 2010). Energy conversion processes are by far the largest source of GHG emissions contributing 69 % of global anthropogenic greenhouse gas emissions. Smaller shares correspond to agriculture (11 %), producing mainly CH_4 and N_2O from domestic livestock and rice cultivation, and industrial processes not related to energy (6 %), producing mainly fluorinated gases and N_2O; with smaller contributions from numerous other sources (14 % combined total) (EC-JRC/PBL, 2011). In terms of energy demand, developed countries have witnessed stabilised CO_2 emissions in the last few years whilst the Middle East and China have recorded the largest increases in CO_2 emissions (IEA, 2014). At the present trajectory, it is very likely a 2-3 ^oC temperature increase will be realised unless large scale abatement of greenhouse gas emissions is introduced (Stern, 2010).

With global population expected to reach nine billion by the year 2050, the increasing demand for energy, water and food (EWF) resources will lead to increasing rates of resource depletion and environmental degradation. In this regard, one of the biggest challenges faced by mankind is the increasing demand for food from a growing and more affluent population and to meet this demand whilst limiting the impact on the environment. In terms of food production, today, agricultural processes contribute approximately 17 – 32 % to global greenhouse emissions (GHG).

It is estimated that food production will need to increase by 70 – 100 %. Sustainable intensification which is a term often used to describe the production of more food in a given land without a corresponding increase in environmental degradation has been considered as a plausible strategy to achieving this aim (Royal Society, 2009). Agriculture transformation associated with sustainable intensification must consider the reduction of: (1) greenhouse emissions from land use and farming by at least 80 % (IPCC, 2007); (2) loss of biodiversity; and (3) unsustainable water withdrawals and pollution (Foley et al., 2011)

Incidentally, agriculture is the largest consumer of fresh water amounting for 70 % of global use and it is predicted that a further 30 % increase in water withdrawal is required to accommodate the increasing demand of food (WWAP, 2014). This, however, cannot be achieved without a substantial utilisation of energy sources to produce the necessary power to extract and distribute water in addition to powering all fertilizer production, food processing and water irrigation facilities. Evidently, the systems representing EWF resources are intrinsically interdependent in what is known as the EWF Nexus. The rapid appropriation of EWF resources witnessed in modern society presents a multi-dimensional security concern. In fact, a study conducted by the World Economic Forum (WEF, 2011) related to global risks has identified the risk related to future security of EWF resources as a chronic impediment to economic growth and social stability. Considering food production, agriculture requires water and energy; the extraction and distribution of water requires energy which in turns requires water as part of the energy extraction and conversion to power process. Furthermore, a food production system also demonstrates crucial inter-dependencies with the Earth's natural sub-systems such as the nitrogen and carbon cycles.

The increasing demand for products and services coupled with the industrial model predominantly practised today is a cause for concern. This industrial model is based on value creation through a series of intermediately steps delivering a final product (Hawken et al., 2010). In most cases, it is a linear sequence encompassing the extraction of raw materials, the use of technology and labour for the transformation into value added products. In this industrial model wastes from production processes and ultimately the product themselves are disposed of in the environment.

To study EWF interdependencies in the context of product systems, the authors have developed a unique EWF Nexus tool as previously reported in Al-Ansari et al. (2015) and Al-Ansari et al. (2016). The EWF Nexus tool was used to evaluate the environmental performance of a hypothetical food security scenario in the state of Qatar. The case study region is chosen for the importance of food security, the ample opportunity to develop renewable energy alongside well established fossil fuel based energy production and because, climatically, it is located in a region of scarce water resources. One important advantage of the EWF Nexus tool is sub-system modulation, which allows expansion and modifications in line with the scenarios considered by industry, policy and government decision makers. Multiple technology options which are represented in the form of sub-systems within the EWF Nexus tool enables the EWF system assessment to be deployed in varying configurations.

Analysis of product/industrial systems using the EWF Nexus refers to the parallel evaluation of the relevant industrial and natural processes and has received widespread interest in recent literature. Governed by the need to adopt a holistic system approach in the analysis of product/systems in terms of their respective environmental characteristics, Nexus analysis has traditionally focused on the utilisation of EWF resources as summarised in Bazilian et al. (2003) and demonstrated in Al-Ansari et al. (2015). Whilst the need to consider the interdependencies between EWF systems in what is eluded to as the Nexus is very well understood, recent publications within the field have advanced the methodological approach for which Nexus analysis can be conducted. Garcia and You (2016) emphasised the need to undertake a process system engineering approach in developing accurate life cycle assessment models to better evaluate EWF Nexus problems and enhance these with optimisation methods. Similarly, Leung Pah Hang et al. (2016) utilised mathematical programming to develop an integrated system design for an eco-town in the UK within the EWF Nexus framework. Irabien and Darton (2015) applied a process analysis method to a tomato production case study in Spain in order to illustrate the integrated supply chain characteristics of the EWF Nexus. These works indicate that a process system engineering approach in the analysis of EWF systems is both relevant and very necessary.

The EWF Nexus tool developed previously in Al-Ansari et al. (2015) is designed with fundamental system options enabling the evaluation of a food production system in Qatar. The system which was previously evaluated by Al-Ansari et al. (2015) considered an increase in Qatar's domestic food production capacity from 8 % to 40 % by the year 2025 using a particular crop profile in addition to the raising of a variety of livestock. The distribution of the crop profile: open field agriculture; i.e. onions and potatoes (20 %), protected agriculture i.e. tomatoes and cucumbers (20 %), fruits i.e. dates and citrus (20 %) and livestock products (40 %). Legumes, fodder and cereals are omitted from the crop profile as they are considered unsuitable for growth due to their respective large water requirements.

In the work presented in this paper, the EWF Nexus tool is enhanced with additional sub-systems in order to encourage cleaner production in the form of greenhouse gas control and cleaner power production. Pertaining to cleaner production objectives, this paper introduces a biomass integrated gasification combined cycle and carbon capture sub-system, which transforms food production from a conventional/linear system to a system that demonstrates circular characteristics that may be considered by decision makers. The benefit of the circular system design is demonstrated in the enhancement of the overall system environmental performance, which is quantified using the EWF Nexus tool.

The EWF Nexus tool supports the process modelling of a full range of technology options which are characteristic of EWF resources, and designed such that the individual EWF resource systems are represented at unit processes level with an emphasis on the interlinkages between the respective systems. This is necessary in order to ensure enhanced evaluation of the respective resource system options. In the analysis presented here, the food system is the focus product system. Furthermore, the design of the sub-systems at a high resolution (unit process level) and from a process systems engineering perspective enables the identification of synergies within the human activity driven EWF resource sub-systems and/or synergies with natural sub-systems such as the nitrogen and carbon cycles. The proceeding section details the conceptual design of the EWF Nexus tool and the EWF Nexus sub-systems including the additional elements introduced in this paper for the first time (Figure 1). These are the biomass integrated gasification combine cycle (BIGCC) and CO_2 capture (CC) sub-systems. The process design of the fundamental EFW Nexus tool sub-system elements have been presented elsewhere in Al-Ansari et al. (2015).

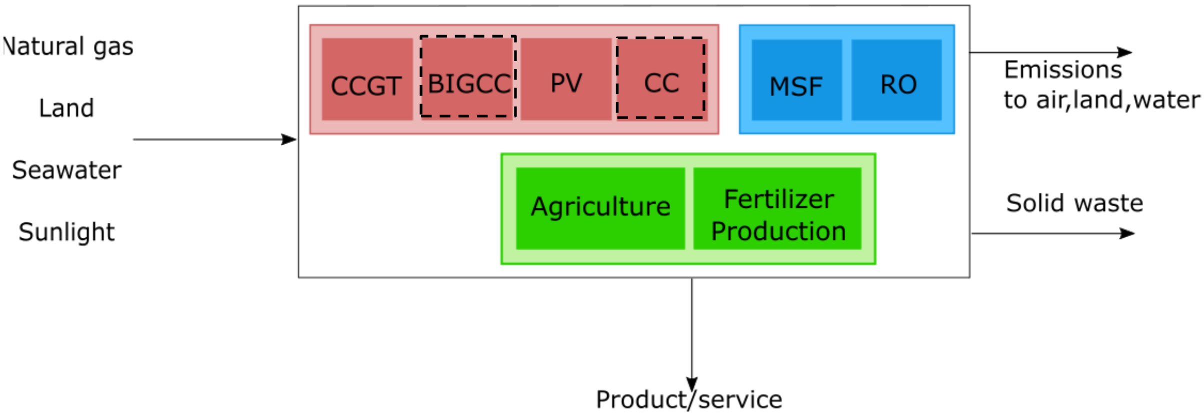

Figure 1: Schematic of EWF Nexus sub-system design.

2. EWF Nexus tool - LCI Model design

The EWF Nexus tool is based on Life cycle assessment (LCA) methodology (BS EN ISO14040, 2006) and comprises of a suit of sub-system life cycle inventory (LCI) models that are designed to quantify material flows, natural resource and energy consumption at component unit process level for each of the subsystems represented. The LCI models are built using a combination of mass balance models, literature emission factors and engineering calculations which are validated using published literature and industry data. The sub-systems are connected through energy and mass, and together deliver a product corresponding to the objective of the system. The EWF Nexus modelling system presented here has adopted a food perspective with the objective of evaluating the environmental impact when raising domestic production in Qatar by 40 %. The flexible structure of the LCI model, provided through modularisation, enables the practitioner to choose component unit processes so that different technological options can be considered (Al-Ansari et al., 2015). EWF sub-systems which are configured to deliver a particular crop profile, are each designed with a corresponding LCI and a functional unit as governed by the LCA methodology. The functional units for the individual sub-systems are defined such that EWF inter-linkages considered are consistent and independent of the type of technology used in order to enable the swift integration of different technology options (see Table 1).

Table 1: Overview of EWF inter-linkages in terms of functional units.

Inter-linkage	Unit	Comment
Energy - Water	MJ/m^3	Energy required in the provision of water
Water- Energy	m^3/MWh	Water requirement in power production
Water - Food	m^3/t	Water requirement for irrigation
Food - Water	m^3/m^3	Virtual water content in food
Energy - Food	MWh/t	Power requirement for agricultural facilities
Food - Energy	MJ/t	Energy potential from biomass or food crops

The food sub-system LCI models represent the production of fertilizers and agricultural activities, including both the application of fertilizers and the raising of livestock. The livestock under management include broilers, dairy, beef, sheep and camels. Water sub-system LCI models are developed for two desalination processes; Multi-Stage Flash (MSF) and Reverse Osmosis (RO) for the production of water. Finally, energy sub-system LCI models required for power generation are developed from both non-renewable and renewable sources. This includes a combined cycle gas turbine plant (CCGT) LCI model driven by natural gas and a solar power plant utilising solar Photovoltaics (PV). Previously, the aforementioned sub-systems were mobilised in three configurations in order to deliver the Qatar food production target (Al-Ansari et al. 2015) reflecting only scenario 1 detailed in Table 2. In scenarios 2 and 3, the power generated from the BIGCC system is distributed back to the EWF Nexus sub-systems proportionally to the energy required.

Table 2: Description of Qatar's food production EWF Nexus scenarios.

Scenario	**a**	**b**	**c**
1 Conventional mode	CCGT is used to power all water and food sub-systems.	PV is integrated with the water sub-system.	PV is integrated with water and food sub-system.
2 Integration of BIGCC	BIGCC power is distributed amongst water and food sub-systems.		
	CCGT is used to power all water and food sub-systems.	PV is integrated with water sub-system. Food sub-system is powered by the CCGT.	PV is integrated with water and food sub-systems.
3 Integration of biochar	BIGCC power and biochar savings are distributed amongst water and food sub-systems.		
	CCGT is used to power all water and food sub-systems.	PV is integrated with water sub-system. Food sub-system is powered by the CCGT.	PV is integrated with water and food sub-systems.
4 Integration of CC	Same as scenario 1(a).	CC is integrated with the CCGT powering the water sub-system.	CC is integrated with the CCGT powering the water and food sub-systems.
5 Integration of PV and BECCS (CC and BIGCC).	BIGCC power is distributed amongst water and food sub-systems.		
	Same as scenario 2(a).	PV is integrated to power the water sub-system. The food sub-system is powered with the CCGT integrated with CC. The BIGCC is integrated with CC.	PV is integrated to power the water and food sub-systems. The BIGCC is integrated with CC.

In determining the corresponding environmental impact, the analysis concluded that the GHG emissions from the livestock sub-system represented the overwhelming majority of the total GWP of the EWF Nexus system. This is consistent across the three configurations analysed. Considering scenario 1 and configurations (a), (b) and (c), the share of emissions from the livestock sub-system correspond to 60 %, 75 % and 99 % of the total GWP (i.e. the share of emissions of livestock sub-system increase as emissions from energy generation are reduced).

The work presented here integrates additional power generation and greenhouse gas control technology options in multiple configurations in order to improve the environmental performance of Qatar's food production system as detailed in scenarios 2-5 (Table 2). The newly built LCI sub-systems are designed with respective functional units that are consistent with previously defined inter-linkages (Table 1).

The function of the biomass integrated gasification combined cycle (BIGCC) LCI model developed is to generate power from waste manure, consequently reducing the dependency on natural gas and PV. Furthermore, an LCI sub-system representing CO_2 capture (CC) technology is integrated to capture and store atmosphere bound CO_2 from both the CCGT and the BIGCC sub-systems. The integration of CC with the BIGCC transforms the carbon neutral BIGCC process to a negative GHG emission technology with CO_2 capture and storage (BECCS). With the integration of the aforementioned sub-systems into the EWF Nexus tool, the possible sub-system configurations delivering an identical product can be expanded. As such scenarios 2-5 (detailed in Table 2) are explored in this study in which the corresponding system characteristics are compared to the reference scenario (scenario 1).

The specific details regarding the sub-system LCI models that refer to the baseline configuration are discussed in Al Ansari et al. (2015). The following sections present the newly introduced BIGCC and CC LCI models in detail.

3. Biomass Integrated Gasification Combined Cycle (BIGCC) and CC LCI models

The BIGCC is essentially a waste management process which utilises recycling techniques to generate a power potential within the EWF Nexus, promote dematerialisation and encourage the substitution of raw material (natural gas). Incidentally, the environmental burden associated with manure from livestock as computed in Al-Ansari et al. (2015) can be reduced significantly if the manure is recycled into an energy potential. The work reported here only considers the thermochemical conversion through gasification as the waste management option of choice.

3.1 Gasification LCI model

Gasification is a process in which organic matter (e.g. manure) is decomposed into a syngas which can be used in power generation or converted into high value products (Ro et al., 2007). It has several advantages over alternative thermo-chemical processes such as combustion which include: (1) converts low value feed stocks to electricity and transportation fuels; (2) has increased efficiency from the use of advanced technologies such as gas turbines from the utilisation of syngas; (3) high temperature combustion generates more NO_x and other emissions when compared to the combustion of syngas; and (4) syngas used n BIGCC systems is cleaned of contaminants such as nitrogen and sulphur efficiently, which reduces emissions (Kumar et al., 2009). The composition of the output syngas generally consists of varying quantities of CO, CO_2, CH_4, N_2, H_2 and H_2S, whilst other compounds are considered to be in trace amounts (Gordillio, 2007). The proportion of each species depends on the fuel input, gasifier technology and process conditions (i.e. temperature and pressure).

The gasification process is considered a preferred technology for low grade fuels which can utilie several oxidizing agents; air, steam, air and steam, pure oxygen and pure oxygen with steam (Gordillo and Annamalai, 2007). Considering a fixed-bed gasifier, the gasification processes occurs in four different zones as seen in figure 2; combustion or oxidation, gasification or reduction, pyrolysis and drying. The oxidation zone is the energy source for the other reactions. The thermal energy generated in the oxidation zone drives the endothermic reactions in the gasification zone. In the pyrolysis zone, most of the gases, along with tars, heavy carbons, and water are generated. In the drying zone, the moisture in the fuel is converted into steam as the fuel is heated and dried (Priyadarsan et al., 2004).

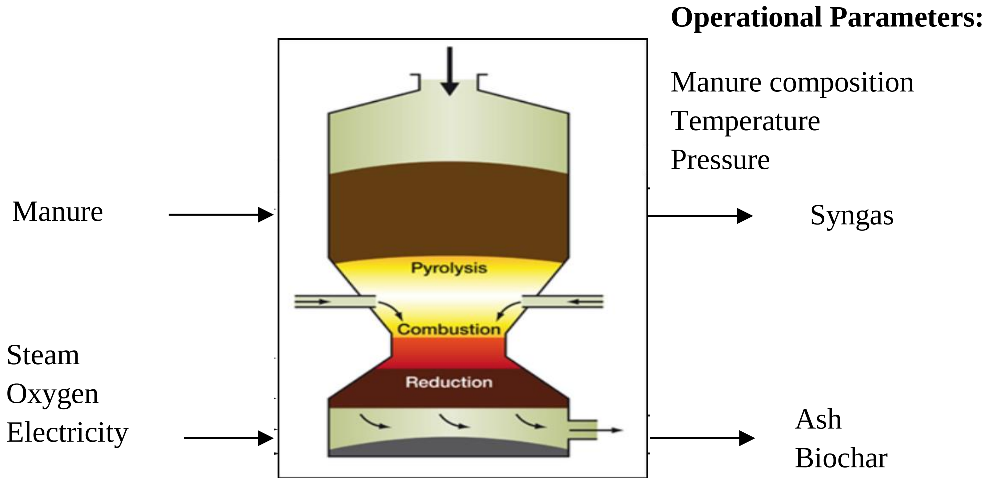

Figure 2: The Scheme of biomass/manure gasification processes LCI model developed.

The process is governed by a series of primary heterogeneous chemical reactions which are illustrated in Table 3, compiled from Bottino et al. (2006) and Choi and Stenger (2003). The reactions which occur in the different zones, are both endothermic and exothermic and take place at different rates.

Table 3: Major reactions involved in the biomass gasification processes.

Stage	Reactions
Combustion in combustion zone	$C + O_2=CO_2$ $2C + O_2=2CO$
Gasification in reduction zone	$C+H_2O=CO+H_2$ $C+2H_2O=CO_2+2H_2$ $C+CO_2=2CO$ $C+2H_2=CH_4$ $S+H_2=H_2S$ $S+2CO=2COS$
Secondary reactions of primary gases in combustions zone	$CH_4{+}_2O_2=CO_2{+}_2H_2O$ $2CO+O_2=2CO_2$ $2H_2+O_2=2H_2O$
Other reactions in reduction zone	$CO+H_2O=CO_2+H_2$ $CO_2+H_2S=COS+H_2O$ $CH_4+H_2O=CO+H_2$

The gasifier (or reactor) converts biomass, oxygen and steam into gaseous products with a high temperature and pressure. The composition depends on the feed (fuel type i.e. manure, oxygen and steam), the temperature and pressure in the gasifier. Experimentally, Priyadarsan et al. (2004) evaluated the gasification of different variations of feedlot manure and poultry litter biomass. At a gasification temperature of approximately 1090K, the product gas composition for the different were in the range of (on dry basis); 23–30 % CO, 4 – 7 % H_2, 0.3 – 1.4 % CH_4, 3 – 9 % CO_2.The highest recorded heating value was attributed to high ash feedlot biomass with a recorded HHV of 10.88 ± 0.33 MJ/m^3 (db and nitrogen free).

The product syngas can also be predicted using (i) mass (or atom) and energy conservation equations for assumed species, and (ii) chemical equilibrium calculations with a larger number of species, including trace species (Gordillo et al., 2009). Utilising a chemical equilibrium approach, the LCI model developed as part of this study, illustrated with its respective inputs and outputs in Figure 2, assumes that dairy manure is a representative composition for all livestock for simplicity as illustrated Table 4 (Gordillo and Annamalai, 2010). Furthermore, it is assumed that the manure is collected every two months reducing the manure emissions by a factor of six in line with the LCA study conducted by Wu et al., 2013).

Table 4: Composition of manure considered.

Parameter	**Value**
Dry Loss %	25.26
Ash %	14.95
VM %	46.84
FC %	12.95
C %	35.27
H %	3.1
N %	1.9
O %	19.1
S %	0.42
HHV (kJ/kg)	12.844
HHVdaf (kJ/kg)	21.482
HHVdb (kJ/kg)	17.185

Emissions from the collection of manure, its transport to and from industrial sites and the handling equipment are not considered. The chemical equilibrium based LCI model, illustrated graphically in Figure 4, can determine the:

- syngas composition per unit input of manure;
- calorific value of syngas generated and the gasification efficiency;
- relative amounts of oxygen and/or steam and/or heat required per unit manure input.

Table 5 outlines the operational parameters considered.

Table 5: Operational parameters considered.

Parameters	Value	Units
Biomass basis	1	kg
Oxygen/carbon ratio (mol.)	0.48	n/a
Steam/carbon ratio (mol.)	0.465	n/a
Gasification zone temperature	1,000	K
Operational pressure	10	bar

The chemical equilibrium model developed is applied to the global gasification process, also known as a single step stoichiometric equilibrium model (Zainal et al., 2001). The procedure integrates the different reactions detailed in Table 3 into one complex general reaction. Essentially one mole of biomass ($CH_{1.047}O_{0.407}N_{0.046}S_{0.0045}$) is gasified with c mole of steam and b mole of air producing a syngas with molar quantities N_i as presented in equation (1).

$$C_{a1}H_{a2}O_{a3}N_{a4}S_{a5}ash + b(O_2 + 3.76N_2) + cH_2O \rightarrow N_{CO_2} + N_{CO} + N_{H_2} + N_{H_2O} + N_{H_2S} + N_{COS} + N_{N_2} + N_{CH_4} + ash \quad (1)$$

I. Reaction kinetics:

The equilibrium constants expressed in terms of partial pressure (Bottino et al., 2006) and temperature in Kelvin (Rostrup-Nielsen and Aasberg-Petersen, 2003) for the water-gas shift and methane steam reforming reactions are detailed in equations 7 and 8. The corresponding equilibrium constant for the carbon shift reaction is detailed in equation 9 (Kohl and Nielsen, 1997)

Methane steam reforming reaction (msr):

$$K_{msr} = \frac{[P_{H_2}^3][P_{CO}]}{[P_{CH_4}][P_{H_2O}]} P^2 = \frac{{N_{H_2}}^3 N_{CO}}{N_{CH_4} N_{H_2O}} P^2 = \exp(30.42 - \frac{27106}{T}) \quad (7)$$

Water-gas shift (wgs):

$$K_{wgs} = \frac{[P_{H_2}][P_{CO_2}]}{[P_{CH_4}][P_{H_2O}]} = \frac{N_{H_2} N_{CO_2}}{N_{CH_4} N_{H_2O}} = \exp(-3.798 + \frac{4160}{T}) \quad (8)$$

The corresponding equilibrium constant for the Carbon shift (c-s) is given by:

$$K_{c-s} = \frac{[P_{COS}][P_{H_20}]}{[P_{CO_2}][P_{H_2S}]} = \frac{N_{COS} N_{H_2O}}{N_{CO_2} N_{H_2S}} = \exp(-0.4633 - \frac{2049}{T}) \quad (9)$$

There are eight variables and eight unknowns, solving through the minimisation method, i.e.:

$$K_{msr} = \frac{[P_{H_2}^3][P_{CO}]P^2}{[P_{CH_4}][P_{H_2O}]{N_t}^2} - \exp\left(-30.42 + \frac{27106}{T}\right) = 0 \quad (10)$$

Where K_{msr} is the equilibrium constant of methane steam reforming reaction, P is the reaction pressure, $N_t = N_{CO_2} + N_{CO} + N_{H_2} + N_{H_2O} + N_{H_2S} + N_{COS} + N_{H_2} + N_{CH_4}$.

II. Thermal performance calculations:

Syngas high heating value:

$$HHV_{Product\ gas} = \left(HHV_{H_2} \times y_{H_2}\right) + \left(HHV_{CO} \times y_{H_2}\right) + \left(HHV_{CH_4} \times y_{CH_4}\right) \quad (112)$$

Gasification efficiency:

$$\eta_{gasification}(\%) = \frac{Heating\ Value\ in\ Syngas\ generated}{HHV\ of\ biomass\ gasified} \quad (12)$$

The calculated syngas composition is provided in Table 6.

Table 6: Product gas composition.

Gas product	Molar (%)
CO_2	12.16
CO	22.10
H_2	17.48
H_2O	16.36
H_2S	0
COS	0
N_2	31.73
CH_4	0.02

3.2 Integrated Gasification Combined Cycle Gas Turbine LCI model

The integration of a gasifier with a combined cycle gas turbine presents several advantages over direct combustion such as: (1) fuel-gas based technologies (i.e. gas turbines) can achieve higher efficiencies than direct combustion; (2) the overall efficiency of gasification is higher because gaseous fuels burn more efficiently than solid fuel; and (3) production of gas enables the removal of contaminants which lead to the emissions of NO_x and SO_x (Bridgwater, 1995).

The gasification process produces a low calorific syngas which can be used in traditional combined cycle gas turbines configurations. The syngas contains combustible carbon monoxide and hydrogen diluted with large amounts of nitrogen and carbon dioxide. Whilst it is possible to design and build greenfield CCGT systems based on syngas fuels, it is also possible to co-fire gasified product with natural gas (Rodrigues et al., 2003) and modify existing facilities to utilise syngas as the fuel for power generation (Chacartegui et al., 2013; Kim et al., 2011). Typical air blown gasifiers produce a gas with high nitrogen content (~ 50 %) and, therefore, a low heating value which implies; increased size of the gasification and gas cooling equipment, and makes syngas cleaning (sulphur removal) more difficult. As such, gasifiers are coupled with air separation units to separate nitrogen from the air to enable the gasification of biomass with O_2 and steam, which in turn produces a syngas with a significantly larger heating value.

From a life cycle perspective, combustion of biomass within the BIGCC produces CO_2 which is in fact returned to the atmosphere after it was originally absorbed by the plants during photosynthesis (Srinivas et al., 2012; Mann and Spath, 1997). Therefore, the net CO_2 emissions from the gasification process is considered to be zero. It is likely that when a life cycle of the process is considered, the process is not 100 % neutral (i.e. carbon closure < 100 %). The amount of CO_2 released from the system includes the emissions from farming operations that use fossil fuels, upstream energy consumption, transportation of the biomass to the power plant and emissions from power generation (Spath and Mann, 2000). Reported life cycle analysis of BIGCC systems, indicate that emissions from transportation and facility construction are negligible in comparison to emissions from the gasifier and the CCGT (Mann and Spath, 1997).

For the purposes of this study, it is necessary to compute carbon balances for BIGCC systems in isolation and when used within food production systems. In this study, the CCGT sub-system described Al-Ansari et al. (2015) is integrated with the gasification model described above to form the BIGCC. The objective of the BIGCC LCI model is the computation of two parameters to be integrated within the broader EWF Nexus tool; (1) power potential (MWh/year), and (2) the rate of CO_2 emissions (kg/MWh). The gasification model is adjusted such that nitrogen is stripped from the air using an air separation unit (ASU). From equation (1):

$$CH_{1.047}O_{0.407}N_{0.046}S_{0.0045} + e(O_2 + \overset{0}{\cancel{3.76N_2}}) + fH_2O \rightarrow gCO_2 + hCO + iCH_4 + jH_2S + kN_2 + lH_2$$

A typical BIGCC is a two part process consisting of a gasifier and the combined cycle detailed in Al-Ansari et al. (2015). Practically, typical mechanical units within CCGT systems such as the gas turbine would be modified in order to utilise fuel with a lower heating value (syngas) therefore altering the process conditions of the combined cycle. It is assumed that the required modifications to a conventional CCGT do not affect the thermodynamic modelling principles. The HHV is however updated to reflect the composition of the syngas. Figure 3 illustrates the coupling of a dryer, ASU, gasification unit and a CCGT to form a BIGCC system.

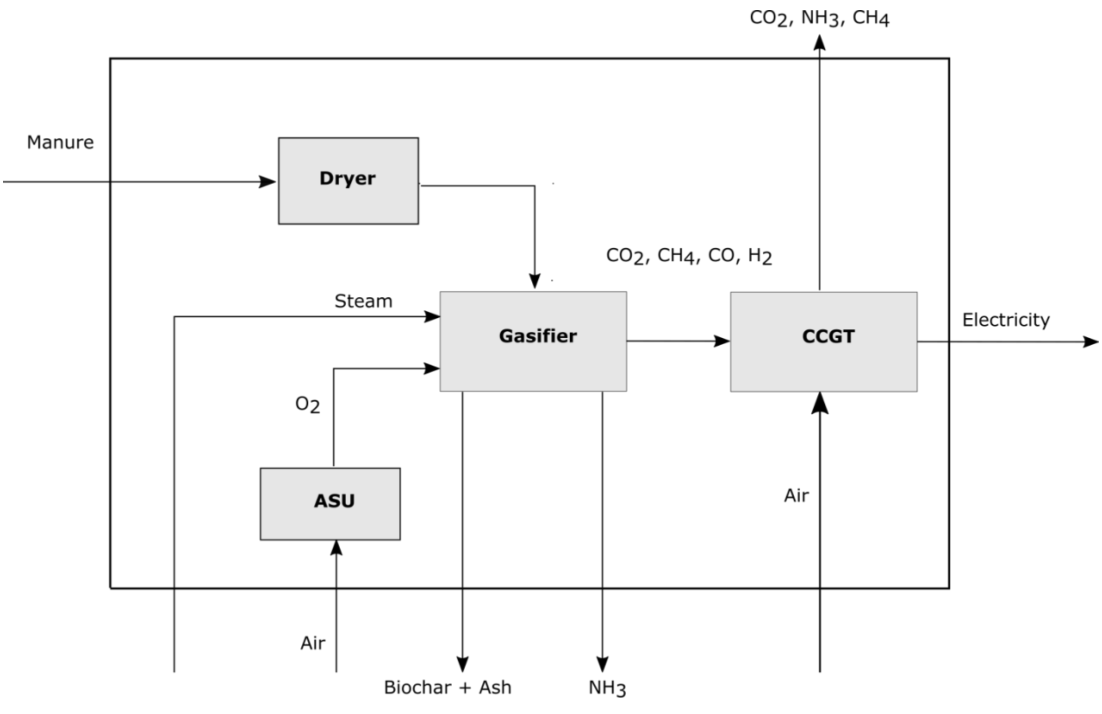

Figure 3: Schematic of BIGCC process flow.

Energy requirement for the generation of steam has been accounted for. Furthermore it is assumed that auxiliary systems such as the dryer and ASU utilise power from within the system and not from an external source. In modelling the output of the BIGCC, the following parameters are omitted: (1) compressor: number of stages, polytrophic efficiency, (2) combustor: pressure loss (%); (3) turbine: turbine rotor inlet temperature, number of stages, stage efficiency, turbine cooling modelling and exhaust pressure loss %. The calculated product gas composition post nitrogen stripping is detailed in Table 7. The syngas is channelled to the BIGCC in which the corresponding performance results are provided in Table 8.

Table 7: Product gas composition after nitrogen stripping.

Gas product	Molar (%)
CO_2	17.61
CO	32
H_2	25.31
H_2O	23.68
H_2S	0
COS	0
N_2	1.15
CH_4	0.03

Table 8: BIGCC performance results.

Parameter	Value	Unit
Ta	25	ºC
Tr	850	ºC
Syngas HHV	4.62	MJ/m^3
Biomass calorific value	17185	MJ
Gasification efficiency	55.26	%
W_{GT}	110	MW
W_{ST}	40	MW
WT	150	MW
W_{Drying}	18	MW
η_{BIGCC}	34	%

3.3 Emissions from BIGCC systems

BIGCC emissions considered in this case study include those pertaining from gasification process and the combustion of syngas. During the gasification process, nitrogen emissions in form of ammonia (NH_3), hydrogen cyanide (HCN), and oxides of nitrogen (NO + NO_2 or NO_x and N_2O) maybe produced from the fuel bound nitrogen (FBN) in the biomass feedstock (Zhou et al., 2000). It is estimated that 90 % of FBN is converted to emissions of NH_3 and N_2 during gasification whilst HCN and NO_x are present in small amounts. Whitty et al. (2008) evaluated the emissions during the combustion of syngas in the turbines, engines and boilers. The types of emissions include unburned fuel components, partial oxidized species, nitrogen and sulphur gases and VOC's. In summary, the presence of H_2, and CO in the syngas results in a high combustion temperature which promote the thermal formation of NO and NO_2. However, higher temperatures encourage complete combustion, in turn reducing the emissions of VOC's (formed from minor fractions of hydrocarbon in the syngas). Cleaning the syngas prior to combustion eliminates emissions of SO_2, HCl and fly ash. Low-NO_x combustion techniques such as air staging, fuel staging (re-burning) and flue gas recirculation reduce NO_x emissions from syngas combustion. In summary, emissions of NO_x, CO and VOC's from syngas combustion are generally lower than emissions from conventional combustion systems (Whitty et al., 2008). In the context of this study, calculating the emission profile from first principles is not possible. As such, in determining the emission factors to be utilised in this study illustrated in Table 9, the following is assumed:

- Through intensive syngas cleaning; the model assumes that particular matter, metallic compounds and other pollutants are removed from the syngas prior to entering the turbine including VOC's, PM_{10}, HCN and H_2S. Sulphur species, halides and trace elements are removed from the syngas prior to combustion (Whitty et al., 2008; Leibold et al., 2008).
- As NO_x emissions are generally independent of fuel composition and dependant on post control methods. The NO_x emission factor for CCGT power generation developed in Korre et al. (2012) are utilised. It should be noted that although some pollution control systems utilise water as part of the cleaning process (equivalent to 15 % by weight of the air and fuel used for combustion (Sarofim and Flagan, 1976), it is assumed that the corresponding water requirement will not be supplied from the water sub-system in the nexus model.
- A $(NH_3)/N_{fuel}$ (%) ratio of 24 and a $(N_2)/N_{fuel}$ (%) of 80.3 corresponding to a gasification temperate of 850 (^oC) is selected (Zhou et al., 2000).

Derivation of CO_2 emission factor from syngas combustion is described in the three step procedure described below:

(a)

$$Total\ CO_2 input = yi_{CO_2\_syngas} \times Fuel_{biomass} \tag{13}$$

$$Total\ CH_4 input = yi_{CH_4\_syngas} \times Fuel_{biomass} \tag{14}$$

$$Total\ CO\ input = yi_{CO\_syngas} \times Fuel_{biomass} \tag{15}$$

Where; $yi_{CO_2\_syngas}$, $yi_{CH_4\_syngas}$ and yi_{CO_syngas} are the mole fractions of CO_2 CH_4 and CO derived previously.

(b)

$$2H_2 + O_2 \rightarrow 2H_2O \tag{16}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{17}$$

$$2CO + O2 \rightarrow 2CO_2 \tag{18}$$

(c)

$$EF_{CO_2} = \frac{Total\ CO_2 output}{(W_{T\_syngas} \times 24\ \times 365)} \tag{19}$$

Where; EF_{CO_2} is the CO_2 released from the combustion of syngas measured in kg/MWh and W_{T_syngas} is the total power potential from the syngas (MWh/year).

Table 9: Summary of main emissions considered in the BIGCC system.

Species	Factor (kg/MWh)	Source
CO_2	1,059	Model
CH_4	0.00027	Literature
NH_3	195.8	Model

3.4 Integrated CC and BIGCC LCI model

Post-combustion CO_2 capture refers to the separation of CO_2 from the flue gases generated in a large-scale combustion process fired with fossil fuels or biomass. The fraction of CO_2 present in the flue gas streams is typically 3–15% by volume, and the other main constituent in flue gas is nitrogen. Due to the low concentration and low pressure of CO_2 in the flue gas, chemical absorption CO_2 capture methods are conveniently applicable to post-combustion systems. A typical chemical absorption unit is based on an aqueous CO_2 absorption in absorber and CO_2 stripping system. In the absorber, CO_2 is chemically absorbed from the inlet gases by contacting it with the counter-current CO_2-lean solvent (e.g. MEA). The treated gas exits the top of the absorber column. The CO_2-rich solvent is passed to the stripper, where, by heating the CO_2-rich solvent solution, the CO_2 is stripped off and the CO_2-lean solvent is regenerated. The regenerated CO_2-lean solvent is then recycled back to the absorber and the CO_2 is passed to compression processes. The schematic of the LCI model developed is shown on Figure which describes the inputs/outputs quantified. The inputs/outputs of chemical absorption CO_2 capture processes are modelled using the same engineering principles as described in Korre et al. (2010). Furthermore, it is important to note that the composition of the flue gas entering the CC per MWh is equivalent to the emissions of the CCGT per MWh detailed in Al-Ansari et al. (2015).

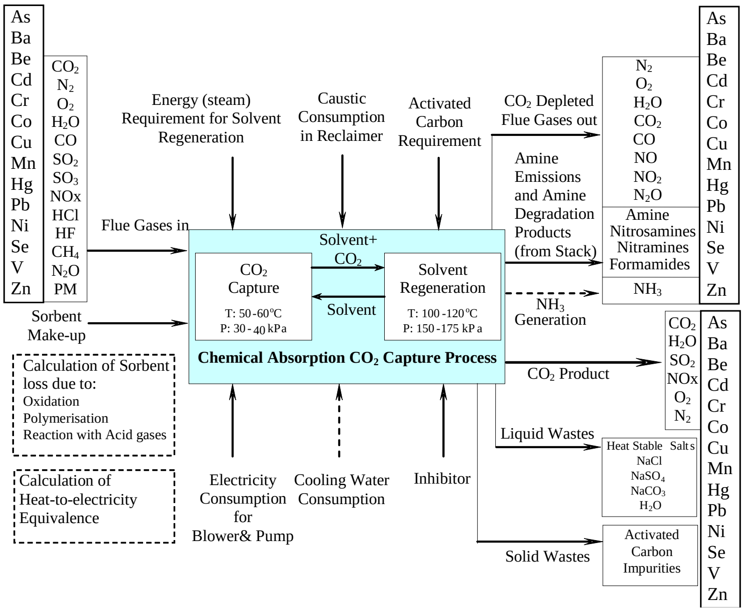

Figure 4: The scheme of chemical absorption CO_2 capture processes LCI model developed. Modified from (Korre et al., 2010).

Carbon capture technology which is traditionally considered in conjunction with fossil fuel systems can be integrated with systems utilising biomass for power generation. Bio-energy with carbon capture and storage (BECCS) utilises biomass that has removed atmospheric carbon during its life cycle offering permanent net removal of CO_2 from the atmosphere (IEA, 2013). BIGCC systems operating in isolation are considered low carbon technologies whilst BECCS systems are considered carbon negative technologies. In theory, BECCS systems can achieve negative life cycle emissions compared to other systems utilising CC and other pollution reduction technologies. McGlashan et al. (2012) discussed the practicalities of negative emission methods which include; augmented ocean disposal, biochar artificial trees, soda/lime process and BECCS. The study concludes that BECCS technologies are mature (i.e. can be introduced in today's energy systems). However, to date BECCS systems, also known as negative emission technologies have not been fully realised (IEA, 2013). Furthermore, some concerns with the BECCS include those related to biofuels in general and their impact on land use change and competing with food crops for valuable resources. However, the utilisation of waste biomass or livestock manure as presented in this study negates those concerns. Gough and Upham (2010) state that commercialisation prospects of the BECCS are heavily dependent on the adoption of carbon capture and sequestration technologies.

Illustrating published work in this field, Rhodes and Keith (2005) studied a BIGCC electric power system consisting of gasification technology, syngas conditioning system, carbon capture and a CCGT. The output of the BIGCC includes a generation capacity of 123 MWe, a thermal efficiency of 28 % and a carbon capture efficiency of 44 %. Studies considering the analysis of BIGCC systems coupled with CO_2 capture technology utilizing coal as a feedstock have been conducted (Platts, 2009; Schaltegger and Sturm, 1989). The model developed in this study is based on the integration of the post-combustion CO_2 capture model developed by Korre et al. (2010b) with the BIGCC sub-system LCI model described in this section. It is important to note that the energy associated with the transportation of CO_2 to a possible end user or storage facility after capture has not been considered as part of this study.

4.0 Scenario analysis

Following on from the analysis presented in Al-Ansari et al. (2015) with the addition of the BIGCC and BECCS LCI sub-system models, this study analyses the environmental impact of Qatar's food security motivated EWF Nexus system for different scenarios. The results presented in Al-Ansari et al. (2015) are considered the baseline Scenario 1, where PV sub-systems representing solar power plants are integrated to drive water and food sub-systems using a liquid slurry management system for the livestock sub-system. Using the same livestock management system, Scenarios 2 and 3 consider the integration of the BIGCC and biochar, Scenario 4 considers the integration of the post combustion carbon capture technology. Scenarios 5 evaluates the impact on the EWF Nexus when the full spectrum of technologies are integrated (PV+BIGCC+CC). The following sections describe each of the scenarios and present the corresponding results.

I. Scenario 2 – Integration of BIGCC

Table 10: *Integration of BIGCC* in Scenario 2.

2(a)	**2(b)**	**2(c)**
BIGCC power is distributed amongst water and food sub-systems.		
CCGT is used to power all water and food sub-systems.	PV is integrated with water sub-system. Food sub-system is powered by the CCGT.	PV is integrated with water and food sub-systems.

Scenario 2, detailed in Table 10, involves the integration of the power available from the BIGCC within different configurations involving the CCGT and PV as illustrated in Figure 6. The GWP impact of the BIGCC will vary significantly depending on whether the BIGCC is considered carbon neutral, i.e. if the CO_2 emissions from the BIGCC are accounted for in the GWP calculations. Figure 7(a) illustrates the GWP from the BIGCC in the case where it is considered carbon neutral (i.e. 100 % CO_2 closure loop). Alternately, Figure 6(b) illustrates the GWP from BIGCC in the case where it is not considered carbon neutral. Incorporating a 100 % CO_2 closure presents a 50 % reduction in the total GWP for the EWF Nexus system across all three configurations. The reduction in GWP is equivalent to the GWP associated with the CO_2 released in the full realisation of the BIGCC potential with an emission factor corresponding to 1,047 kg/MWh.

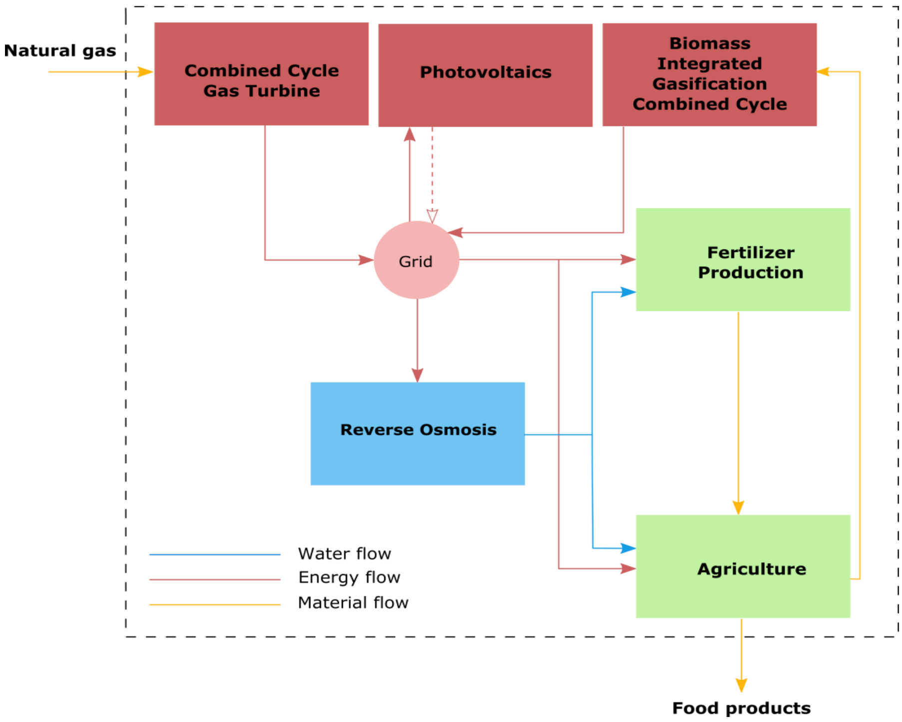

Figure 6: Process flow diagram for scenario 2(b), where PV is integrated with water sub-system, while the food sub-system is powered by the CCGT.

The human toxicity potential decreases with increasing deployment of PV as illustrated in Figure 8(a). The non-energy related emissions from the within food sub-systems remain constant as the integration of power technologies do not have an impact on emissions. The BIGCC releases a large amount of NH_3 in comparison which is equivalent across scenarios 2(b) and (c). The NH_3 released represents 92 % of the total human toxicity potential originating from the energy emissions from within food sub-systems, equivalent to 68 % from the total human toxicity potential considering all categories (i.e. including non-energy related emissions from food sub-systems). With respect to the total acidification potential, the impact across all three categories is heavily influenced by NH_3 emissions, representing a share of over 90 % for all three configurations as illustrated in Figure 8(b).

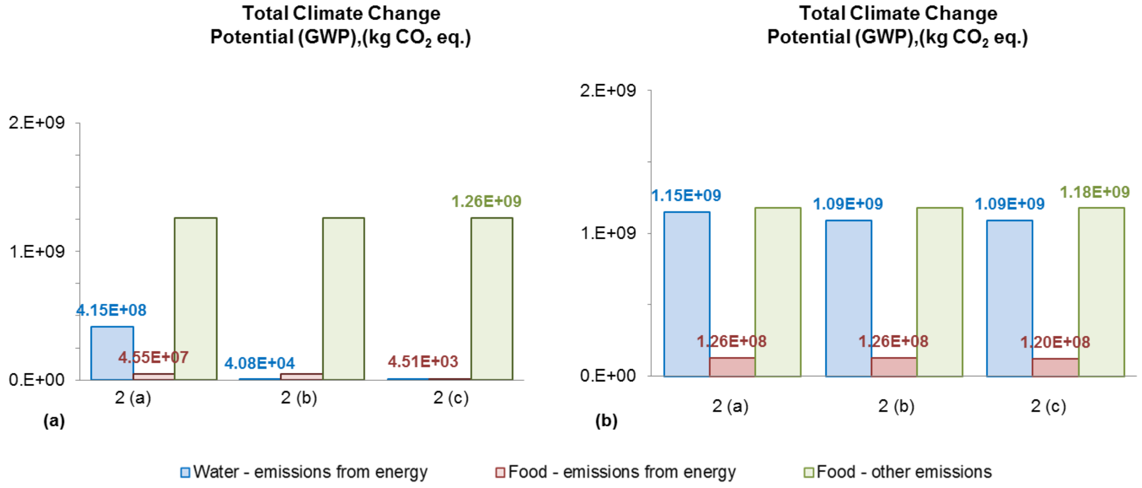

Figure 7: Total GWP for the BIGCC integration in Scenario 2 (a) 0 % carbon closure and (b) 100 % carbon closure for Qatar's EWF nexus system.

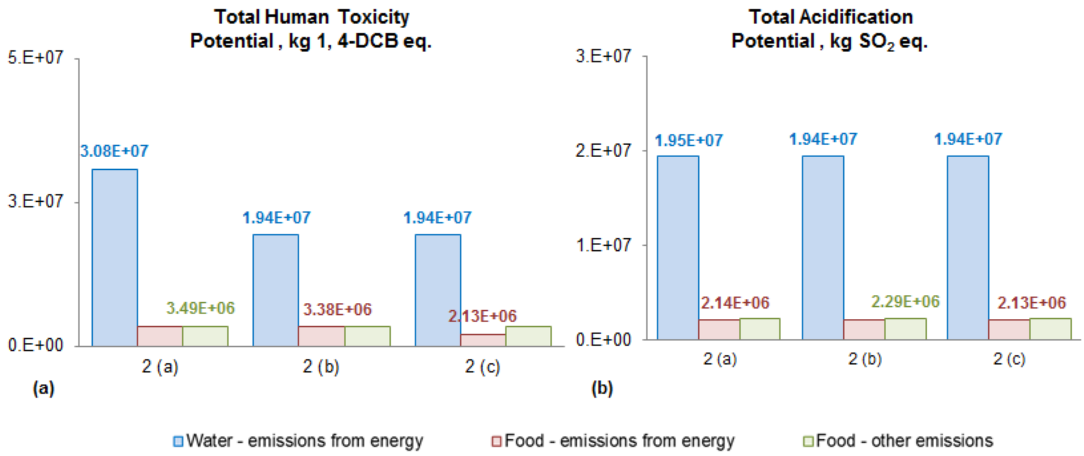

Figure 8: Total human toxicity potential per year (a) and acidification potential per year (b) for Qatar's EWF Nexus system for the BIGCC integration in Scenario 2.

The introduction of the BIGCC reduces the total land requirement in comparison to the previous scenario evaluated (Scenario 1) as illustrated in Figure 9(a). The maximum required land footprint is reduced by 20 % in the full deployment of PV and BIGCC scenario. The integration of the BIGCC reduces the natural consumption required for power generation amongst the three scenarios as illustrated in Figure 9(b). In fact, the integration of the BIGCC enables a natural gas credit when PV is deployed to drive the water sub-system (1.25×10^8 kg/year) and both the water and food sub-systems (1.42 ×10^8 kg/year).

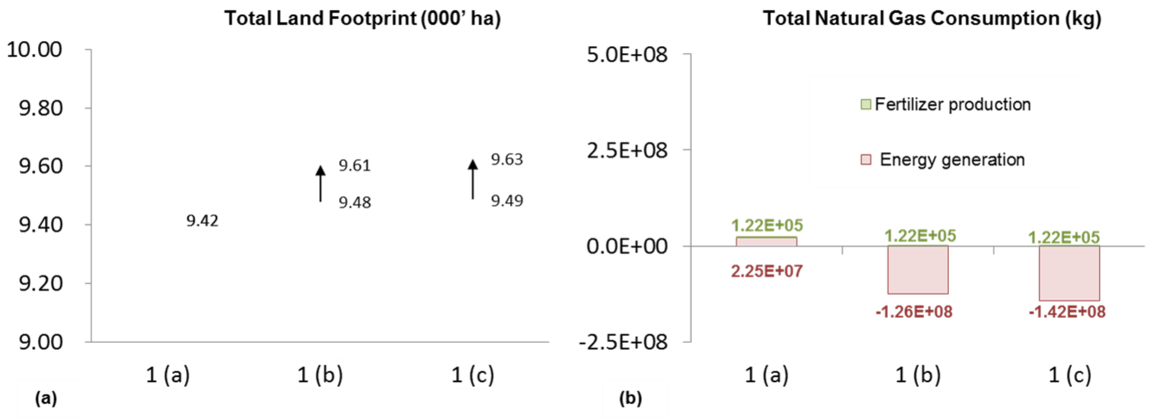

Figure 9: Total land footprint (a) and natural gas requirement per year (b) for Qatar's EFW nexus system for the BIGCC integration in Scenario 2.

II. Scenario 3 – Integration of biochar

Scenario 3, detailed in Table 11 integrates biochar into the 100 % carbon closure system presented in Scenario 2. Evidently, there is small improvement with the integration of biochar. This is because it is assumed that the biochar has no impact on the physical processes within the livestock management sub-system (i.e. enteric fermentation and manure management).

Table 11: *Integration of biochar* in Scenario 3.

3(a)	3(b)	3(c)
BIGCC power and biochar savings are distributed amongst water and food sub-systems.		
CCGT is used to power all water and food sub-systems.	PV is integrated with water sub-system. Food sub-system is powered by the CCGT.	PV is integrated with water and food sub-systems.

The integration of biochar corresponds to an improved WUE, which in turn reduces the irrigation requirement. In scenario 3, the total GWP is reduced by 3 %, 0.7 % and 0.4 % as compared to scenario 2 across all three configurations. Although, this study adopted a conservative 50 % improvement in WUE and 50 % improvement in nutrient uptake, it is unlikely that a more optimistic assumption would yield significant improvements in the total GWP. This is due to the large emissions from non-energy related processes generated within the food sub-systems. Not considering the aforementioned emissions, which are constant amongst the three configurations, the total GWP considering the energy related emissions from the water and food sub-system is reduced by 50 %, 50 % and 75 % across the three configurations as illustrated in Figure 10 (a). The total human toxicity is significantly reduced with the addition of biochar across all categories, with near negligible emissions from energy related emissions when powering the water and food sub-systems with PV as illustrated in Figure 10 (b). The major reduction in the human toxicity potential is a result of the decreased emissions from reduced fertilizer production.

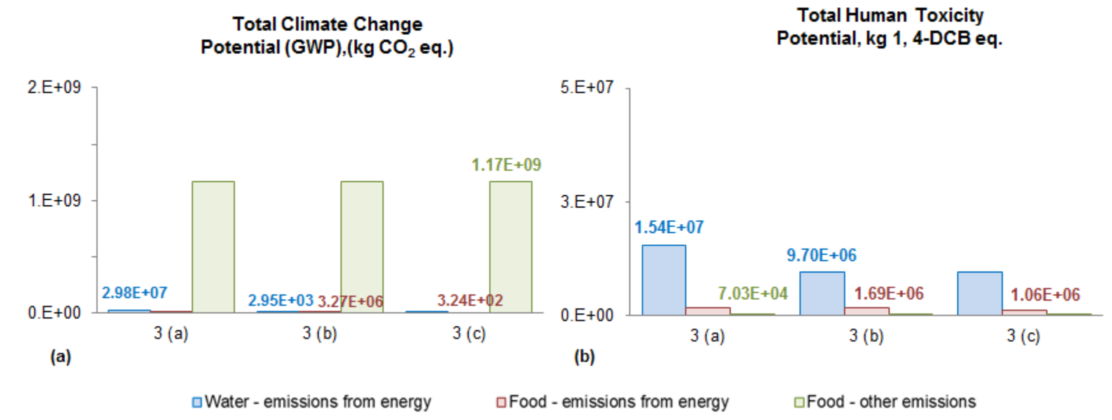

Figure 10: Total GWP per year (a) and human toxicity potential per year (b) for Qatar's EWF Nexus system with the integration of biochar in Scenario 3.

The maximum PV deployment extends the land foot print by approximately 100 ha beyond the agriculture zone as illustrated in Figure (a). Figure (b) presents the natural gas requirement in Scenario 3.

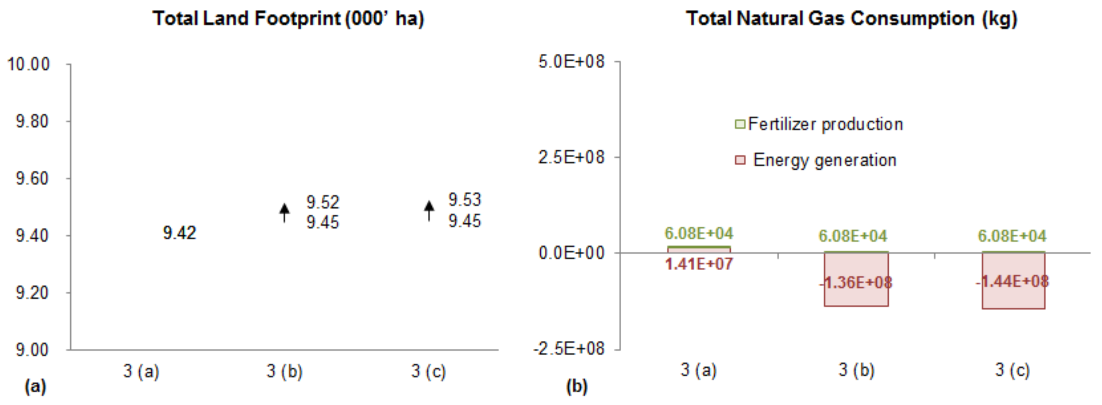

Figure 11: Total land footprint (a) and natural gas requirement per year (b) for Qatar's EWF Nexus system with the *integration of biochar* in Scenario 3.

The integration of biochar decreases the overall natural gas required to support the EWF Nexus. This is through the decreased CCGT requirement when driving the water sub-system and food sub-system, in addition to the decrease process requirement for natural gas in the manufacture of ammonia. In this scenario, the natural gas credit is increased to a maximum of 1.44×10^8 kg in the case where the BIGCC, biochar and PV are integrated.

III. Scenario 4 – Integration of CC

Scenarios 4(b) and 4(c) (see Table 12) utilise CC technology for emission reduction as a replacement for the PV used in the corresponding scenarios 1(b) and 1(c). The process flow system diagram illustrated in Figure represents the full integration of CC as described by scenario 4(c). In the computation of integrated results, it is assumed that a CCGT-RO system will provide the additional water requirement for the CC sub-system. This includes the process water requirement in addition to the water requirement for power generation. Furthermore, in this scenario the additional power required to drive the CC process is converted into a natural gas fuel cost (quantity) which is accounted for in the integrated results. The total GWP from scenario 4(a) can be reduced by approximately 40 % with the full integration of CC in scenario 4(c) as illustrated in Figure 13 (a).

Table 12: Description of CC integration in Scenario 4.

4(a)	4(b)	4(c)
Same as scenario 1(a).	CC is integrated with the CCGT powering the water sub-system.	CC is integrated with the CCGT powering the water and food sub-systems.

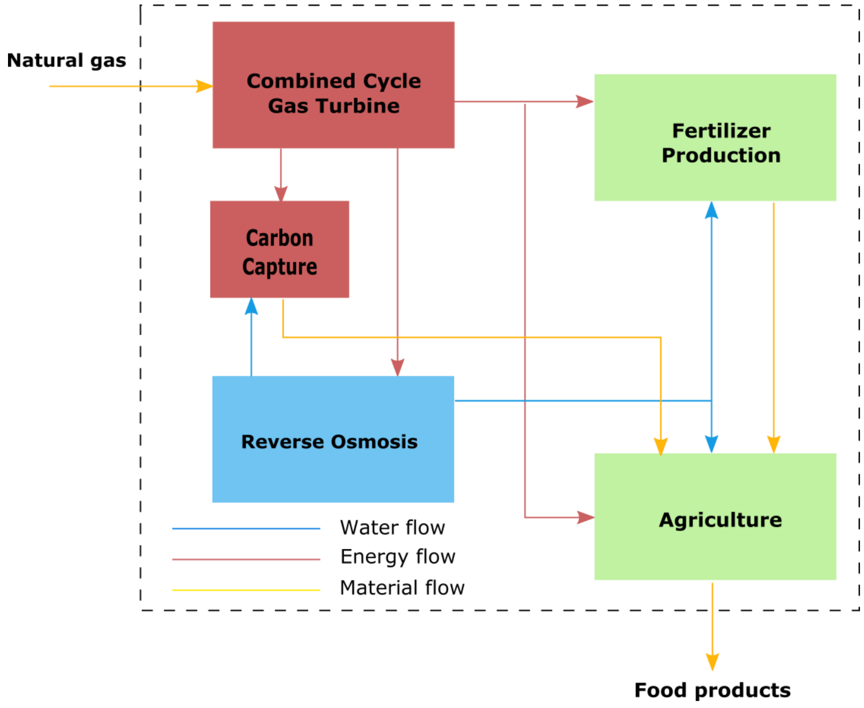

Figure 12: Process flow diagram illustrating the integration of CC within the EWF Nexus for Scenario 4c.

The majority of GWP originates from the non-energy related emissions from the sub-systems amounting to 65 %, 95 % and 99 % of the total, representing a larger share as mitigation technologies are introduced in other sub-systems. Assuming, the process water required for CC is provided by desalination plants; the corresponding power requirement from a CCGT source is also considered as part of the water-emissions from energy category.

Furthermore, the corresponding natural gas input into the CCGT power dedicated to desalinate water is also integrated in Figure 13(b). The total increase in the natural gas requirement in scenario 4 is a direct consequence of the added energy cost from the carbon capture and compression processes which together result in an approximate 12 % increase. Although, the CC process has an added energy cost, it ultimately decreases the GWP potential.

Table presents the energy, water and natural gas requirements corresponding to scenarios 4(b) and 4(c).

Table 13: Energy, water and natural gas requirements after the integration of CC with the CCGT driving the water (4b) and food sub-systems (4c).

	Integration with water sub-system (4b)	**Integration with water and food sub-systems (4c)**
% increase in CCGT load due to CC	11.7	11.7
Additional natural gas requirement (kg)	1.88×10^7	3.48×10^7
CC process water requirement (kg)	1.17×10^7	1.30×10^7

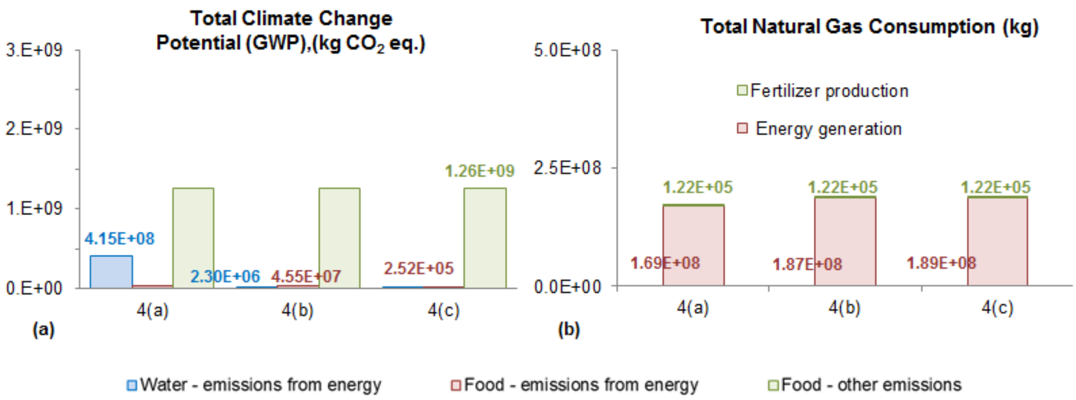

Figure 13: (a) Total GWP per year and (b) natural gas footprint per year for Qatar's EWF Nexus system with CC integration in Scenario. 4.

IV. Scenario 5 – Integration of PV and BECCS (CC and BIGCC).

Scenario 5 described in Table 14 integrates the full spectrum of technology options (PV, BIGCC, BECCS) to achieve maximum environmental benefits with the added benefit of negative emissions from the BECCS system as illustrated in Figure 14. The configurations deployed within this scenario avoid the direct use of natural gas for power generation (other than towards the manufacture of PV). The significant benefits of this integration in terms of GWP are illustrated in Figure 16. The environmental savings from the livestock sub-system are highly dependent on two factors; the portion of manure that is captured and transferred to the process facility and the carbon closure ratio (%) of the system.

Table 14: Description of PV and BECCS integration in Scenario 5.

5(a)	5(b)	5(c)
BIGCC power is distributed amongst water and food sub-systems.		
Same as scenario 2(a).	PV is integrated to power the water sub-system. The food sub-system is powered with the CCGT integrated with CC. The BIGCC is integrated with CC.	PV is integrated to power the water and food sub-systems. The BIGCC is integrated with CC.

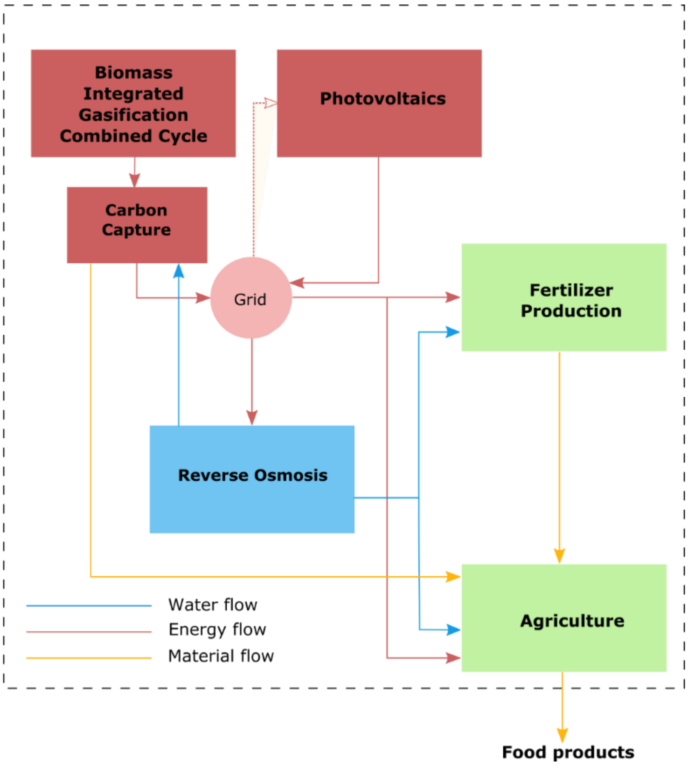

Figure 14: Process flow diagram for the PV and BECCS integration in Scenario 5(c).

In the assumed manure capture efficiency of 50 % although conservative, alongside the 100 % carbon closure for the EWF Nexus provides the maximum theoretical achievable negative emission of 1.15×10^9 kg CO_2/year as illustrated in Figure 15. The integration of the PV, BIGCC, and progressively the BECCS result in profound emission savings for the Qatar EWF Nexus. When considering the negative emission phenomena of the BECCS, the large GWP specifically from enteric fermentation can be largely balanced.

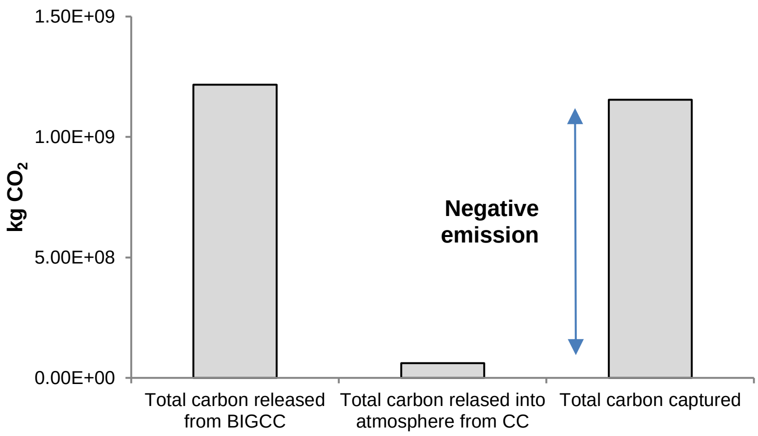

Figure 15: Negative emission per year from the integration of the BECCS in Scenario 5.

The complete roll out of PV and the BECCS (BIGCC +CC) in the water and food sub-systems results in a GWP decrease from 1.24 ×109 kg CO_2eq. to 2.01×107 kg CO_2eq/year (~98 % reduction) as illustrated in Figure 16 (a), and a 127 % decrease in natural gas consumption (27 % in credit) as illustrated in Figure 16 (b). As with previous scenarios, the energy needed to desalinate the process water required for gasification and carbon capture is assumed to be sourced from a RO desalination plant which is driven by a CCGT system.

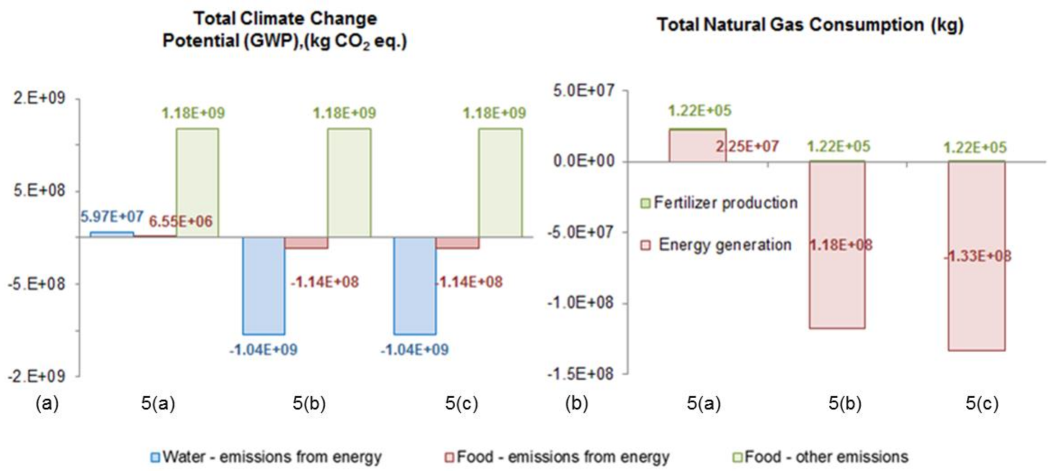

Figure 16: (a) Total GWP per year and (b) natural gas footprint per year for Qatar’s EWF Nexus system from the PV and BECCS integration in Scenario 5.

4.3 Scenario Comparison

The best results for the different scenarios (i.e. full integration of technology options with sub-systems within each scenario), listed in Table15, are compared in Figure17-20 with the conventional Scenario 1, and considered as the reference scenario. Figure 17 illustrates the total GWP for the scenarios evaluated. Evidently, the reference scenario displays the highest GWP with a full technology integration in scenario 5 displaying the lowest GWP.

Table 15: Summary of scenarios for comparison**.**

Scenario	Description
1(a)	Baseline
1(c)	Complete PV integration
2(c)	Complete BIGCC and PV integration
3(c)	Complete BIGCC, biochar and PV integration
4(c)	Complete CCGT integration with CC
5(c)	Integration of PV and BECCS

Scenarios 1(c) – 4(c) demonstrate similar emission savings from the baseline configuration (Scenario 1a) in terms of GWP, which is completely driven by CCGT; 27 %, 32 %, 32 %, and 27 %. Scenario 5(c) reduces the GWP potential by 98.8 % as illustrated in Figure 18. Figure 19 illustrates a comparison for the natural gas consumption for the different scenarios evaluated. The largest reduction in resource consumption is observed within Scenarios 2, 3 and 5. The natural gas consumption in Scenario 4 increases from the baseline scenario (1a) by 12 % which is equivalent to the added power required to drive the carbon capture sub-system. Whilst Scenario 5 results in the largest reduction in GWP, Scenarios 2, 3 and 5 result in the lowest natural gas consumption, thereby achieving resource credits.

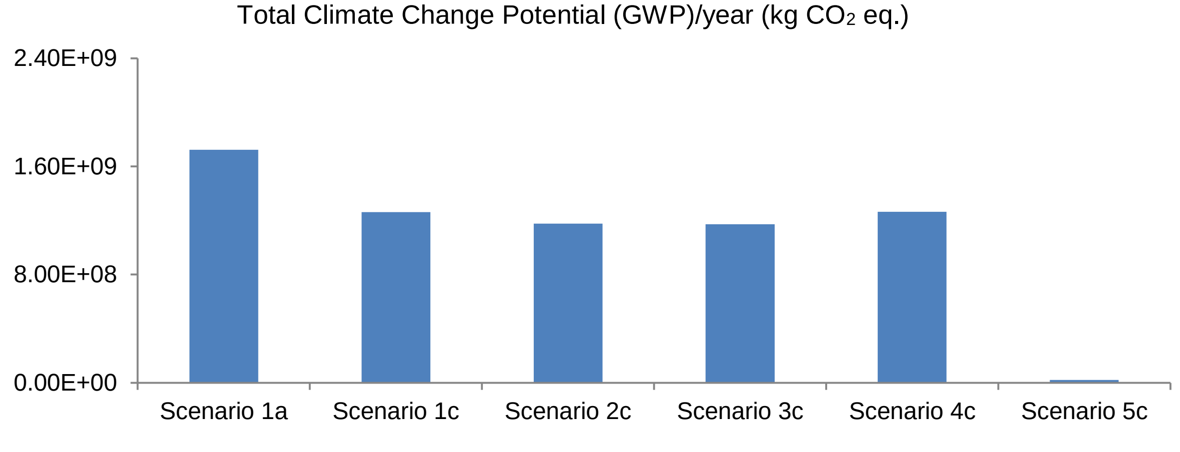

Figure 17: Comparison of the calculated GWP for different EWF Nexus scenarios.

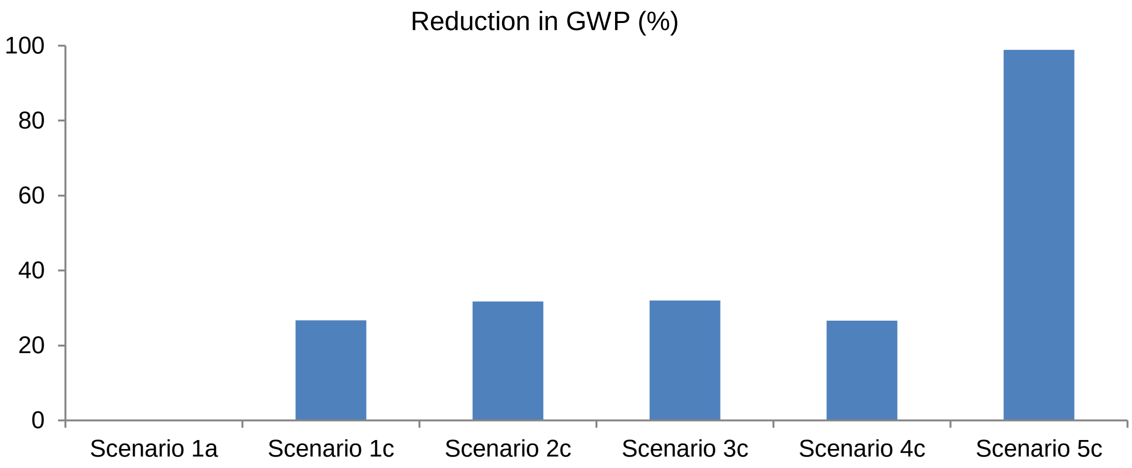

Figure 18: Reduction in GWP (%) for different EWF Nexus scenarios.

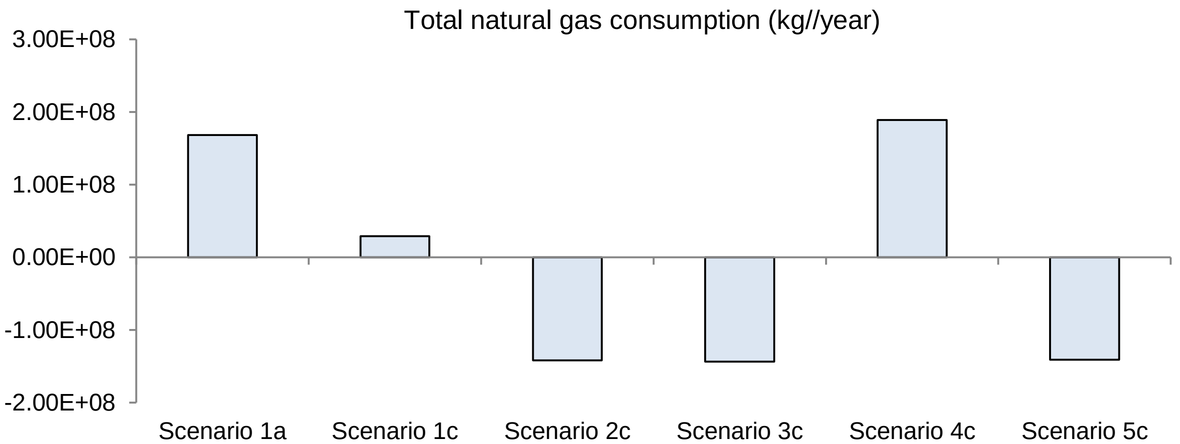

Figure 19: Total natural gas consumption (%) for different EWF Nexus scenarios.

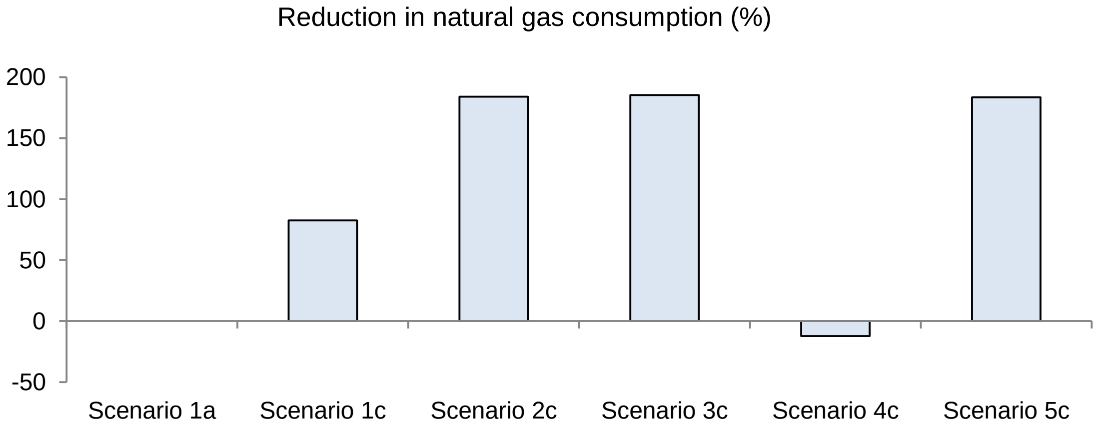

Figure 20: Reduction in natural gas consumption (%) for different EWF Nexus scenarios.

5. Conclusions

The EWF Nexus assessment tool developed accounts for the inter-linkages between EWF resources when evaluating product system systems, and can be used to compares different system options in the context of the natural environment. The characteristics of the EWF Nexus tool include; (1) an engineering functionality enabling the parameterisation of key unit processes, (2) capacity to account of for product system inputs and outputs and track material flows through individual unit processes, (3) ability to identify trade-offs and synergies and compute environmental degradation, and (4) a modular unit processes and sub-system design which facilitates the integration of multiple industrial and natural processes.

With sub-system modulation, the integration of different processes in the form of technology options becomes possible and, therefore, the transformation from a linear to a circular system is accomplished. In this regard, the integration of the CC and BIGCC has facilitated the cycling of previously waste materials and created a power potential whilst reducing the environmental burden of the overall food system, and ensuring that the product system outputs are consistent across all scenarios. Importantly, this work has demonstrated that the parallel integration of the PV, BIGCC and the BECCS can significantly reduce the requirement of raw material (i.e. natural gas) flowing into the system and in some cases generate a resource credit. The CO_2 closure % determines the extent to which the ~1,000 kg/MWh released from the BIGCC process is a credit to the system. In this study it is assumed that carbon closure is 100 % which implies that full CO_2 release from the BIGCC is not considered in GWP calculations.

A CC and utilisation sub-system is also incorporated into the EWF model. With respect to GWP, the CC technology can provide the comparable advantages as PV in reducing the GWP. The EWF Nexus coupled with its sub-system modelling approach enables the substitution of raw material as illustrated in Scenarios 2-5 with the introduction of the BIGCC. The integration of the BIGCC results in a decreased overall GWP as the CCGT is driven by syngas from the gasified manure.

The dematerialisation of the EWF Nexus system is evident as the natural gas input into the system is reduced, achieving a credit in some cases. It should be noted, that introduction of the BIGCC reduces emissions from manure deposits and has no direct effect on enteric fermentation from livestock. On site experimental research is required in order to understand the true potential for agricultural productivity enhancement through the use of biochar. It is possible that this study may have underestimated the environmental savings with the 50 % improvement rate used in the analysis. The objective of such work would be to identify the optimum productivity increase.

Carbon capture technology is introduced as a sub-system as it is both a consumer of energy and water. In Scenario 4, the GWP is reduced with the adoption of the CC sub-system and the largest rate of GWP decrease is when the CC is integrated with CCGT sub-system driving water sub-systems. With the added energy burden required to operate the technology, the natural gas requirement rises in proportion to the decrease in GWP. Extending the use of CC beyond a natural gas driven CCGT, this study presented the theoretical potential from BECCS systems. Whilst the results presented are favourable, it is important to consider that a life cycle economic analysis encompassing the gasification, combustion, carbon capture, transportation and storage in the subsurface is required to ensure the viability of the process.

The absence of a fully functioning commercial BECCS plant makes it difficult to predict the commercial prospect of the process. The commercial prospects of the BECCS system is largely influenced by the end use of the carbon captured. As such, the creation of a suitable and local market for captured CO_2 is one way to alleviate concerns with respect to CC technology especially in the area of storage and present an interesting commercial opportunity. In this regard, it is important to consider the energy associated with the transportation of CO_2 to a possible end user or storage facility. The benefits of BECCS and the extent of negative emissions are a function of the distance and means by which CO_2 is transported to its final destination. As such, future studies will consider the spatial context of the EWF Nexus model which will include the location of the agriculture production sites in addition to the CO_2 transportation distances.

The work presented illustrates that the EWF tool developed enables a robust and transparent environmental assessment of a large spectrum of technologies that may be considered in order to meet societal needs. The food security objective is considered in the case presented, with deployment of different technology options in multiple configurations. It should be noted that, determining the ideal system configuration would require additional analysis beyond what is presented here by evaluating environmental impacts while also considering economic factors.

Acknowledgments

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