Spatial Energy System Modelling under Uncertainty with application to Thailand

by

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Abstract

The current awareness of the depletion in the fossil fuels reserves and the effect of green house gases (GHG) toward global warming has motivated many researchers in the area of energy system modelling. This thesis presents mathematical models to aid decision makers in determining the optimal spatially aggregated energy supply chain network to satisfy the future energy demand at the national level.

Firstly, the energy planning problem using Thailand's energy system as the case study is addressed by the development of a multi-period environmentally conscious deterministic energy system optimisation model. The model is formulated as a linear programming (LP) model that can address decision-making of the optimal future energy supply chain network at the national level with consideration of the scale of GHG emissions of the network. The determination of data required for the development of the proposed model is also tackled.

Secondly, the reformulation of the multi-period deterministic model as a three-staged stochastic energy system optimisation model that can support decision-making under uncertainty in energy demand is addressed.

Further extensions to the deterministic model include its reformulation to take into account the geographical location of an energy system. The linear programming model is reformulated as a mixed integer linear programming model (MILP) that can incorporated the spatial nature of the energy system as part of the decision-making process. The decisions to be determined include: (1) scale, type and location of energy production facility, (2) scale and type of resource usage in each location, (3) flow of

resources and energy between grids to satisfy the energy demand throughout the planning horizon.

Next, the Biomass-to-Energy supply chain network over long-term planning with application to Thailand is focused, based on the spatial MILP formulation. A higher complexity of geographical location is addressed as well as increases in types of biomass and biomass thermal conversion technologies. The objective function is modified to maximise the total network profit rather than minimising the total network costs.

Finally, the long-term planning of a Waste-to Energy supply chain network with application to Thailand is investigated. The Waste-to-Energy system is addressed in view of investors as decision-makers as the objective function is also to maximise the total profit of the network. Different network structures of converting waste into energy are applied. The problem is also formulated as a MILP problem.

This thesis reveals that, based on the model assumptions, the optimal environmentally conscious energy supply chain networks rely heavily on the utilisation of renewable resources throughout the country. With the abundant amount of biomass and waste resources available in Thailand, Biomass and Waste-to-Energy projects have a high potential in diversifying the use of fossil fuels as primary energy sources in Thailand.

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Chapter 1

Introduction

1.1 Background and Motivation

Energy and a country's economic growth are undeniably interlinked. Energy represents the basic background for the economic and social development of a country. Aggregate energy consumption in the developing countries is not far less than the developed countries, which is likely to increase in the near future. Developing countries tend to consume more energy to satisfy their growing needs and to increase the standard of living of their population. Socio-economic development, through education, provision of good healthcare or income generating activities cannot be achieved without utilisation of energy.

Environmental issues are gaining more and more importance especially after the Rio Summit of 1992 and the release of targets for greenhouse gas reduction through Kyoto Protocol of 1998. It has been recognised worldwide that increasing energy consumption not only results in depletion of energy resources but also gives rise to problems like global warming and the greenhouse effect through emissions generated by burning of fossil fuels.

Thailand is currently heavily dependent on fossil fuels for energy consumption, with oil, gas, and lignite being the predominant energy sources, accounting for 80% of the total primary energy consumption in 2004. In 2004, the total Energy Demand of Thailand amounted to 61,262 kilo tonne of oil equivalent (ktoe), up 8.8% from the previous year, while the Thai economy expanded by 6.1%. Modern or Commercial Energy shared 50,746 ktoe or 82.8% of the total Energy Demand whereas Renewable

Energy constituted 10,516 ktoe or 17.2%. The total Energy Supply was 100,495 ktoe, rose 8.7% from Year 2003, with a net import of 50,355 ktoe or 50.1% of the total Energy Supply, and Domestic Production of 50,140 ktoe or 49.9% [DEDE, 2004a].

In light of the global warming situation, higher attention from both the government and the public sectors in renewable energy technologies in Thailand has been growing steadily over the past twenty years. The increased awareness was due to a number of concerns over the use of conventional energy technologies and their environmental impacts.

Thailand ratified the United Nations Framework Convention on Climate Change (UNFCCC) in 1994 and later signed but not yet ratified the Kyoto Protocol. Though the impact of greenhouse gas (GHG) emissions has not been one of the major environmental concerns in Thailand; GHG emissions have been given particular interest in recent years.

In 1998, the amount of GHG emissions from the energy sector was 152 million tons of carbon dioxide (CO_2)-equivalent, accounting for 51% of the total net greenhouse gas emissions [World Bank, 2002]. The amount of GHG emissions from the energy sector was estimated around 2.5 tons of CO_2-equivalent per capita in 2000 and is projected to increase from 148 million tons of CO_2-equivalent in 2000 to 361 million tons of CO_2-equivalent in 2020 [Amatayakul, 2002].

In addition to its concerns over the impact of fossil fuels being the main driving factor for cleaner energy, Thailand, being an oil importing country, has been severely affected by oil price volatility in recent years. In 2004, the total energy imported represented 55% of the total net primary energy supply. Furthermore, in 2004, the combined cost of the total energy imported represented 6.9% of the GDP and 13% of the commodity import [DEDE, 2005a]. Out of the total energy import, crude oil represented 75.5 % in 2004 [DMF, 2005a] [DEDE, 2005a]. In order to reduce dependency on oil imports and to ensure the national energy supply security and sustainable energy development, Thailand's energy policy has placed greater emphasis on diversification of energy supplies.

Thailand is generously endowed with abundant renewable energy resources such as biomass, solar, and hydro energy, which are widely distributed across the country and can be harnessed via commercially viable technologies to generate energy or electricity. Thailand, however, has so far exploited relatively a small portion of its full potential. The total commercial power generation potential, for instance, from the abundant biomass residues and biogas, has been estimated at around 7000 MW [DEDE, 2005b] whereas the current installed capacity for direct combustion for biomass is around 480 MW [Shrestha, 2006].

In rural Thailand, where the majority of the poor live, the traditional use of biomass (charcoal and fuelwood) for cooking and other needs requiring heat, still appears to be the most used fuel-type. However, the disadvantages of using such cheap conventional sources are well-known and include adverse health impacts on local people through the inhalation of particulate matters and emission of fumes from the combustion process. Furthermore, inefficient and unsustainable use of these local resources can lead to local environmental degradation, such as deforestation.

Renewable energy technologies have been increasingly considered as a viable alternative to satisfy energy needs for both domestic and productive uses, especially in the remote areas and many demonstration projects have been implemented in developed and developing countries. However, these renewable energy technologies promotion programmes suffered setbacks [Shrestha, 2006]. Concerted research and development is needed to make these technologies more reliable and affordable.

In Thailand, and similarly in other developing countries, availability of limited funds is also considered as another resource constraint that is to be most judiciously utilised for growth. This situation demands an optimised approach for resource preservation and promotion of renewable energy based systems for long-term benefits. Energy planning with embedded environmental concerns is therefore required for optimum utilisation of available resources including funds, conservation of fossil fuel reserves and promotion of renewable energy for improving sustainability through reduction of greenhouse gas emission.

The objective of this research study is to address the problem of energy planning challenges by developing quantitative modelling tools which capable of determining optimal spatially disaggregated energy supply chain network with embedded environmental impact analysis over long-term horizons under demand uncertainty with application to Thailand. Throughout the research, each design issue including (1) dealing with multi-period long-term energy system modelling, (2) capturing uncertainty in energy demand, (3) taking into account geographical location, (4) focusing on renewable energy such as energy from biomass and waste, should be investigated.

1.2 Thesis Outline

The thesis is organised as follows:

- Chapter 2 provides a review of existing energy planning models

- Chapter 3 describes the energy situation in Thailand and introduces a multi-period deterministic environmental conscious energy system optimisation model over a long-term planning horizon at a national level using Thailand's energy system as a case study.

- Chapter 4 reformulates the multi-period deterministic model to a scenario-based multi-period three-staged stochastic energy system optimisation model over a long-term planning under uncertainty in energy demand.

- Chapter 5 establishes the spatially disaggregated nature of an energy system in a national level by considering different regions of a nation as grids. The work in Chapter 3 is revisited to incorporate the spatial nature to develop a multi-period spatial energy system optimisation model over a long-term planning horizon at a national level.

- Chapter 6 revisits the work in Chapter 5 to concentrate only the Biomass-to-Energy supply chain network, considering different types of biomass as

sources of renewable energy to form a Biomass-to-Energy spatial energy system optimisation model over a long-term planning horizon at a national level with application to Thailand.

- Chapter 7 considers the current waste management situation in Thailand and proposes different Waste-to-Energy supply chain networks to create a higher degree of sustainability for the overall energy system of Thailand. This chapter modifies the work in Chapter 6 to describe a Waste-to-Energy spatial energy system optimisation model over a long-term planning horizon at a national level.

- Chapter 8 concludes the thesis by providing a summary of the work that has been done, while also presenting possible future research directions.

Chapter 2

Literature Review

2.1. Review of energy planning models

The history of the energy planning discipline started in the 1960s [Schlenzig, 1998] when the first studies which focused on energy supply were carried out. However, energy planning caught serious attention only after the 'Gulf-Crisis' in the early 1970s. The oil crisis caused countries to give special attention to critical assessment of fuel reserves, rational use and conservation of resources and long-term energy planning. The aim was to study the best way an economy could adapt, for example, to an abrupt change in availability of crude oil as a primary energy source. Energy models based on single energy carriers were no longer sufficient. The most typical energy planning models developed at this occasion are MESSAGE (a linear programming model developed at the IIAASA) [Messner and Strubegger, 1995], EFOM (a linear programming model developed for the European Commission) [Voort, 1985], and MARKAL (a linear programming model developed for the IEA) [Fishbone et al, 1983] [Goldstein, 2001]. The methodology used in all these models is Optimisation, which allows the convenient computation of a partial equilibrium (P.E.) on energy markets. Examples of other representative energy planning models are MIS, MACRO, MEDEE, MAED, AIM, MESSAGE-MACRO, and MESSAGE-MACRO [Lapillonne, 1983][Beeck, 1999][Morita et al., 1994][Morita et al, 1996][Grubler, 1999][IRG, 1999].

As, MARKAL is one of the most recognised models which has been applied to many countries around the world, the MARKAL model is explained in more detail below.

MARKAL is a dynamic linear programming model which uses the bottom-up energy system modelling approach for analysing energy systems for one or several regions. The model provides a technology-rich basis for estimating energy dynamics over a multi-period horizon. MARKAL depicts both the energy supply and demand side of the energy system. MARKAL provides policy makers and planners in the public and private sector with extensive detail on energy producing and consuming technologies [Fishbone et al, 1983] [Goldstein, 2001] [Nguyen, 2005] [Fishbone et al, 1983] [Jebaraj and Iniyan (2006)].

The model was developed by a consortium of OECD countries under the aegis of the International Energy Agency (IEA) in the late 1970's. The formulation of MARKAL is currently written in the General Algebraic Modelling System (GAMS) modelling language. One key features of MARKAL is the *Reference Energy System* (RES) which is typically a flowchart showing all energy carriers involved with primary supplies, conversion, processing, and end-use demand for energy services. The flow chart in Figure 2.1 shows a simplified RES [Nguyen, 2005][Goldstein, 2001] [Loulou, 2004]. The MARKAL energy system may be thought of as a network of five kinds of element, energy sources, sinks, technologies, demands, commodities The relationship among these various entities are to be represented in the form of a network referred to as the Reference Energy System (RES) mentioned above [Nguyen, 2005].

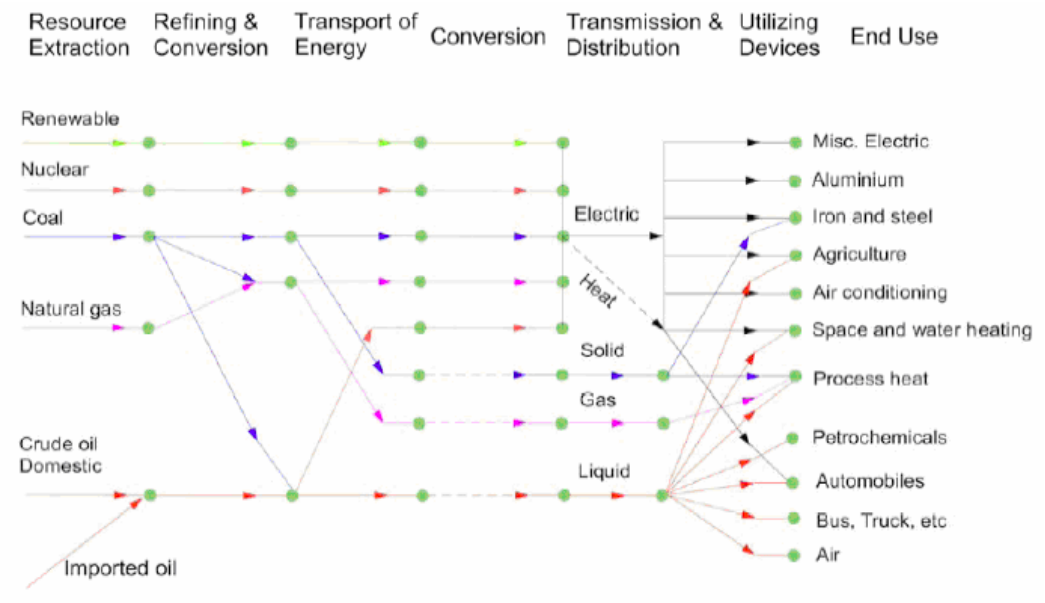


Figure 2.1: Simplified Reference Energy System (RES)

Many modifications were made to the basic MARKAL model. The first model was formulated as a linear programming (LP) application. It was followed by a non-linear programming (NLP) formulation to account for macro-economic growth, stochastic programming (SP) to address future uncertainties, mixed integer programming (MIP) techniques to model endogenous technology learning, and to model multiple regions (NLP/LP). The publications related to MARKAL family of models include [Seebregts, 2001] [Hamilton et al 1992] [Manne, 1992] [Gielen et al., 1998] [Condevaux-Lanloy, 2000] [Wallace, 1995] [Ybema at al., 1998] [Kanudia, 1998] [Mattsson 1997][Barreto and Kypreos, 1999] [Barreto and Kypreos, 2001] [Barreto and Kypreos, 2002] [Grubb, 2002].

A detailed literature review of energy models focusing on national levels up to the year 2004 has been presented by Jebaraj and Iniyan (2006) and Nguyen (2005). In the literatures, energy models have been categorised into many types including energy-planning models, energy supply-demand models, forecasting models, renewable energy models, emission reduction models, energy models based on neural networks and optimisation models. Moreover, Hiremath et al (2007) presented a modelling and application review of decentralised energy planning. The authors classified energy models into optimisation models, decentralised energy models, energy supply-demand driven models, energy and environmental planning models, resource energy planning models and finally energy models based on neural networks.

Furthermore, more energy models that were developed for energy systems planning in various conditions can be found in Cai et al. (2008), Naughten (2002), Wang (2007), Yao et al. (2006), Kambo et al. (1991), Nilsson and Martensson (2003), Li et al. (2004), Kaewniyompanit et al. (2006), Lin et al. (2008), Berglund and Soderholm (2006), Endo and Ichinohe (2006), Turtona and Barreto (2006).

2.2. Uncertainty in energy system modelling

The long term analysis of an energy system is fraught with uncertainties. Uncertainty issues stem from varying assumptions of modelling, model input, calculation techniques and other exogenous process assumptions, and greatly affect results. The

accuracy of the data input to the model determines the level of uncertainty in the model. Various possible uncertainties in data input to energy planning include variations in demand of energy in the future, future impact of climate change, variations in critical economic parameters (costs of resources, technologies, Fuel prices, Exchange and Interest rates), unknown performance of new technologies, unknown amount of potential resources.

In the past decades, much research has been carried out to deal with modeling various uncertainties in many areas including energy systems planning. The three main methods that have been receiving attention are stochastic mathematical programming, fuzzy programming and interval programming. The stochastic mathematical programming and fuzzy programming approaches express uncertainties as probabilistic distributions. On the other hand, interval programming defines uncertainties as interval numbers [Muela et al., 2007] [Lin and Huang, 2008] [Cai et al. (2009)] [Lin et al. (2009)] [Lu et al. (2009)] [Rentizelas et al. (2009)].

2.2.1 Stochastic Programming

Since 1960, the stochastic mathematical programming method has been developed and published by many authors. Anderson (1968) was one of the earlier researchers which used a stochastic programming method for the optimisation of a waste management system. As the deterministic representations of stochastic programming problems are excessively large, Birge (1985) developed the decomposition and partitioning methods for the multistage stochastic linear programs. Birge and Louveaux (1988) introduced a multicut algorithm for two-stage stochastic linear programs. Gassmann (1990) described an implementation of a nested decomposition algorithm for the multistage stochastic linear programming problem. Eiger and Shamir (1991) formulated a stochastic optimisation model for a multi-reservoir system with uncertain inflows and water demands which was solved by the Finite Generation Algorithm. The chance constraints were used to capture the uncertainties. Ruszczynski and Swietanowski (1997) described a method to improve the regularised decomposition method for two stage stochastic linear problems. Beraldi et al. (2000) introduced parallel algorithms to solve two-stage stochastic linear programs with

robustness constraints. The algorithm was based on a primal-dual path-following interior point algorithm. Dai et al. (2000) considered the convergence properties of two-stage stochastic programming. Zhao (2001) investigated a log-barrier method with Benders decomposition for solving two- stage stochastic linear programs.

Stochastic programming has been applied to many problems including financial planning, supply chain management, economic policy analysis, waste management, energy planning and many other applications. The stochastic mathematical programming approach is agreed by many researchers to be one of the most suitable methods for modelling planning problems under uncertainties [Krukamont and Tezuka, 2007] [Kann and Weyant, 2000] [Morgan and Henrion, 1990].

From all commercial national energy systems modelling tools mentioned above, a few bottom-up models have been developed further to include various uncertainties in their formulations. For example, a stochastic version of the MARKAL model has been proposed to incorporate uncertainties in energy demand [Kanudia and Loulou, 1998] [Kanudia and Shukla, 1998]. The MESSAGE model has been modified to deal with uncertainties in costs of technologies and energy resources [Gritsevskyi and Nakicenovic, 2000]. A more recent bottom-up model has been developed by Krukanont and Tezuka (2007) to describe the energy system of Japan using two-stage stochastic programming to capture uncertainties in end-use energy demands, plant operating availability and carbon tax rate. The model can assist decision makers by analysing the investment cost of near-term capacity expansion under uncertainties. From the point of view of top-down modelling, Birge and Rosa (1995) developed the stochastic Global 2100 model to include the uncertainties in investment cost of global CO2 emission policy.

2.2.2 Fuzzy Programming

The stochastic programming method is often chosen by developers for modelling energy system planning under uncertainties. Although the method has been applied comprehensively, Sadeghi and Hosseini (2006) stated that it could not efficiently solve the uncertainty problems caused by fuzziness. For that reason, another method

has been introduced, namely fuzzy programming. Similar to stochastic programming, fuzzy programming has been applied to deal with uncertainties in many research areas including energy system planning problems. However, only a few researches have applied the fuzzy programming method to energy system planning at the national level. For example, Sadeghi and Hosseini (2006) developed a fuzzy linear programming (FLP) for energy supply planning using Iran as a case study. The model captured uncertainties of investment cost using fuzzy coefficients. Other literature on energy system planning using fuzzy programming method on a smaller scale can be found in Borges and Antunes (2003) and Muela et al. (2007). One of the earlier publications which evaluate the potential of fuzzy linear programming in assisting decision makers in energy system planning under uncertainty was reported by Canz (1996).

2.2.3 Interval Programming

The stochastic programming and fuzzy programming methods are effective for dealing with energy system planning problems with known probability density functions for input parameters. However, obtaining reliable probability density functions for various input parameters such as energy demand and investment cost can be very challenging. One of the methods to capture uncertainties in energy system modeling without probability distribution information is interval programming. The interval programming method expresses uncertainties as interval numbers rather than probability density functions. There is much research with regard to interval programming; however this has not been applied to energy system planning at the national level. On the other hand, many optimization models for air, water and waste management have been effectively developed using interval programming to tackle various uncertainties [Cai et al., 2007] [Huang et al., 2001a] [Huang et al., 2001b] [Huang, 1998] [Huang et al., 1995a] [Huang et al., 1995b] [Huang et al., 1994] [Huang et al., 1993] [Huang et al., 1992] .

Furthermore, one of the recent approaches to developing an optimisation model for energy systems planning was proposed by Lin et al. (2009) where all three methods were combined to formulate a hybrid interval-fuzzy two-stage stochastic optimisation

model for regional energy systems planning under various uncertainties. As the model integrated all three methods, the uncertainties can be presented as fuzzy numbers, probability density functions and interval numbers.

Cai et al. (2009) also recently proposed an interval chance-constrained optimisation model for community–scale renewable energy systems planning under uncertainty. The model allows uncertainties to be expressed as both probability distributions and discrete intervals.

Li et al. (2010) recently developed an inexact fuzzy stochastic programming approach for planning energy and environmental systems (EES) management under multiple uncertainties. The authors incorporated methods of interval parameter fuzzy linear programming and multistage stochastic programming with recourse into a mixed-integer linear programming framework. Similar to the work by Lin et al. (2009), the model can capture uncertainties in terms of fuzzy sets, probability distribution and interval values.

2.3. Review of biomass-based energy production models

Much research has been carried out to analyse the role of biomass in renewable-energy production. In order to successfully develop a biomass-to-energy facility, there are many components that investors have to be carefully considered. The components include the technology in converting biomass to energy, the type and availability of the biomass and also the cost of biomass supply chain. Many simulation models have been created to improve logistics operations of biomass supply chains. A review of some of the simulation models can be found in Rentizelas et al. (2009). Moreover, Mitchell (2000) provided an in depth review of modelling tools for biomass supply chains up to the year 1999.

As well as simulation techniques, optimisation techniques have also been applied into many models which are presented in many publications. For example, Cundiff (1997) proposed a linear programming approach for designing a herbaceous biomass delivery system. Mitchell et al. (1995) described a techno-economic assessment of biomass to

energy. Mitchell (2000) developed decision support systems for bio-energy applications. Tatsiopoulos and Tolis (2003) formulated a linear programming optimisation model to optimise the supply chain of cotton-stalk. Caputo et al. (2005) presented an optimisation model for economics of biomass energy utilisation in combustion and gasification plants.

The optimisation models mentioned earlier were formulated with the main objective of reducing the total cost of converting biomass into energy (biomass logistics and energy conversion costs), while at the same time assuming that there are demands for the produced energy. Therefore, those models do not take into account the real energy demand in their formulations. Rentizelas et al. (2009) stated that "In a practical case, one should first identify a suitable application for the biomass-to-energy facility and then examine the economic potential of exploiting the locally existing biomass types with the objective of satisfying real energy demand". Recently developed demand-driven optimisation models are reviewed below.

Nagel (2000a, 200b) developed a mixed-integer linear optimization model to determine an economic energy supply structure based on biomass. Only one type of biomass was utilised to supply the district heating demand in the state of Brandenburg, Germany. Nilsson and Hansson (2001) proposed a simulation model to supply average heating demand load from converting straw and reed canary grass into heat energy.

Freppaz et al. (2004) formulated an optimisation model for forest biomass exploitation for energy supply at a regional level. The model integrated the geographic information system (GIS) based techniques with a mathematical programming method to create a decision support system to determine the optimal plant locations, sizing and also biomass collecting and harvesting. The system was applied to a small region of Val Bormida, Savona district, Italy.

In Bruglieri and Liberti (2008), mixed-integer nonlinear programming models for optimising running and planning of a biomass-based energy production process have been developed. Spatial branch-and-bound type of algorithm has been used to solve the problems. The models are able to determine the optimal amount of biomass to be

produced or to buy, transportation of materials to the respective plants and plant site locations. The conversion technologies include liquid biomass plant, squeeze plant, compost plant dry plant and fermentation-distillation plant. The models consider various types of biomass as input, for example, maple, poplar, maize, sunflower, straw and wheat. The problem is structured so that there are several outputs from processing plants to reflect the real world (e.g., bio-ethanol as output of the fermentation-distillation plant).

Alfonso et al. (2009) pushed forward the concept of integration between GIS techniques and mathematical programming methods to optimise management and final energy use of distributed biomass resources in three districts of the Valencia region in Spain where logistics along with biomass resource properties, plant size, technologies and CO2 emission are considered as main factors. The model aims to determine the optimal locations of biomass plant from the point of view of logistics, energy application and employed technology. Many types of biomass including cereal straw, maize cobs, and fruit peels were applied to the model.

Rentizelas et al. (2009) presented a demand-driven optimisation model for multi-biomass (wheat straw, corn stalks cotton stalks, olive tree prunings and almond tree prunings) tri-generation (electricity, heating and cooling) energy supply where the main objective is to maximise the net present value (NPV) of the project. The model can provide the investor with the optimal location of the biomass-to-energy facility, the optimal size of the CHP unit and also the type, amount and location of biomass to be used. The model has been applied to the district of Thessaly, Greece.

Another integrated GIS and mathematical programming environmental decision support system (EDSS) for biomass-based energy production was developed by Frombo et al. (2009a). The demand-driven model considered long-term planning with regard to optimisation of biomass plant locations, technologies (direct combustion, gasification and pyrolisis) and harvested biomass. The system has been applied to the community of Val Bormida, inside the Savona Province, Italy. A strategic decision model for planning woody biomass logistics for energy production has also been proposed by Frombo et al. (2009b). The literature described the strategic planning level in detail. The factors that differentiate the model from the above mentioned ones

consist of the possibility to include different types of biomass-to-energy technologies and the introduction of different slope classes of the territory. However, this model assumes that a plant location has already been selected.

Apart from the approaches mentioned above, systems engineering and modeling approaches, in particular the state-task-network (STN) has also been applied to enhance the decision-making for the biomass supply chain. Dunnett et al. (2007) investigated the use of STN in developing a mixed integer linear programming (MILP) optimization model for the simultaneous design and operations scheduling of a biomass to heat supply chain. The model covers various factors affecting biomass to heat supply chains including harvested yield, crop moisture content, ambient drying rates and seasonal demand. Previous literature using systems engineering approaches can be found in De Mol et al. (1997), Cundiff et al. (1997), Gigler et al. (2002) and Gunnarsson et al. (2004).

Moreover, Eksioglu et al. (2009) also presented a mixed integer programming (MIP) model that analyzes and designs the supply chain of biomass to bio-refinery in production of c-ethanol biofuel. The supply chain problem is structured as a network design problem. The network design is built from only two harvesting sites, two potential locations for collection facilities, two potential locations for bio-refineries and two blending facilities. The model has been applied to ethanol production in Mississippi. Furthermore, supply chain management for biomass to bio-refineries is described in Hamelinck et al. (2005), Sims and Venturi (2004).

As biomass is not the only renewable energy resource, many optimization models were proposed for investigating and evaluating effects of renewable energy resources (solar wind, biomass and bio-energy) and associated conversion technologies in producing energy for sustainable development. The models can be found, for example in Jebaraj and Iniyan (2006), Cai et al. (2009).

2.4. Review of municipal solid waste management models

Several approaches have been used to create the most suitable strategies for waste management options in many regions around the world. The approaches consider various aspects of waste management including capacity expansion, transportation, economic, legislative, technical, and environmental.

Shmelev and Powell (2006) reviewed previous and current methods for municipal solid waste management decision-making. Some of the popular methods are life cycle inventory (LCI), impact assessment (EIA), geo-information system (GIS), multi-criteria decision analysis (MCDA) and optimisation. The approach used for modelling municipal solid waste management in this thesis is the latter approach which is consistent with the method used in previous models presented in this thesis.

Since the 1960s, a large number of MSW-management models using operations research methods have been developed and applied to many cities in the world.

2.4.1 Linear programming (LP)

Anderson, (1968) was the first to originate economic optimisation of a waste management system. Kirca and Erkip (1998) created a LP model to determine transfer station locations in the MSW management system of Istanbul, Turkey. Hsieh and Ho, (1993) introduced optimisation of a solid waste disposal system by a linear programming technique. Kuclar (1996) formulated an optimisation model for solid waste collection in Brussels.

2.4.2 Mixed-integer linear programming (MILP)

Baetz, (1990) advanced forward optimisation and simulation of waste management capacity planning. Kuhner and Harrington, (1975) initiated a MILP model to optimise a regional waste management system. Or and Curi (1993) suggested a MILP model to minimise cost for waste collection and transportation costs in the City of Izmir, Turkey. Chen et al. (2000), Li et al. (2003) and Xue et al. (2004) developed a

optimisation model for MSW in medium to small cities in China. Chang et al. (2005) proposed integer programming for sustainable development of a material recovery facility in the City of San Antonio, Texas, USA. Fiorucci et al. (2003) formulated a decision-support-system (DDS) for solid waste-management in the City of Genova, Italy.

The above list of publications reviewed deterministic optimisation models for waste management systems. However, there are many uncertainties that may exist in modelling the waste management system. The following section presents previous research on waste management systems under uncertainties. Most of them can be categorised into stochastic, fuzzy and interval mathematical programming methods.

2.4.3 Stochastic mathematical programming

Masqood and Huang (2003) formulated a two-stage interval-stochastic programming model for waste management under uncertainty. Li et al. (2008) applied integrated two-stage stochastic programming to the development of long-term waste-management in the City of Regina, Canada. Li and Huang (2006) advanced an inexact two-stage mixed-integer linear programming (ITMILP) model to tackle long term planning of waste management in the City of Regina. Li and Huang (2007) proposed an inexact two-stage chance-constrained linear programming (ITCLP) method for planning waste management system. The model incorporates the two-stage and chance-constrained methods within a general interval-optimisation framework to tackle uncertainties. Lu et al. (2009) presented an inexact dynamic optimisation model for MSW-management in association with greenhouse gas emission control.

2.4.4 Fuzzy mathematical programming

Zou et al (2000) introduced fuzzy linear programming for waste flow allocation planning. Chang and Wang (1997) developed a fuzzy goal programming approach for waste management. Their objectives in the optimisation model include economic costs, noise control, air pollution control and traffic congestion limitations. More publications that deal with uncertainties using fuzzy programming in waste

management systems can be found in Chang and Lu (1997), Haung et al. (1993, 1995, 2001), Haung et al. (2002) and Zeng and Trauth (2005).

2.4.5 Interval mathematical programming

Huang et al. (1997) utilised interval-parameter programming methods for solid waste planning and capacity expansion under uncertainties in the Regional Municipality of Hamilto-Wentworth, Ontario, Canada.

Several authors proposed optimisation models with economic aspects as their main objective. However, solid waste management is a complex problem where having the economic aspect as the only objective may not be enough to represent the problem in the real world. Therefore to solve the issue, many researchers have applied the multi-objective mathematical programming method to their models where other components to modelling solid waste management such as legislation, environmental and social aspects were also considered as their objectives.

2.4.6 Multi-objective programming

Thomas et al. (1990), Chang and Wang (1996) and Mincirardi et al. (2002) introduced multi-objective mixed-integer linear programming for solid waste management models that take into consideration both the environmental and economic issues. Sakawa and Yano (1985) and Chang et al. (1997) tackled the optimisation of a solid waste management system by using fuzzy multi-objective programming techniques. Costi et al. (2004) produced a decision model for urban solid waste management that addressed both the economic and environmental aspects. Minciardi et al. (2008) described a multi-objective non-linear optimisation model of solid waste flows that take into account economic costs, unrecycled waste, sanitary landfill disposal and environment impact. Su et al. (2008) proposed an IMODP model to tackle the dynamic, interactive and uncertain characteristics of MSW-management in the city of Fo Shan, China.

2.5. Summary

The previous studies indicate that many commercial large-scale optimisation models for energy systems planning at the national level over a long-term have been developed and applied to many countries around the world. The general objectives of the models were to describe interactions among energy, economy and environment. Some of the models were proposed to assist decision makers in suggesting capacity expansion of power plants while minimising economic costs of selected country. However, only a few have been applied to developing countries using real data, in particular Thailand.

Apart from the commercial energy systems planning models, many small-scale optimisation models for energy systems planning have also been introduced, each designed to tackle the problems from different angles. Differences between the models include the model purpose, the model structure, analytical approach, study methodology, mathematical approach, geographic coverage, sectoral coverage, the time horizon, and data requirements [Schlenzig, 1998] [Beeck, 1999] [MIT, 1997].

However, a few researchers in the area of energy systems planning commented that the previous studies could not fully represent the real world energy systems planning problems in term of the complex linkages throughout energy production processes and energy usage by different sectors including social and environmental aspects in a multi-period and multi-objective context [Cai et al., 2009].

Many of the studies effectively captured the uncertain nature of the planning problems, which were based on stochastic programming, fuzzy programming and interval programming methods. On the other hand, only a few commercial large-scale energy models at the national level can express uncertainties in their general framework.

Furthermore, only a few studies consider the *spatial* nature of the energy systems planning. In order to fully represent the complex structure of an energy system, it is important to realize the overall supply chain network of the system. The supply chain

comprises different parts including location and amount of resources around the selected region, locations of potential power plants, areas of energy demand, distances between locatiosn of resources and power plants, distances between locations of power plants and areas of energy demand and transportation methods.

Of all the different approaches reviewed, the bottom-up technology oriented MARKAL model offers the most suitable framework for energy systems modelling at the national level. One key features of MARKAL is the *Reference Energy System* (RES) which is typically a flowchart showing all energy carriers involved with primary supplies, conversion, processing, and end-use demand for energy services. However, MARKAL lacks the ability to incorporate the complexity of supply chain network of spatial energy systems.

One of the main objectives of the work described in this thesis is to develop an optimisation model for spatial energy systems planning with application to Thailand. Before achieving the objective, some models were formulated to demonstrate different methods for energy systems modelling. These models are explained in Chapter 3, 4 and 5 of this thesis.

Thailand is a country that is filled with different types of biomass resources such as rice husk and rice straw. As the previous models only consider different types of biomass resources as a whole, a spatial optimization model for energy production from different types of biomass has been presented where real data related to Thailand has been used.

Furthermore, as Thailand currently lacks the knowledge and experience in managing municipal solid waste (MSW) along with a new policy proposed by the government of Thailand to promote capacity expansion of Waste-to-Energy power plants in Thailand, a spatial optimization model for energy production from solid waste with application to Thailand has been developed and explained in Chapter 7.

The energy situation of Thailand along with the first version of the model is described in the next chapter.

Chapter 3

Multi-Period Deterministic Energy System Modelling

3.1 Introduction

The previous chapter gave a review of some major energy planning models. In this chapter, prior to the development of a multi-period deterministic energy system optimisation model over long-term planning horizon at the national level, the energy situation of Thailand and the problem facets of modelling an energy system are described. The energy system of Thailand is used as the case study for all models developed in this Thesis.

3.1.1 Energy Situation in Thailand

The energy situation in Thailand can be described by four main components including the domestic primary energy production, imported energy, exported energy and the final energy consumption. The main sources of primary energy available in Thailand include crude oil, condensate, natural gas, lignite and renewable energy sources such as biomass, waste, hydro, wind, geothermal and solar. It is worth noticing that Thailand does not have high quality coal such as bituminous coal as energy reserve, only lignite is available. The list of energy production technologies currently in operation in Thailand is shown in Table 3.5.

Moreover, the domestic primary energy production, imported energy, exported energy and the final energy consumption in 2004 were 50,140 ktoe, 57,714 ktoe, 8,388 ktoe and 61,262 ktoe. Furthermore, the total value of energy imported was 560,702 million

Baht. The total value of energy exported was 109,520 million Baht [DEDE, 2005a] [DEDE, 2005c].

The detailed energy situation in Thailand in 2004 is described in DEDE, 2005a and DEDE, 2005b. A summary of the four components is shown in Table 3.1 to Table 3.4 below.

Table 3.1: Domestic Primary Energy Production in 2004

Primary Energy Supply	**Domestic**	**Unit**	**Change**
Crude Oil	4,297	kilo tons	-10.10%
Natural Gas	19,446	Ktoe	3.40%
Condensate	3,115	Ktoe	8.10%
Lignite	5,610	Ktoe	-6.80%
Hydro	1,340	Ktoe	-17.20%
Geothermal, Solar and Wind	2	Ktoe	0%
Fuel Wood and Biomass	16,030	Ktoe	8.30%
Total	50,140	Ktoe	4.10%

[DEDE, 2005a] [DEDE, 2005b]

Table 3.2: Imported Energy in 2004

Primary Energy Supply	**Import**	**Unit**	**Change**
Crude Oil	43,535	kilo tons	12.40%
Natural Gas	7,607	Ktoe	8.60%
Petroleum Products	1,511	Ktoe	71.80%
Coal and its products	4,749	Ktoe	5.50%
Electricity	289	Ktoe	37%
Total	57,714	Ktoe	12.50%

[DEDE, 2005a] [DEDE, 2005b]

Table 3.3: Exported Energy in 2004

Final Energy Consumption	**Export**	**Unit**	**Change**
Petroleum products	5467	ktoe	12.60%
Crude oil	2,835	ktoe	-
Natural gas	59	ktoe	-
Electricity	25	ktoe	-
Total	8388	ktoe	5.50%

[DEDE, 2005a] [DEDE, 2005b]

Table 3.4: Final Energy Consumption of Thailand in 2004

Final Energy Consumption	Electricity	Petroleum products	Coal	Lignite	Natural gas	Fuel Wood and Biomass	Unit
Agriculture	19	3,424					ktoe
Residential	2,108	1,046				5,216	ktoe
Mining	99	36					ktoe
Manufacturing	4,437	4,401	4,189	1,729	2,549	4,307	ktoe
Construction		171					ktoe
Commercial	3,136	730			27		ktoe
Transport	4	22,876			27		ktoe
Total	9,803	32,684	4,189	1,729	2,603	9,523	ktoe

[DEDE, 2005a] [DEDE, 2005b]

3.1.1.1 Thailand Reference Energy Infrastructure

The energy situation of Thailand can be best described by means of a balance sheet of the supply and consumption type of energy production. The balance sheet is given in Table 3.5. From the balance sheet, the reference energy infrastructure of Thailand in 2004 representing the activities and relationships of the energy system, depicting energy demand, energy conversion technologies, fuel mixes, and the resources required to satisfy energy demands could be built. It is graphically represented through a network diagram indicating energy flows and the associated process parameters of technologies employed in various stages of the energy system, which is given in Figure 3.1.

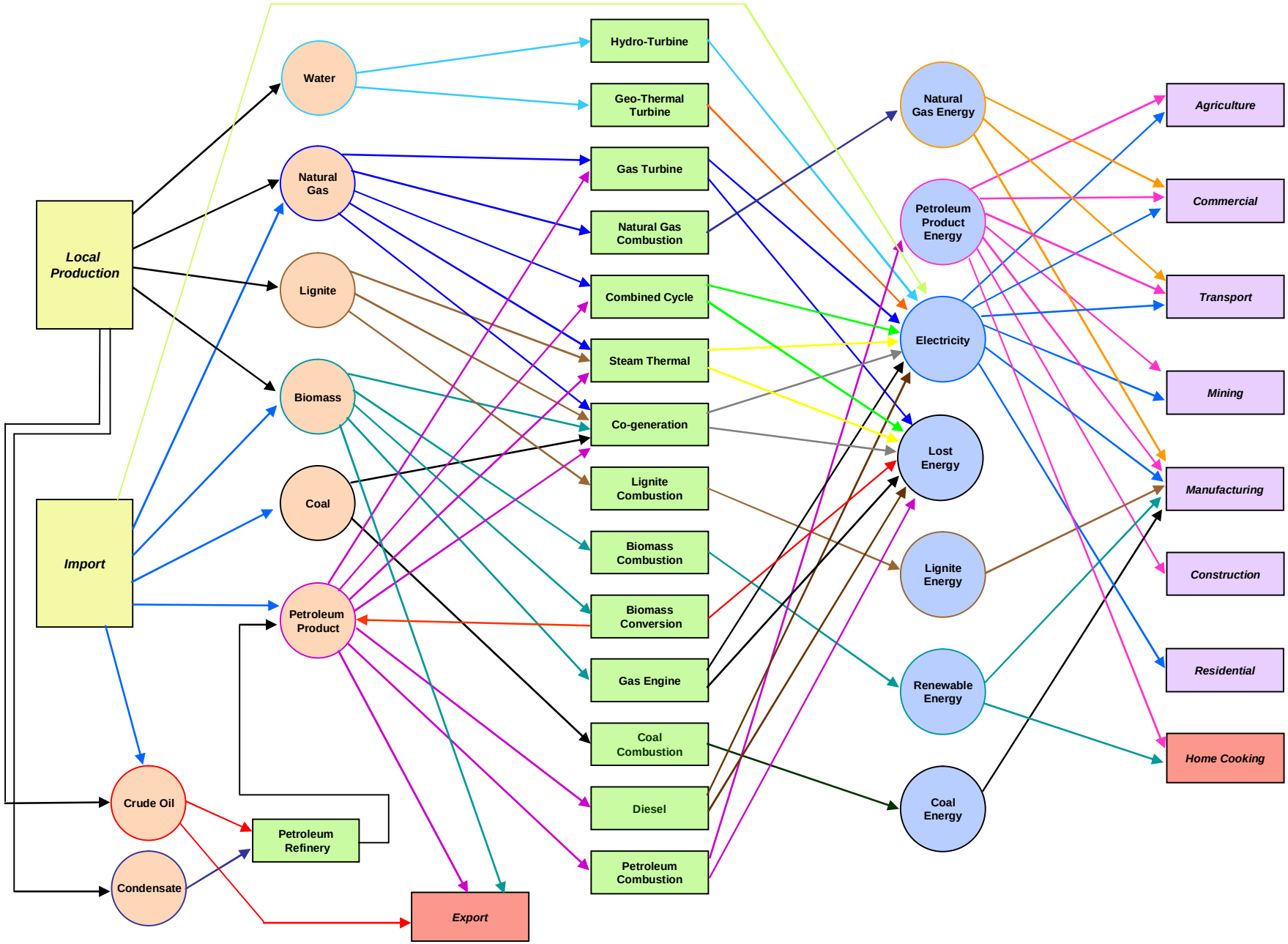
From the figure, it can be seen that the first stage of the energy system is the production of petroleum products from crude oil and condensate. The second stage is the production of electricity and heat energy through various conversion technologies from primary energy sources such as coal, lignite, natural gas, biomass and petroleum products. The third stage is the final energy consumption stage by different sectors such as residential, commercial and transport sectors.

Table 3.5: Balance sheet of the supply and consumption type of energy production in Thailand (ktoe)

Supply and Consumption / Type(ktoe)	*Coal*	*Lignite*	*Natural Gas*	*Crude Oil*	*Con-densate*	*Petroleum Product*	*Electricity*	*Biomass*	**Total**
Domestic production		5,610	19,446	4,297	3,115			14,694	47,162
Imports	4,749		7,607	43,535		1,511	289	23	57,714
Exports				-2,827		-5,467	-32	-3	-8,329
Stock Change		216		1,680	-330	-523			1,043
Petroleum Refineries				-46,498	-438	37,140			-9,796
NG Processing Plants						1,991			1,991
Hydro Power Plants							1,340		1,340
Steam Thermal Plants		-4,096	-4,323			-1,606	3,535		-6,490
Gas Turbine Plants			-343			-2	97		-248
Combined Cycle Plants			-12,980			-89	5,413		-7,656
Diesel Plants						-4	1		-3
Cogeneration Plants	-560	-1	-2,266			-14	1,152	-730	-2,419
Gas Engine							1	-12	-12
Geothermal Plants							2		2
Biomass Conversion						242		-4,449	-4,207
Total Transformation	-560	-4,097	-19,912	-46,498	-438	37,658	11,541	-5,191	-18,220
Own uses			-4,538				-317		-4,855
Losses				-187			-850		-1,037
Non Energy uses					-2,347	-495	-828		-3,670
Final Energy Consumption	-4,189	-1,729	-2,603	0	0	-32,684	-9,803	-9,523	-60,531
All Usage	-4,749	-5,826	-27,053	-46,685	-2,785	-34,894	-11,798	-14,714	

[DEDE, 2005a] [DEDE, 2005b] [DEDE, 2005c] [DMF, 2005a]

Figure 3.1: Thailand Reference Energy Infrastructure in 2004



3.2 Problem facets

3.2.1 Complexity of the problem

Energy planning at a national level is a highly complex problem. The inter-linkages between resource depletion, energy demand, economy and the environment add complexity to the problem. Changing governmental policies and macroeconomic uncertainties and advancement in new technologies also add to the complexity of decision-making in the energy sector.

Similar complexities exist within the context of operational planning, distribution and pricing. In addition to these general complexities, energy and economy dynamics specific to developing countries such as Thailand present unique challenges to energy policy modellers.

3.2.2 Data Collection

One of the most important parts of creating a complete model that can represent the complexity of the real-world problem is data collection. The objective of this research is to create an optimisation model that helps in making decisions to create the most efficient energy systems in Thailand. The process of collecting complete sets of data to represent the real-world energy systems is one of the main challenges. Most of the data presented in this Thesis are from publications and government reports. Some data is very difficult to obtain due to confidentiality and the scale of the data required. Therefore, it is necessary to use estimated values based on theoretical assumptions. However, the data is still believed to be representative of Thailand's energy system. The data required for energy system modelling is described in section 3.5.2.

The proposed model structure for the long-term energy planning optimisation model with application to Thailand is described in the next section.

3.3 Model Structure

From the reference energy infrastructure of Thailand, a proposed model structure for a multi-period deterministic energy system optimisation model is developed. The model structure consists of four components including input resources, energy production technologies, energy and time. Each component is described in more detailed below.

3.3.1 Input Resources

The input resources are the primary energy sources such as crude oil, condensate, different types of coal, petroleum products, natural gas. The renewable resources such as solar, wind, hydro and biomass are also included in this component of the model. The input resources are represented by index r in the proposed mathematical formulations of the deterministic model described in section 3.4.

3.3.2 Energy Production Technologies

A number of energy production technologies could be utilised to produce energy at different costs, performances and emissions. A total of 35 power generation technology options are considered in this proposed model as well as a petroleum refinery technology to transform crude oil and condensate to petroleum products. In addition to the described technologies, 5 direct usages of resources including coal, natural gas, lignite and petroleum products are also included in this component. Therefore, a total of 41 technologies are included in this energy production technologies component.

From the 35 power production technologies taken into account in this proposed model, 17 of them are the existing technologies which are operating in Thailand, the rest are other advanced conversion technologies such as nuclear, advance gas combined cycle, and integrated gasification combined cycle (IGCC). The technologies are indicated by index i

3.3.3 Energy

Three types of energy are required from the energy production facilities to fulfill the energy demand. The three types are electricity energy, heat energy and petroleum energy which are given by index v.

3.3.4 Time

Apart from the above components, the time element is also presented in the mathematical formulation to account for variations of different parameters such as the predicted demand from one time period to another. In implementing a multi-period model, the time element is required. The time elements are indicated by index t

3.4 Mathematical Formulation

The proposed multi-period deterministic energy system optimisation model is formulated as a linear programming model (LP). The mathematical formulation for the proposed model can be categorised into two groups which are the objective function and the constraint. The notation used in describing the formulation is presented below.

3.4.1 Notation

Indices

b	=	Both resource and energy vector
i	=	Process of energy production
r	=	Resource for energy production (Raw material)
t	=	Time period
v	=	Energy vector

Parameters

$CostFOM_i$	=	Fixed operating and maintenance cost of process i ($/ktoe/year)
$CostVOM_i$	=	Variable operating and maintenance cost of process i ($/ktoe)
$CostIV_i$	=	Investment cost for newly-built capacity i ($/ktoe)
$CostR_{rt}^{domestic}$	=	Cost of domestic resource r during time period t ($/ktoe)
$CostR_{rt}^{import}$	=	Cost of imported resource r during time period t ($/ktoe)
$CostV_{vt}^{import}$	=	Cost of imported energy v during time period t ($/ktoe)
α_{vi}^{output}	=	Proportion of energy v produced per unit of process i
γ_{ri}^{input}	=	Proportion of resource r required for unit amount of process i
LF	=	Load factor
TL	=	Percentage of transmission loss
Dem_{vt}^{all}	=	Total demand of energy v in time period t (ktoe)
$Ryear_r^{\max}$	=	Maximum resource r available per year ((ktoe/year)
$R_r^{\max}$	=	Maximum total resource r available (ktoe)
$conE$	=	Ratio for converting ktoe into MW (MW/ktoe)
GHG_i^{rate}	=	Green house gas emission rate for process i (gCO_2/MW)
$Emi^{\max}$	=	Maximum emission (gCO_2)
β	=	Emission factor
DF_t	=	Discount factor during time period t

Variables

dp_{rt}	=	Decision variable for using potential domestic resource r in time period t (ktoe)
dri_{rt}	=	Decision variable for importing resource r in time period t (ktoe)
dvi_{vt}	=	Decision variable for importing energy v in time period t (ktoe)
dve_{vt}	=	Decision variable for exporting energy v in time period t (ktoe)

$dinv_{rt}$	=	Decision variable for inventory of unused resource r in time period t (ktoe)
U_{rit}	=	Usage of resource r of process i in time period t (ktoe)
C_{it}	=	Capacity of process i in time period t (ktoe)
C_{it}^{MW}	=	Capacity of process i in time period t (MW)
E_{it}	=	Expansion of process i in time period t (ktoe)
E_{it}^{MW}	=	Expansion of process i in time period t (MW)
EP_{vit}	=	Production of energy vector v of process i in time period t (ktoe)
EP_{vt}^{net}	=	Net production of energy vector v of process i in time period t (ktoe)
RP_{rt}	=	Production of resource r in time period t (ktoe)
UE_{rit}	=	Usage of resource r of process i in time period t (ktoe)
AU_{rt}	=	Total usage of resource r in time period t (ktoe)
$OMCost_{it}$	=	Operating and Maintenance cost of process i in time period t ($)
$FOMCost_{it}$	=	Fixed O&M cost of process i in time period t ($)
$VOMCost_{it}$	=	Variable O&M cost of process i in time period t ($)
$RCost_{rt}^{domestic}$	=	Cost of domestic resource r used in time period t ($)
$RCost_{rt}^{import}$	=	Cost of imported resource r used in time period t ($)
$VCost_{vt}^{import}$	=	Cost of imported energy v in time period t ($)
$InvCost_{it}$	=	Investment cost for new process i in time period t ($)
Emi_{it}^{year}	=	Emission from process i in time period t (gCO_2)
$Cost^{total}$	=	Total cost ($)
Emi^{total}	=	Total emission (gCO_2)

The multi-period deterministic energy system optimisation model formulation consists of two types of entities; constraints and objective functions, which are described below.

3.4.2 Objective Function

In this model, the objective is to minimise the total cost of the system, appropriately discounted over the planning horizon. Each year, the total cost includes the following elements:

- **Investment costs**

Investment costs include all capital investments required to make the incremental capacity operational for all technologies plus any transmission and/or distribution investment costs of conversion technologies. No account is taken of the costs already invested in the energy system, which existed at the start of the optimisation period.

The total investment cost of process i during time period t ($InvCost_{it}$) can be expressed in terms of capacity of newly-built processes i (E_{it}) and the investment cost of each newly-built capacity i as follows:

$$InvCost_{it} = E_{it} \cdot CostIV_i \qquad \forall i,t \qquad (3.1)$$

where

$CostIV_i$ is the investment cost for newly-built capacity i

- **Operation and Maintenance (O&M) costs**

The O&M costs of process i during time period t ($OMCost_{it}$) can be expressed as the sum of Fixed O&M costs ($FOMCost_{it}$) and Variable O&M ($VOMCost_{it}$) of each process i during time period t. The variable $OMCost_{it}$ is given in the form:

$$OMCost_{it} = FOMCost_{it} + VOMCost_{it} \qquad \forall i,t \qquad (3.2)$$

$$FOMCost_{it} = C_{it} \cdot CostFOM_i \qquad \forall i,t \qquad (3.3)$$

$$VOMCost_{it} = C_{it} \cdot CostVOM_i \qquad \forall i,t \qquad (3.4)$$

where

$CostFOM_i$ is the fixed O&M cost for capacity i

$CostVOM_i$ is the variable O&M cost for capacity i

- **Domestic Raw material cost**

The cost of domestic raw material r used during time period t ($RCost_{rt}^{domestic}$) can be described in term of amount of domestic raw material used r during time period t (dp_{rt}) and the domestic cost of each raw material r ($CostR_{rt}^{domestic}$) as follows:

$$RCost_{rt}^{domestic} = dp_{rt} \cdot CostR_{rt}^{domestic} \qquad \forall r,t \qquad (3.5)$$

- **Imported Raw material cost**

The cost of imported raw material r used during time period t ($RCost_{rt}^{import}$) can be described in terms of amount of imported raw material r used during time period t (dri_{rt}) and the imported cost of each raw material r ($CostR_{rt}^{import}$) as follows:

$$RCost_{rt}^{import} = dri_{rt} \cdot CostR_{rt}^{import} \qquad \forall r,t \qquad (3.6)$$

- **Imported Energy cost**

The cost of imported energy v during time period t ($VCost_{vt}^{import}$) can be described in term of amount of imported energy v during time period t (dvi_{vt}) and the imported cost of each energy v ($CostV_{vt}^{import}$) as follows:

$$VCost_{vt}^{import} = dvi_{vt} \cdot CostV_{vt}^{import} \qquad \forall v,t \qquad (3.7)$$

In order to calculate the total cost over a period of time, it is important to incorporate the effect of the interest rate and the inflation rate to the model as well. The financial term for the effect of these rates is called the discount factor (DF_t).

The discount factor at year t (DF_t) can be described as a function of the interest rate (Int) and the inflation rate (Ifa) and time t. The parameter is given in the form:

$$DF_t = \left(\frac{1+Ifa}{1+Int} \right)^{t-1} \tag{3.8}$$

The total cost can be expressed as the following equation.

$$Cost^{total} = \sum_t \left(DF_t \cdot \left(\begin{array}{l} \sum_i InvCost_{it} + \sum_i OMCost_{it} \\ \sum_r RCost_{rt}^{domestic} + \sum_r RCost_{rt}^{import} \\ + \sum_v VCost_{vt}^{import} \end{array} \right) \right) \tag{3.9}$$

The objective function is to minimise the total cost which is given in the form:

$$\textbf{\textit{Minimise}} \qquad Cost^{total} \tag{3.10}$$

3.4.3 Constraints

Energy Production Constraints

Production variables and production constraints are formulated to describe the processes and conversion technologies of each model. Annual production of output b (both energy v and raw material r) from each process i, which is represented by EP_{bit}

can be described by parameter α_{bi}^{output} and variable C_{it}, where α_{bi}^{output} is the proportion of output b produced by process i. The expression for EP_{bit} is given in the form:

$$EP_{bit} = \alpha_{bi}^{output} \cdot C_{it} \qquad \forall b,i,t \qquad (3.11)$$

The production of output b for each process i in time period t can then be either used to supply the energy demand or can be exported. Moreover, as electricity energy is influenced by the load factor (LF) and also the transmission lost (TL). The net electricity energy production v in time period t (EP_{vt}^{net}) is given in the form:

$$EP_{vt}^{net} + dve_{vt} = LF \cdot \left((1-TL) \cdot \sum_i EP_{vit} \right) \qquad \forall v,t : v = electricity \qquad (3.12)$$

The net heat and petroleum energy production v in time period t (EP_{vt}^{net}) is given in the form:

$$EP_{vt}^{net} + dve_{vt} = \sum_i EP_{vit} \qquad \forall v,t : v \neq electricity \qquad (3.13)$$

where dve_{vt} is the decision variable for exporting energy v (the variable can also mean the safe stock of energy v)

As input raw materials such as petroleum products can also be produced by process i and included in variable EP_{bit}, the production of raw material r from process i in time period t RP_{rt} can be expressed as:

$$RP_{rt} = \sum_i EP_{rit} \qquad \forall r,t \qquad (3.14)$$

Resource Usage Constraints

The total resource usage r required by process i (UE_{rit}) can be described in term of process capacity, as the proportion of resource r required for process i, which is represented by γ_{ri}^{input} multiply by capacity of process i, which is represented by C_{it}. The expression for UE_{rit} is given in the form:

$$UE_{rit} = \gamma_{ri}^{input} \cdot C_{it} \qquad \forall r,i,t \qquad (3.15)$$

The total resource usage which is represented by, AU_{rt} can be expressed as the sum of resource usage r for all processes i . The variable is described in the form:

$$AU_{rt} = \sum_{i} UE_{rit} \qquad \forall r,t \qquad (3.16)$$

Energy Balance Constraints

The energy balance between the net production rate of energy v during time period t and the total demand can be expressed as follows:

$$EP_{vt}^{net} = Dem_{vt}^{all} - dvi_{vi} \qquad \forall v,t \qquad (3.17)$$

As the total energy demand may not be met by only the domestic energy production, the net production rate of energy v during time period t (EP_{vt}^{net}) must be equal to the total demand during time period t (Dem_{vt}^{all}) less the imported energy v during time period t (dvi_{vt}).

Resource Balance Constraints

The resource balance between the decision variable for using the available domestic resource r (dp_{rt}), the decision variable for using the imported resource r (dri_{rt}), the

resource r which is domestically produced (RP_{rt}) and the total resource usage r during time period t (AU_{rt}) is given in the form:

$$dp_{rt} = AU_{rt} - dri_{rt} - RP_{rt} \qquad \forall r,t \tag{3.18}$$

The total resource balance must be written to determine the total amount of raw material usage r and therefore demand of raw material r.

The amount of chosen domestic resource r in time period t (dp_{rt}) must be less than or equal to the maximum availability of resource r in year t which is given in the form:

$$dp_{rt} \leq Ryear_r^{\max} \qquad \forall r,t \tag{3.19}$$

where

$Ryear_r^{\max}$ is maximum resource r available per year

Furthermore, the total domestic resource usage throughout the planning horizon must be less than the total availability of resource r. The constraint can be expressed as:

$$\sum_t dp_{rt} \leq R_r^{\max} \qquad \forall r \tag{3.20}$$

where

$R_r^{\max}$ is the maximum total resource r available

Unit Conversion Constraints

In general the unit for the capacity of power plant is in MW. The following equations are formulated to convert capacity of process i during time period t in ktoe (C_{it}) to capacity in MW (C_{it}^{MW}).

$$C_{it}^{MW} = C_{it} \cdot conE \qquad \forall i,t \tag{3.21}$$

where

$conE$ is conversion ratio to convert ktoe into MW

The same applies to converting unit for expansion of capacity of process i during time period t in ktoe (E_{it}) to expanded capacity in MW (E_{it}^{MW}).

$$E_{it}^{MW} = E_{it} \cdot conE \qquad \forall i,t \tag{3.22}$$

Capacity constraints

For this proposed multi-period model. The capacity of process i in year t (C_{it}) can be expressed as the previous year's capacity of process i plus an expansion of process i in period t (E_{it}) which is given by:

$$C_{it} = C_{i,t-1} + E_{it} \qquad \forall i,t \tag{3.23}$$

The capacity constraints control the necessary capacities installed and the maximum expansion of capacity of newly-built processes. The rate of growth of technologies in this model is restricted by means of imposing explicit bounds on technology capacity.

Upper bounds are placed on the rate of market penetration for new energy technologies that are supposed to become available at specified points in the future. Bounds on technology capacity can be written as follows:

$$E_{it}^{MW} \leq E_{it}^{\max} \qquad \forall i,t \tag{3.24}$$

where

$E_{it}^{\max}$ is the maximum capacity expansion of process i in time period t

Emission constraints

The amount of emission released from process i during time period t (Emi_{it}^{year}) can be described in term of the capacity of process i in MW during time period t as:

$$Emi_{it}^{year} = C_{it}^{MW} \cdot GHG_{i}^{rate} \qquad \forall i,t \tag{3.25}$$

where

GHG_i^{rate} is the rate of emission releases for process i

Moreover, the total emission produced can then be described as:

$$Emi^{total} = \sum_{t} \sum_{i} Emi_{it}^{year} \tag{3.26}$$

To control the amount of emission produced from all processes, upper bounds are placed on the total amount of emission produced. The constraint is given in the form:

$$Emi^{total} \leq \beta \cdot Emi^{\max} \tag{3.27}$$

where

$Emi^{\max}$ is the maximum total emission produced by the network

β is the emission factor

By limiting the value of emission factor between 0 and 1, factor can be used to limit the total emission produced.

3.5 Case Study: Thailand Energy System

As mentioned earlier, the energy system of Thailand is applied as the case study for all models described in this thesis. The proposed multi-period deterministic energy system optimisation model is used to determine the optimal energy planning strategies for Thailand according to different scenarios which are described below.

3.5.1 Description of scenarios

This section describes three scenarios which are created to test the feasibility of the proposed multi-period deterministic energy system optimisation model. The scenarios are also designed to represent the possible real-world cases. The five scenarios are described below.

1) Optimising the proposed model without considering the existing energy infrastructure of Thailand.
2) Optimising the proposed model with consideration of the existing energy infrastructure of Thailand.
3) Same as scenario 2 but with the emission factor equal to 0.7 to see the effect of reducing the total emission by 30% to the energy planning strategy.
4) Same as scenario 2 but with the emission factor equal to 0.9 to see the effect of reducing the total emission by 10% to the energy planning strategy.
5) Same as scenario 1 but with interest rate and inflation rate equal to 4% and 2% respectively. (The previous 4 scenarios assumed that the interest rate and the inflation rate are the same)

The first scenario is implemented to determine the optimal structure for the energy system of Thailand if the current infrastructure had not been in place. The second scenario considers the future expansion to the existing infrastructure to the future long-term energy planning of Thailand. The third and fourth scenarios extend the second scenario to include the possible changes to the government policy on the maximum amount of GHG emissions permitted from the energy sector. The fifth scenario studies the effect of inflation rate and interest rate.

For all scenarios, the planning horizon is set to be 20 years. The planning horizon can be divided into three time periods with different energy demands. The duration of the first, second and third periods are 3 years, 7 years and 10 years respectively. The input data required for the proposed model is described below.

3.5.2 Input Data

In this section the specifications of various exogenous parameters for the establishment of the Thailand energy model is described. The exogenous parameters are grouped into four categories: resource data, technology data, demand data and financial data. These are necessary components for the determination of optimal energy planning strategy for Thailand.

3.5.2.1 Technology Data

The technology data necessitated by the proposed model is the input and output factors, and the capacities of existing energy production technologies in Thailand. The input and output factors are calculated from the expected heat rate of each of the power generation technologies. The full list of the power generation technologies considered in this proposed model is presented along with the heat rate and the conversion efficiencies used in this model are shown in Table 3.6. The heat rate and the costs of each technology are derived from various sources, including (CERI, 2005), (EIA, 2007), (EIA 2009,) and Breeze, 2005.

From the conversion efficiencies, the input and output factors for the power generation technologies can be derived. The input factors are the value of the raw material in ktoe to produce 1 ktoe of the associated output. The input and output factors shown in Table 3.7. Moreover, the list of direct usage processes and petroleum refinery processes along with their input and output factors are shown in Table 3.8. The input and output factors for petroleum refinery to produce petroleum products from crude oil and condensates are derived from data provided in DEDE, 2005a.

Table 3.6: Heat Rate and Efficiency for each power generation technology

Technology		**Efficiency From Heat Rate**	**Heat Rate Btu/kWh**
Nuclear	*Nuclear*	32.83	10400
Geothermal	*Turbine-Geo*	9.16	37259
Hydro	*Hydro*	33.02	10338
Wind Onshore	*Wind*	33.21	10280
Solar thermal parabolic	*Solar-TP*	33.21	10280
Solar Photovoltaic	*Solar-PV*	33.21	10280
Sub-critical Steam Pulverized Coal (bituminous)	*Sub-C SteamBC*	36.00	9483
Supercritical Steam Pulverized Coal (bituminous)	*Steam-BC*	40.00	8535
Supercritical Steam Pulverized Coal (lignite)	*Steam-LIG*	38.00	8984
Supercritical Steam Pulverized Coal (sub-bituminous.)	*Steam-SB*	40.00	8535
Sub-critical Steam Pulverized Coal (bituminous) with Flue gas desulphurization	*Sub-C SteamBC-FGD*	34.00	10041
Supercritical Steam Pulverized Coal (bituminous) with Flue gas desulphurization	*Steam-BC-FGC*	38.00	8984
Supercritical Steam Pulverized Coal (lignite) with Flue gas desulphurization	*Steam-LIG-FGC*	36.00	9483
Supercritical Steam Pulverized Coal (sub-bituminous.) with Flue gas desulphurization	*Steam-SB-FGC*	38.00	8984
Coal Integrated Gasification Combined Cycle	*IGCC*	41.09	8309
Coal Integrated Gasification Combined Cycle with Carbon Sequestration	*IGCC-CS*	35.15	9713
Biomass Integrated Gasification Combined Cycle	*BIGCC*	38.31	8911
Biomass Steam Cycle	*BSC*	26.26	13000
Oil Steam Turbine	*Steam-ThermalP*	35.94	9500
Gas Steam Turbine	*Steam-ThermalG*	35.94	9500
Oil/Gas Steam Turbine	*Steam-ThermalGP*	35.94	9500
Gas Internal Combustion Engine (ICE) - Diesel	*Diesel*	28.98	11780
Gas Internal Combustion Engine (ICE) Gas	*Gas-Engine*	28.98	11780
Combustion Gas Turbine Combined Heat Power (sub-bituminous)	*Co-generationSB*	61.38	5562
Combustion Gas Turbine Combined Heat Power (bituminous)	*Co-generationB*	61.38	5562
Combustion Gas Turbine Combined Heat Power (gas)	*Co-generationG*	61.38	5562
Conventional Gas Combined Cycle	*CCGT-G*	45.86	7444
Conventional Oil Combined Cycle	*CCGT-P*	45.86	7444
Advance Gas Combined Cycle	*ACCGT-G*	53.76	6350
Advance Oil Combined Cycle	*ACCGT-P*	53.76	6350
Advance Gas Combined Cycle with Carbon Sequestration	*ACCGT-GCS*	46.77	7300
Advance Oil Combined Cycle with Carbon Sequestration	*ACCGT-PCS*	46.77	7300
Conventional Combustion Gas Turbine (Petroleum Product)	*Gas-TurbineP*	31.38	10878
Conventional Combustion Gas Turbine	*Gas-TurbineG*	31.38	10878
Advance Combustion Gas Turbine	*Adv-Gas-TurbineG*	36.75	9289

[CERI, 2005][EIA, 2007] [EIA, 2009] [Breeze, 2005]

Table 3.7: Final Input ratio relative to Final Output of each technology

Technology	**Input Raw Material**	**Output**	**Final Input**
Nuclear	Uranium	Electricity Energy	3.0463
Turbine-Geo	Geo Energy	Electricity Energy	10.9136
Hydro	Water Energy	Electricity Energy	3.0281
Wind	Wind Energy	Electricity Energy	3.0111
Solar-TP	Solar Energy	Electricity Energy	3.0111
Solar-PV	Soar Energy	Electricity Energy	3.0111
Sub-C SteamBC	Bituminous	Electricity Energy	2.7778
Steam-BC	Bituminous	Electricity Energy	2.5000
Steam-LIG	Lignite	Electricity Energy	2.6316
Steam-SB	Sub-Bituminous	Electricity Energy	2.5000
Sub-C SteamBC-FGD	Bituminous	Electricity Energy	2.9412
Steam-BC-FGC	Bituminous	Electricity Energy	2.6316
Steam-LIG-FGC	Lignite	Electricity Energy	2.7778
Steam-SB-FGC	Sub-Bituminous	Electricity Energy	2.6316
IGCC	Bituminous	Electricity Energy	2.4338
IGCC-CS	Bituminous	Electricity Energy	2.8450
BIGCC	Biomass	Electricity Energy	2.6101
BSC	Biomass	Electricity Energy	3.8079
Steam-ThermalP	Petroleum Product	Electricity Energy	2.7827
Steam-ThermalG	Natural Gas	Electricity Energy	2.7827
Steam-ThermalGP	Natural Gas Petroleum Product	Electricity Energy	1.3913
Diesel	Petroleum Product	Electricity Energy	3.4505
Gas-Engine	Natural Gas	Electricity Energy	3.4505
Co-generationG	Natural Gas	Electricity Energy Heat Energy	3.2583
Co-generationBC	Bituminous	Electricity Energy Heat Energy	3.2583
Co-generationSB	Sub-Bituminous	Electricity Energy Heat Energy	3.2583
CCGT-G	Natural Gas	Electricity Energy	2.1804
CCGT-P	Petroleum Product	Electricity Energy	2.1804
ACCGT-G	Natural Gas	Electricity Energy	1.8600
ACCGT-P	Petroleum Product	Electricity Energy	1.8600
ACCGT-GCS	Natural Gas	Electricity Energy	2.1383
ACCGT-PCS	Petroleum Product	Electricity Energy	2.1383
Gas-TurbineP	Petroleum Product	Electricity Energy	3.1863
Gas-TurbineG	Natural Gas	Electricity Energy	3.1863
Adv-Gas-TurbineG	Natural Gas	Electricity Energy	2.7209

Table 3.8: Input and Output factors of others technologies

Technology	**Input Raw Material**	**Output**	**Final Input**	**Final Output**
Direct Coal Usage	Bituminous	Heat Energy	1	1
Direct LigniteUsage	Lignite	Heat Energy	1	1
Direct Natural Gas Usage	Natural Gas	Heat Energy	1	1
Direct BiomassUsage	Wood	Heat Energy	1	1
Direct Petroleum Usage	Petroleum Product	Petroleum Energy	1	1
Petroleum Refiniery	Crude Oil	Petroleum Product	1.2520	1
	Condensate		0.0118	

[DEDE, 2005a]

Table 3.9: Capacity of existing technologies in Thailand in ktoe

Technology	**Capacity (ktoe)**
Geothermal	0.226
Hydro	2579.213
Wind Onshore	0.145
Solar thermal parabolic	0.408
Supercritical Steam Pulverized Coal (Bituminous)	1014.39
Supercritical Steam Pulverized Coal (Lignite)	1808.05
Biomass Steam Cycle	440.18
Oil Steam Turbine	256.14
Gas Steam Turbine	1084.83
Oil/Gas Steam Turbine	2810.09
Gas Internal Combustion Engine (Diesel)	4.068
Combustion Gas Turbine Combined Heat Power (Sub-bituminous)	128.07
Combustion Gas Turbine Combined Heat Power (Bituminous)	135.604
Combustion Gas Turbine Combined Heat Power (Gas)	1143.59
Conventional Gas Combined Cycle	8666.542
Conventional Combustion Gas Turbine (Petroleum Products)	459.548
Conventional Combustion Gas Turbine	178.54
Petroleum Refinery	38831.718

[DEDE, 2005a] [DEDE, 2009a] [PDP, 2007].

Furthermore, the capacities of existing technologies in Thailand are shown in Table 3.9 [DEDE, 2005a] [DEDE, 2009a] [PDP, 2007].

To calculate the total emission produced by each technology, the CO_2 emission rates for each technology are required. The emission rates are shown in Table 3.10 [Spadaro et.al., 2000] [EIA, 2009].

Table 3.10: CO_2 emission rate for each technology

Technology	**Carbon emission gCeq/kWh**	**Carbon emission gCO_2/kWh**
Nuclear	0	0
Geothermal	0	0
Hydro	0	0
Wind Onshore	0	0
Solar Thermal Parabolic	0	0
Solar Photovoltaic	0	0
Sub-critical Steam Pulverized Coal (Bituminous)	181	664
Supercritical Steam Pulverized Coal (Bituminous)	181	664
Supercritical Steam Pulverized Coal (Lignite)	217	796
Supercritical Steam Pulverized Coal (Sub-bituminous.)	200	733
Sub-critical Steam Pulverized Coal (Bituminous) with Flue gas desulphurization	181	664
Supercritical Steam Pulverized Coal (Bituminous) with Flue gas desulphurization	181	664
Supercritical Steam Pulverized Coal (Lignite) with Flue gas desulphurization	217	796
Supercritical Steam Pulverized Coal (Sub-bituminous) with Flue gas desulphurization	200	733
Coal Integrated Gasification Combined Cycle	181	664
Coal Integrated Gasification Combined Cycle with Carbon Sequestration	181	664
Biomass Integrated Gasification Combined Cycle	0	0
Biomass Steam Cycle	0	0
Oil Steam Turbine	121	444
Gas Steam Turbine	90	330
Oil/Gas Steam Turbine	105.5	387
Gas Internal Combustion Engine (Diesel)	121	444
Gas Internal Combustion Engine (Gas)	90	330
Combustion Gas Turbine Combined Heat Power (Sub-bituminous)	200	733
Combustion Gas Turbine Combined Heat Power (Bituminous)	181	664
Combustion Gas Turbine Combined Heat Power (Gas)	90	330
Conventional Gas Combined Cycle	85	312
Conventional Oil Combined Cycle	155	568
Advance Gas Combined Cycle	75	275
Advance Oil Combined Cycle	105	385
Advance Gas Combined Cycle with Carbon Sequestration	30	110
Advance Oil Combined Cycle with Carbon Sequestration	40	147
Conventional Combustion Gas Turbine (Petroleum Product)	155	568
Conventional Combustion Gas Turbine	90	330
Advance Combustion Gas Turbine	90	330
Petroleum Refinery	0	0
Direct Coal Usage	181	664
Direct Lignite Usage	217	796
Direct Natural Gas Usage	90	330
Direct Biomass Usage	0	0
Direct Petroleum Usage	155	568

[Spadaro et.al., 2000] [EIA, 2009]

3.5.2.2 Resource Data

The resource data required by the proposed model include the estimated availability of each resource per year and the estimated reserve of each resource. The two data types are shown in Table 3.11.

Table 3.11: Availability per year and total reserve of each resource

Resource (ktoe)	**Year**	**Total**
Crude Oil	10,000	47,797
Condensate	5,000	89,639
Uranium	0	0
Underground Heat	164	Unlimited
Water	7,983	Unlimited
Wind	3,629	Unlimited
Solar	11,340	Unlimited
Natural Gas	30,000	753,199
Petroleum Product	0	0
Bituminous	0	0
Lignite	20,000	745,382
Sub-Bituminous	0	0
Wood	30,000	Unlimited

[Shrestha, 2006] [Jaimsin, 2005] [DEDE, 2003e] [DEDE, 1999] [DEDE, 2003d] [Limjeerajarus et al., 2004] [DEDE, 2004a] [Wongsapai, 2004c] [Szwarc, 2004] [DEDE, 2004c] [Keawsompong et al., 2002] [DEDE, 2004b] [Limjeerajarus et all, 2004b] [World Bank, 2001] [Raksaskulwong, 2004] [Ramingwong et al., 2000] [Raksaskulwong and Chaturongkawanich, 2001] [CMU, 2004] [Pacudan, 2003] [Greacen, 2004] [DMF, 2005a] [MOE, 2008] [MOE, 2007] [DEDE, 2009a] [DEDE, 2009b] [DEDE, 2009c] [Sajjakulnukit, 2005]

3.5.2.3 Financial Data

The financial data required for the proposed model are the cost parameters presented in the mathematical formulation which are (1) the costs data related to each technology including investment cost, fixed and variable operation and maintenance costs, (2) the costs data related to each resource including the domestic cost and imported cost, and (3) the cost of importing energy.

The domestic and imported costs for each resource are shown in Table 3.12 [DEDE, 2005a]. In order to calculate the costs in $/ktoe, it was necessary to obtain the domestic and imported costs of each resource as well as their heat value in their own

units. The heat values for each resource are shown in Table 3.13 [DEDE, 2005a] [DEDE, 2009a] [DEDE, 2009b] [DEDE, 2009c].The estimated imported cost for electricity energy is assumed to a large number to ensure domestic production of energy. The costs of each technology are shown in Table 3.14 [CERI, 2005] [Breeze, 2005] [EIA, 2007] [EIA, 2009] [Sajjakulnukit, 2005]. The unit used for all the costs are in $/ktoe.

Table 3.12: Domestic and Imported costs for each resource in $/ktoe

Resource	**Domestic Cost ($/ktoe)**	**Imported Cost ($/ktoe)**
Crude Oil	406,196	430,356
Condensate	433,932	463,932
Uranium	-	300,000
Underground Heat	-	-
Water	-	-
Wind	-	-
Solar	-	-
Natural Gas	133,278	210,780
Petroleum Product	-	550,000
Bituminous	-	75,000
Lignite	90,265	100,000
Sub-Bituminous	-	80,000
Wood	92,000	-

[DEDE, 2005a]

Table 3.13: Heat value for each resource

Resource	**Heat Value MJ/Kg**	**Heat value Tons/ktoe**
Crude Oil	-	-
Condensate	-	-
Uranium	544,284	0.077
Underground Heat	-	-
Water	-	-
Wind	-	-
Solar	-	-
Natural Gas	49.683	842.703
Petroleum Product	44.992	1074.616
Bituminous	26	1610.308
Lignite	11	3806.182
Sub-Bituminous	20	2093.400
Wood	16.85	2484.748

[DEDE, 2005a] [DEDE, 2009a] [DEDE, 2009b] [DEDE, 2009c]

Table 3.14: Technologies costs in $/ktoe

Technology	Capital Cost $/ktoe	Fixed O&M Cost $/ktoe per Year	Variable O&M Cost $/ktoe
Nuclear	2,559,662	78,556	4,652
Geothermal	2,924,759	105,254	0
Hydro	1,926,385	16,396	53,498
Wind Onshore	1,347,540	35,063	0
Solar Thermal Parabolic	3,929,772	66,687	0
Solar Photovoltaic	5,930,503	13,728	0
Sub-critical Steam Pulverized Coal (Bituminous)	1,702,016	22,224	19,469
Supercritical Steam Pulverized Coal (Bituminous)	1,247,968	22,224	19,469
Supercritical Steam Pulverized Coal (Lignite)	1,391,352	25,092	21,353
Supercritical Steam Pulverized Coal (Sub-bituminous.)	1,303,728	22,224	19,469
Sub-critical Steam Pulverized Coal (Bituminous) with Flue gas desulphurization	1,927,712	24,694	21,632
Supercritical Steam Pulverized Coal (Bituminous) with Flue gas desulphurization	1,473,664	24,694	21,632
Supercritical Steam Pulverized Coal (Lignite) with Flue gas desulphurization	1,617,048	27,880	23,725
Supercritical Steam Pulverized Coal (Sub-bituminous) with Flue gas desulphurization	1,529,425	24,694	21,632
Coal Integrated Gasification Combined Cycle	1,861,331	45,418	30,005
Coal Integrated Gasification Combined Cycle with Carbon Sequestration	2,663,217	53,450	45,706
Biomass Integrated Gasification Combined Cycle	2,332,638	62,637	34,425
Biomass Steam Cycle	2,004,715	66,381	17,445
Oil Steam Turbine	1,476,320	43,413	11,630
Gas Steam Turbine	1,476,320	43,413	11,630
Oil/Gas Steam Turbine	1,476,320	43,413	11,630
Gas Internal Combustion Engine (Diesel)	1,367,454	13,728	48,148
Gas Internal Combustion Engine (Gas)	1,367,454	13,728	48,148
Combustion Gas Turbine Combined Heat Power (Sub-bituminous)	1,222,743	25,225	19,771
Combustion Gas Turbine Combined Heat Power (Bituminous)	1,222,743	25,225	19,771
Combustion Gas Turbine Combined Heat Power (Gas)	1,222,743	25,225	19,771
Conventional Gas Combined Cycle	719,573	16,463	24,074
Conventional Oil Combined Cycle	719,573	16,463	24,074
Advance Gas Combined Cycle	816,490	13,728	24,074
Advance Oil Combined Cycle	816,490	13,728	24,074
Advance Gas Combined Cycle with Carbon Sequestration	1,444,457	19,821	30,005
Advance Oil Combined Cycle with Carbon Sequestration	1,444,457	19,821	30,005
Conventional Combustion Gas Turbine (Petroleum Product)	548,309	13,728	48,148
Conventional Combustion Gas Turbine	548,309	13,728	48,148
Advance Combustion Gas Turbine	618,674	10,979	36,053
Petroleum Refinery	97,140	232,600	0

[CERI, 2005] [Breeze, 2005] [EIA, 2007] [EIA, 2009] [Sajjakulnukit, 2005]

3.5.2.3 Demand Data

The final energy consumption of Thailand in the 2004 shown in Table 3.4 was used as the basis for predicting energy demands for each time period. From the actual percentage increases in the final energy consumption from the year 2003 [DEDE, 2005a], the predicted demand for the year 2007 was generated. This demand is used as the demand of the first time period for all models developed in this Thesis.

For this proposed model, the percentage increases in demands are assumed to be constant for the first three years, 50% between the fourth and tenth years, and 150% for the rest of the planning horizon. From the percentage increases, the demand for each time period can be forecasted which is shown in Table 3.15.

Table 3.15: Energy demand throughout the planning horizon in ktoe

Energy Type	**Year 1 and Year 3**	**Year 4 to Year 10**	**Year 11 to Year 20**
Electricity Energy	12496.120	18744.180	31240.300
Heat Energy	23542.600	35313.900	58856.500
Petroleum Energy	42078.880	63118.320	105197.200

3.5.3 Solving the mathematical model with GAMS

The General Algebraic Modelling System (GAMS) modelling language is a high-level modelling system for mathematical programming and optimisation which automates the process of transforming a mathematical formulation of a problem to the solution. The GAMS system converts the mathematical formulation to representations required by solver engines such as CPLEX. The modelling system is specifically designed for modelling linear, nonlinear and mixed integer large-scale optimisation problems. The CPLEX solver uses solution algorithms such as the branch and bound algorithm to solve the optimisation problem.

For every model described in this thesis, the GAMS modelling language and the CPLEX solver have been used.

3.5.4 Results and Discussion

The aim of the proposed multi-period deterministic energy system optimisation model was to determine the optimal energy supply chain network at the national level that can satisfy the predicted energy demand. The model was applied with the energy situation of Thailand. As mentioned in section 3.5.1, three scenarios have been created. The proposed model was constrained to the conditions of each scenario. The proposed model was able to determine the optimal energy supply chain network for each scenario. In the suggested network, the types and capacities of the chosen technologies, the types and amounts of resources, the amounts of imported resources and energy for each time period were determined. The results for the three scenarios are discussed below.

Scenario 1: Without existing infrastructure and $\beta = 1$

Considering the optimal solution for the first scenario, the proposed model suggested that the advanced gas combined cycle technology and the combustion gas turbine combined heat and power (bituminous) are the most economical non-renewable technology options for electricity production.

Moreover, the supercritical steam pulverized coal (lignite) and biomass integrated gasification combined cycle (BIGCC) were also suggested when the upper bound of capacity expansion was set. Although the investment and O&M costs for the two technologies are not the cheapest among the considered technologies, the costs of lignite and biomass to produce 1 ktoe are the two cheapest resources (excluding other renewable sources). For these reasons, the two technologies were selected.

Another feature to notice is that all the renewable technology options were recommended to be developed at the maximum achievable capacities. Even though the investment and O&M costs for renewable technologies are more expensive than others, most of the renewable sources are free to utilise. However, capacities of the renewable technologies are bounded by the country's geographical location.

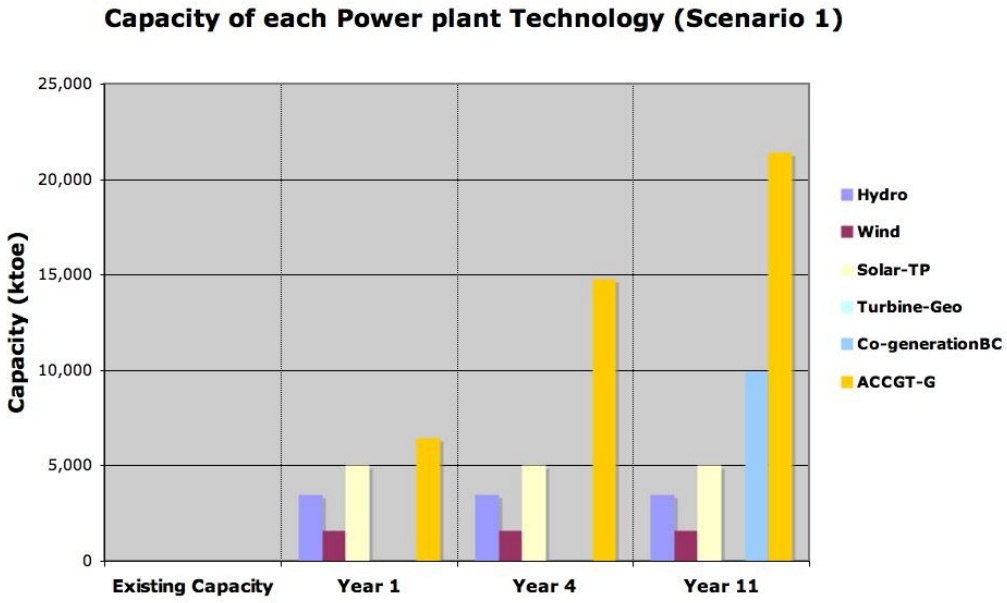


Figure 3.2: Capacity of power generation technology (Scenario 1)

Table 3.16: Suggested expansion of energy production technologies in MW (Scenario 1)

Technology	**Year 1**	**Year 4**	**Year 11**
Petroleum Refiniery	55864.973	27932.487	55864.973
Direct Coal Usage			1815.974
Direct Natural Gas Usage			
Direct LigniteUsage	26552.5		
Direct BiomassUsage	4703.244	15627.872	19497.634
Direct Petroleum Usage	55864.973	27932.487	55864.973
Geothermal	20		
Hydro	3500.022		
Wind Onshore	1600.015		
Solar Thermal Parabolic	4999.923		
Advanced Gas Combined Cycle	6470.201	8295.081	6648.025
Combustion Gas Turbine Combined Heat Power (Bituminous)			9942.137

The suggested capacity of each power generation technology for year 1, year 4 and year 11 are shown in Figure 3.2. The capacity of year 1 also represents the capacities of year 2 and year 3. The capacity of year 4 represents the capacities of year 5 to year 9. Finally the capacity of year 11 is the same as year 12 to year 20. This is because the planning horizon is divided into three time periods with different energy demands

as shown in Table 3.15. The suggested capacity expansions of energy production technologies for each time period for scenario 1 are shown in Table 3.16.

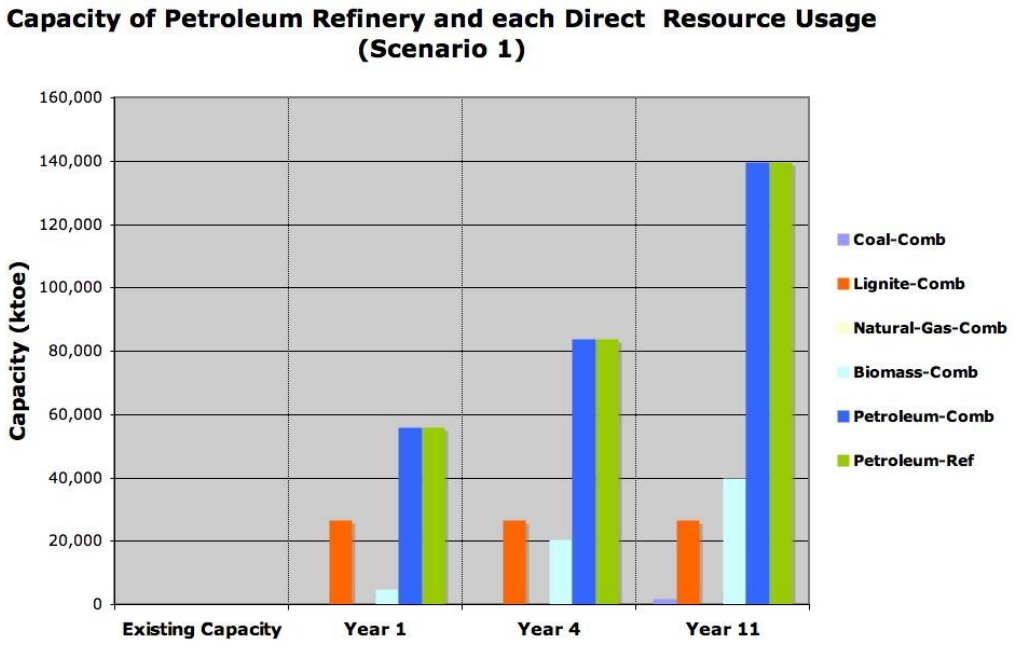


Figure 3.3: Capacity of petroleum refinery and each direct resource usage (Scenario 1)

For heat energy production, lignite was suggested as the main heat energy source. This decision was also made based on the fact that lignite is the cheapest resource available in Thailand. However, as there is a bound on the availability of lignite available to be utilised each year, biomass and bituminous coal were also suggested in the later period to meet the increase in heat demand as shown in Figure 3.3. As bituminous coal is not available in Thailand, the model suggested that the import of bituminous coal from overseas is required.

It is also worth noticing that, as the amount of crude oil production in Thailand cannot meet the petroleum products demand, a large amount of crude oil was suggested to be imported which is as expected. The suggested network in this scenario represents the most economical energy supply chain option. However, the amount of CO_2 emission was not taken into consideration. The total CO_2 emission for the suggested network over the whole time horizon is 1.6E+10 Tons of CO_2.

Scenario 2: With existing infrastructure and β = 1

For this second scenario, the existing energy production technologies as shown in Table 3.9 have been added to the first time period of equation 3.22 in the capacity constraints. The suggested capacities of each power generation technology are shown in Figure 3.4.

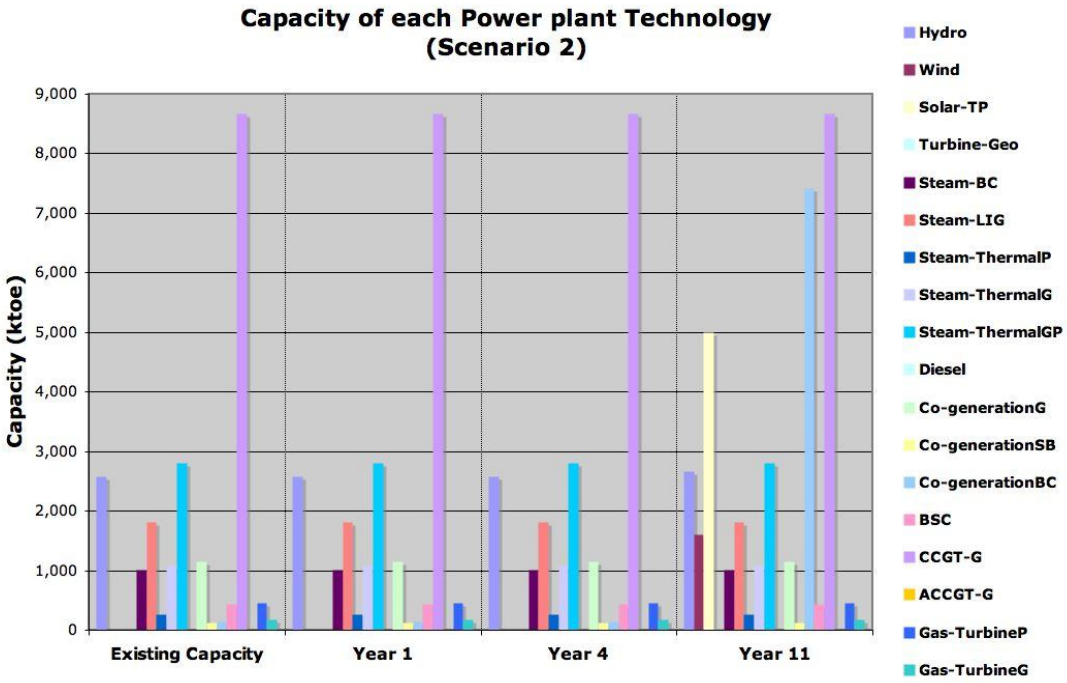


Figure 3.4: Capacity of power plants (Scenario 2)

From analysing the results, similar recommendations to the first scenario have been suggested by the proposed model. However, the suggested energy supply chain throughout the planning horizon contains the existing production technologies as well as the new technologies suggested by the proposed model. The suggested capacity expansions for each time period are shown in Figure 3.4. One of the main differences between this scenario and the previous one is the amount of electricity unused in each time period. From the suggested network, more than 8,000 ktoe was generated above the predicted demand between the first and the third year. Moreover, nearly 2,000 ktoe was also available between the fourth and the tenth year. This can be implied that with the current energy infrastructure in Thailand, the total energy supply is well over the predicted demand used in this chapter. The Figure 3.5 clearly shows that no

capacity expansion was suggested during the first two time periods. For the last time period, wind, solar thermal parabolic and combustion gas turbine CHP (bituminous) technologies were suggested. The capacity of petroleum refinery and each direct resource usage are also shown in Figure 3.6.

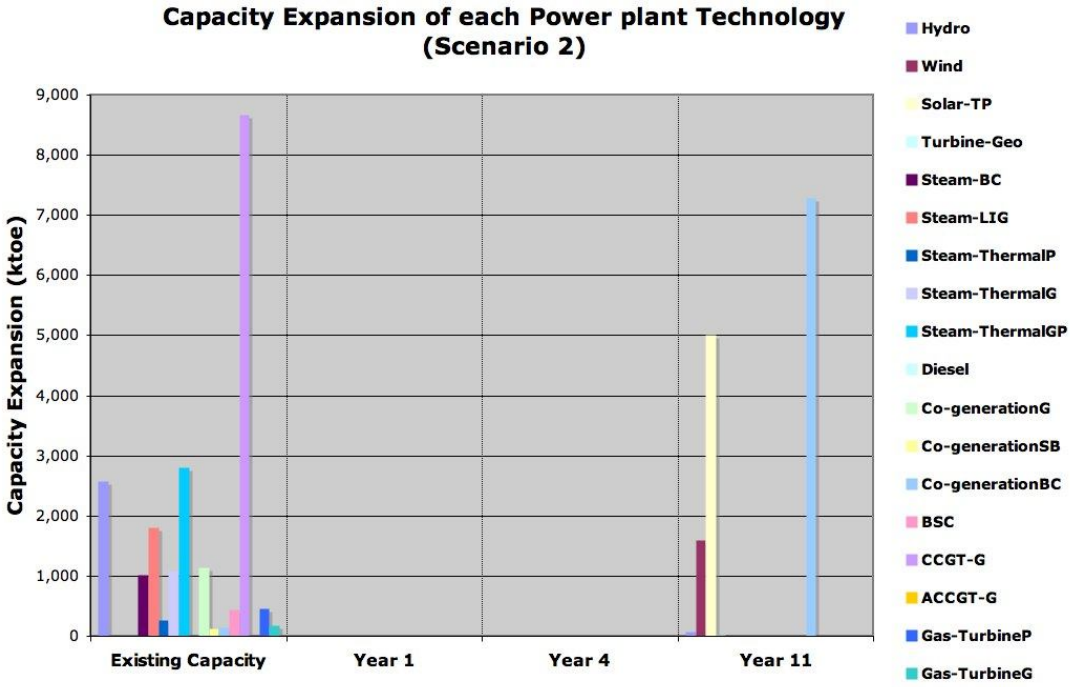


Figure 3.5: Capacity expansion of power plants (Scenario 2)

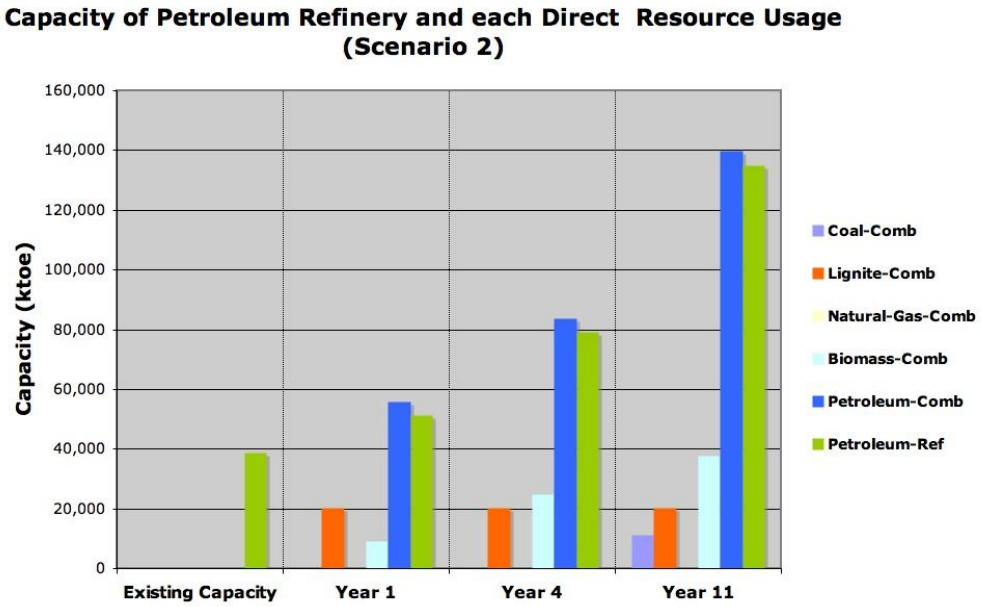


Figure 3.6: Capacity of petroleum refinery and direct resource usage (Scenario 2)

Furthermore, the suggested amounts of imported resources are different from the previous scenario. This is due to the existing power generation technologies in Thailand, as some of them use bituminous and sub-bituminous coals which are not available in Thailand. Some natural gas also has to be imported to satisfy the demand of existing natural gas power plants.

Scenario 3: With existing infrastructure and β = 0.7

In the third scenario, the proposed model constrained the suggested network so that only 70% of the total emission produced by scenario 2 can be produced for this scenario. For this case, the results became infeasible; this was because it was not possible to reduce the emission by 30% while satisfying the energy demand. Another factor that made the reduction of emission impossible was the incapability of the model to close down a facility, as this proposed model only considers capacity expansion.

Scenario 4: With existing infrastructure and β = 0.9

The optimal solution was determined in the attempt to reduce the CO_2 emission by 10%. The suggested capacity expansions are shown in Table 3.17. The capacity of petroleum refinery and each direct resource usage are shown in Figure 3.6.

Table 3.17: Suggested expansion of energy production technologies in MW (Scenario 4)

Technology	**Year 1**	**Year 4**	**Year 11**
Petroleum Refiniery	12410.5	27932.487	55864.973
Direct Natural Gas Usage			17345.634
Direct LigniteUsage		7411.861	6624.034
Direct BiomassUsage	29387.425	8216.011	
Direct Petroleum Usage	55864.973	27932.487	55864.973
Geothermal			19.7
Hydro			75.794
Wind Onshore			1599.822
Solar Thermal Parabolic			4999.381
Advanced Gas Combined Cycle			
Combustion Gas Turbine Combined Heat Power (Bituminous)			7286.077

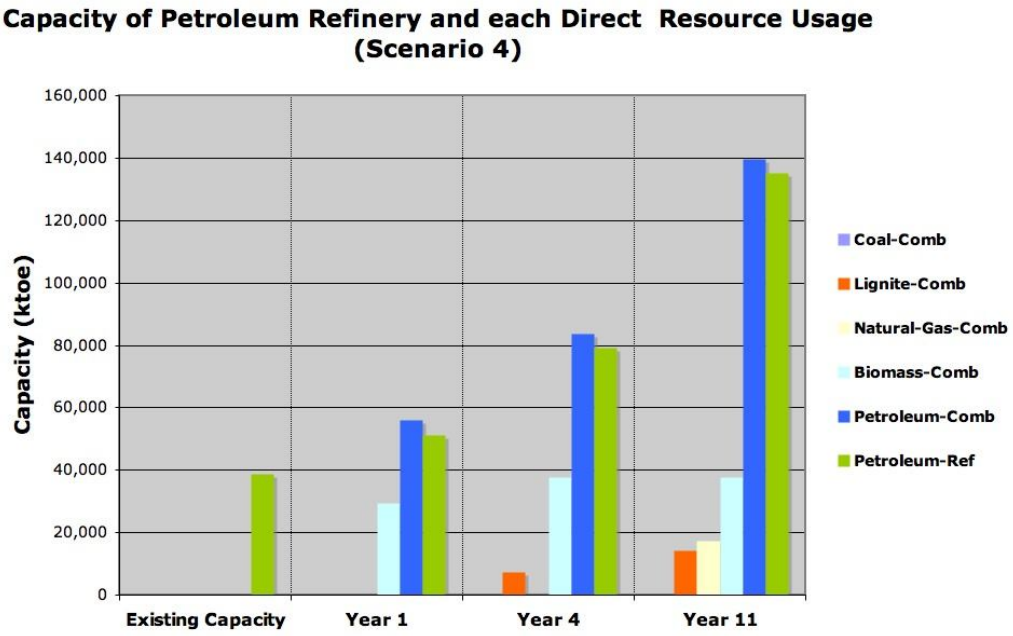


Figure 3.7: Capacity of petroleum refinery and direct resource usage (Scenario 4)

From Table 3.17 and Figure 3.6, it can be seen that the suggested direct usage of resources to produce heat energy has been changed from the most economical ones to the more environmentally conscious resources, for example the amount of direct use of coal and lignite has been replaced by the natural gas and biomass resources. The expansion of power generation technologies suggested by the proposed model is the same as the previous scenario, as most of them were renewable power generation technologies.

The total costs and the total emissions of the three energy supply chain networks are shown in Figure 3.8. From the figures, the first feature to notice is that the total costs for the fourth scenario are much higher than the first two scenarios. The results were as expected, as the cost of technologies which produces less GHG emissions are more expensive than the traditional technologies. From the results, in order to reduce 1 kilo ton of the CO_2 emission, 0.32 million $ was added to the total energy supply chain network cost.

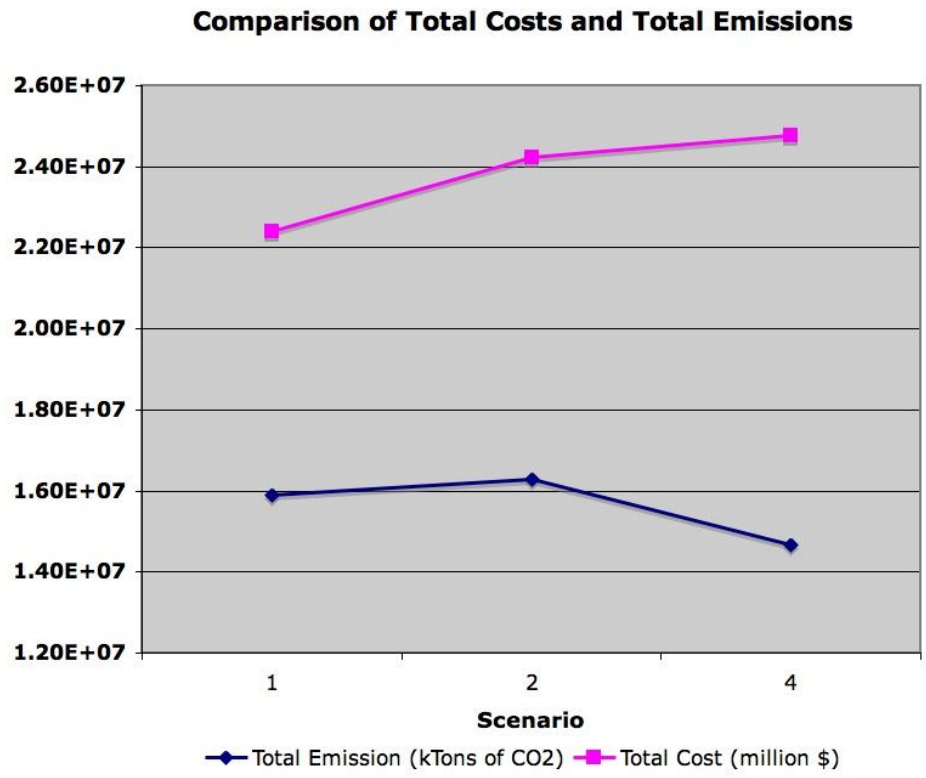


Figure 3.8: Comparison of the total costs and total emissions

Considering the optimal solutions generated from optimising the three scenarios using the proposed multi-period deterministic energy system optimisation model, the patterns of the suggested network were as expected, however, without the modelling tool, many tasks including determining the most economical technology, the exact amount of capacity expansion, the amount of required resource for large scale energy system throughout long-term planning horizon would be very difficult.

Scenario 5: Without existing infrastructure, β = 1, interest rate = 4% and inflation rate = 2%

The suggested capacity expansion for each technology is the same as the suggested network for scenario 1. However, the difference isthat the cost of the network becomes a lot cheaper due to the discount factor. The total cost of scenario 5 equals to $1.80593E+13 while the total cost for scenario 1 equal to $2.24097E+13. The total cost reduced by nearly 20% when compared to the result of scenario 1.

From the definition of discount factor, when the interest rate increases both cost and revenue of a project decrease through time. However, when the inflation rate increases both cost and revenue of a project increase through time. The discount factor for this scenario is described in Table 3.18.

Table 3.18: Discount factor (Interest rate = 4%, Inflation rate = 2%)

Year	Discount Factor
t01	1.00000000
t02	0.98076923
t03	0.96190828
t04	0.94341005
t05	0.92526755
t06	0.90747394
t07	0.89002252
t08	0.87290670
t09	0.85612003
t10	0.83965619
t11	0.82350895
t12	0.80767224
t13	0.79214008
t14	0.77690662
t15	0.76196611
t16	0.74731291
t17	0.73294151
t18	0.71884648
t19	0.70502251
t20	0.69146439

For the previous four scenarios, the interest rate and the inflation rate are assumed to be the same which resulted in discount factor equals to 1.

For all the models described in this thesis, a Pentium 4, 1.8 GHz Dell machine was used to solve them. As mentioned in section 3.5.3 that the GAMS modelling tool and CPLEX v9.0 were used to solve each model. The corresponding computational statistics for solving the LP models in this chapter are summarised in Table 3.19. The results clearly show that the time required to solve the four different configurations are minimal.

These results show that the models are capable of identifying optimal energy planning strategies for Thailand according to various assumptions. However, the short time to

solve each model is as expected as the complexity of a spatially-aggregated multi-period deterministic model is not very high.

Table 3.19: Summary of computational results for the multi-period deterministic model

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
Number of variables	43155	43155	43155	43155	43155
Number of equations	42975	42975	42975	42976	42975
CPU time (sec)	1.177	1.014	Infeasible	0.831	1.185

3.5.5 Concluding Remarks

The work in this chapter describes an optimisation tool which can help decision makers in making strategic decision regarding long-term energy planning at the national level. The developed model was able to establish optimal energy supply chain networks for different scenarios, representing real-world cases. The model considers 41 energy production technologies consisting of the existing technologies in operations in Thailand and also others advances technologies that are currently available around the world. The model also takes account of various resources that can be domestically produced and also imported. Different types of renewable sources are also considered. Prior to the development of the proposed model, the energy situation in Thailand has been studied; an overview of the situation is also described in this chapter. Moreover, the main data required to develop the model is identified and collected from various sources.

In this work, three scenarios concerning with the long-term energy planning of Thailand were studied. The results obtained proved the feasibility of the proposed model and also shown the benefits of using such model in determining the future energy supply chain network. Founded on the assumptions made and the data used in the proposed model, the advanced gas combined cycle is the most economical non-renewable power generation technology while lignite is the most economical source of heat energy. However, in the attempt to reduce the total CO_2 emission, renewable sources and renewable power generation technologies were chosen even though the costs for those technologies and resources were more expensive.

The multi-period deterministic energy system optimisation model described in this chapter is based on the assumption that the energy demands for each time period were known beforehand. However, this statement is not entirely true as the forecasting of the future energy demand is a difficult task. There are many uncontrollable factors that could affect the future demand including variation in economic growth or changes in government policies. The next chapter investigates the scenario-based stochastic programming approach which can be used to capture the uncertainty in demand in the developed model.

Chapter 4

Multi-period Stochastic Energy System under Demand Uncertainty

4.1 Introduction

The problem of how to deal with the impact of uncertainty is characteristic of most aspects of national development planning, but in few sectors is the pervasive influence of uncertainty as serious as in the energy sector. The long term analysis of an energy system is fraught with uncertainties. Different uncertainties pose unique problems to the planner. The selected uncertainties in energy planning are variations in critical economic parameters, unknown performance of new technologies, lack of data on traditional energy uses and most importantly the variations in demand of energy in the future.

The aim of this chapter is to develop a stochastic energy system optimisation model which capture uncertainty in future demand. Uncertainty can be incorporated into optimisation model in several ways. Traditionally, future uncertainties have usually been examined individually through comparisons of multiple deterministic scenarios. However, an alternate approach to such scenario analysis is a branch of mathematical programming known as ***Stochastic Programming***. The next section describes the scenario analysis and scenario-based stochastic programming modelling techniques in more detail.

Scenario analysis (Deterministic)

Scenario analysis involves comparisons of different generated scenarios based on an analyst's assumptions to discern the implications of the scenarios various outcomes.

A specification of all the exogenous parameters involved in an energy model constitutes a scenario. In the case of an energy model, energy scenarios may account for future uncertainties via contrasted scenarios of demands, technological development, and emission constraints.

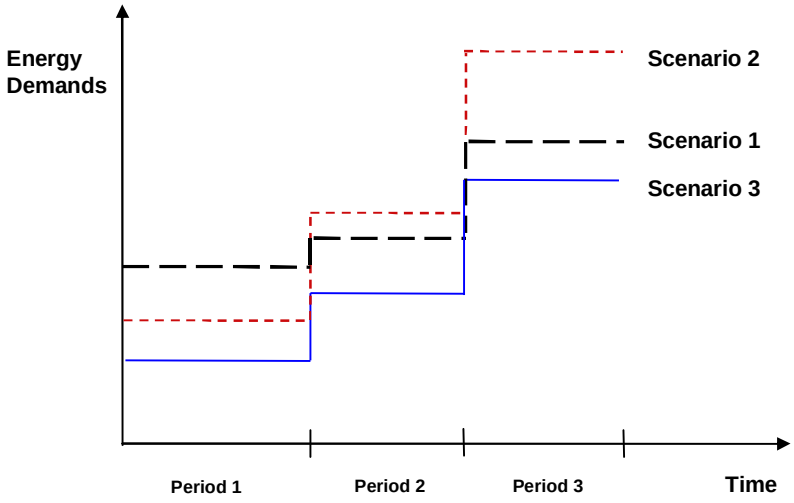


Figure 4.1: Energy demands of three deterministic scenarios over time.

One important characteristic of the approach is that it implicitly assumes perfect foresight of the economic agents, which lead to the deterministic nature of each scenario. Figure 4.1 shows levels of energy demands for three deterministic scenarios over time. To emphasise the perfect foresight of the deterministic scenarios, it can be seen in Figure 4.1 that each scenario is a distinct profile of energy demands over time, where all energy demands for each scenario have been defined since the initial stage.

However, such scenario analysis has evident drawbacks, whenever two contrasted scenarios give widely different recommendations in the immediate future. Then the analysts will have no easy way of resolving the dilemma.

Stochastic programming paradigm with Recourse

The stochastic programming paradigm consists of representing multiple scenarios, each having a relative weight (probabilities or likelihood of occurring), within a single coherent formulation. The resulting stochastic scenario is best represented by an ***event tree*** describing the unfolding of the uncertainty over the period of energy planning.

A stochastic scenario is represented by a path from the root to an end of the event tree. A given probability is predicted for each scenario depending on the likeliness of each path. Each node of the event tree represents different deterministic scenarios with a defined set of constraints and an economic function, which involves variables specific to that node and its predecessor nodes [Almansoori, 2006] [Condevaux-Lanloy, 2000] [Wallace, 1995] [Ybema at al., 1998] [Kanudia, 1998].

The standard stochastic programming was extended as a recourse problem by Wets in 1989. The term "recourse" means that *some decisions will be decided after the true information about an uncertainty has been obtained*. In terms of energy planning modelling, the recourse means that an energy planning policy or a strategy can be decided after the true value of an uncertainty is revealed.

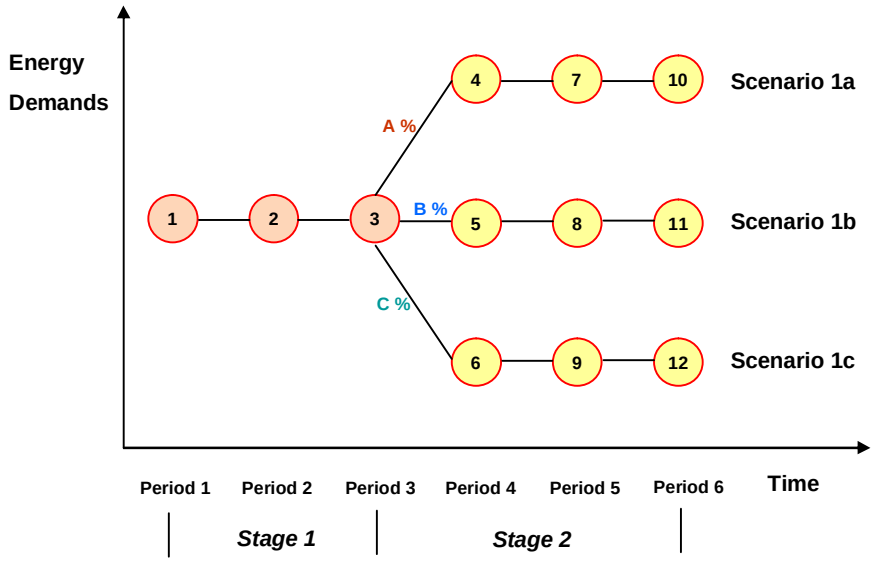


Figure 4.2: An event tree showing energy demands of a stochastic model over time.

The event tree in Figure 4.2 represents an example of two-stage stochastic model. The model consists of three alternate stochastic scenarios (three paths from the root to leaves of the tree. In many energy planning models, the first few periods are defined with very little or no uncertainty. This results in a single path branch over these period(s), which are period 1 to period 3 in this case. On the other hand, the second stage signifies the later periods, where uncertainties are induced, and causing branch breaking into multiple paths along with their probability of occurring (A %, B % and C %) at that point. The three stochastic scenarios combine to form a probabilistic composite scenario.

Unlike the scenario analysis technique where as many strategies as there are deterministic scenarios are produced, stochastic programming creates only a single strategy. However, that strategy is composed of contingent (conditional) actions that will diverge at periods with unresolved uncertainties. This type of solution defines contingency plans instead of predefined decisions. The scenario-based stochastic programming approach is adopted to formulate a stochastic energy system optimisation model under uncertainty in demand. The model structure and mathematical formulations are described below.

4.2 Model Structure

The model structure of the multi-period deterministic model is used as the basis for the structure of the proposed stochastic model in this chapter. The only difference is the additional component to capture the demand uncertainty in energy system modelling. The component is discussed in more detail below. Others components will not be repeated in this chapter as they were addressed in depth in the previous chapter.

4.2.1 Scenario for capturing demand uncertainty

From the theory of scenario-based stochastic programming, different demand paths are used to capture possible fluctuations of demand. The different demand paths can be represented by scenarios, indicated by the index c in the stochastic mathematical

formulation. Three time periods are considered in this proposed model, resulting in 9 possible scenarios. The stochastic demand is described in more detail in section 4.4.2.

4.3 Mathematical Formulation

The stochastic mathematical formulation is similar to the previous deterministic formulation presented in section 3.4. The stochastic model is formulated as a LP model. However, the main difference lies in the addition of the demand scenario which is used in capturing the multiple demand scenarios.

To reformulate the deterministic formulation to a stochastic one, all the decision variables described in the previous chapter will be augmented by the index c. The modification is applied to all the decision variables in each of the constraints and the objective function, to account for the multiple demand scenarios.

Considering the changes required for each parameter, apart from the new stochastic demand and the addition of new parameters containing the probabilities of each scenario, the rest of the parameters remain the same as before. Furthermore, the objective function becomes a minimisation of the probability weighted average cost of the energy system. The stochastic mathematical formulation is described below.

4.3.1 Notation

Indices

c = scenario

Parameters

$SDem_{vtc}^{all}$ = Stochastic demand of energy v at year t in scenario c (ktoe)

$\Pr ob_c$ = Event probabilities for scenario c

$eEmi^{\max}$ = Maximum total expected emission (gCO_2)

Variables

$eCost^{total}$	=	Expected cost of the energy supply chain network ($)
$Cost_c^{total}$	=	Total cost of the network in scenario c ($)
Emi_c^{total}	=	Total emission in scenario c (gCO_2)
$eEmi_c^{total}$	=	Total expected emission (gCO_2)

4.3.2 Objective Function

To account for multiple demand scenarios, the objective function can be represented as the sum of the product of the total cost of each scenario c ($Cost_c^{total}$) and the probabilities event tree (Pb_c) of all time periods for all scenarios, which is equal to the expected total cost $eCost^{total}$ for the entire energy supply chain network. The objective function can now be expressed as:

Minimise $$eCost^{total} = \sum_c Pb_c \cdot Cost_c^{total} \quad (4.1)$$

4.3.3 Constraints

Emission constraints

For the stochastic model, an expected emission will be used to constrain the amount of emission produced from the energy network configurations of each scenario. The expected emission can be defined in the similar was as the expected cost which is given below.

$$eEmi^{total} = \sum_c Pb_c \cdot Emi_c^{total} \quad (4.2)$$

To control the amount of emission produced from all processes, upper bounds are placed on the total amount of emission produced. The constraint is given in the form:

$$eEmi^{total} \leq \beta \cdot eEmi^{\max} \tag{4.3}$$

where

$eEmi^{\max}$ is the maximum total expected emission produced by the network

β is the emission factor

By limiting the value of emission factor between 0 and 1, factor can be used to limit the total expected emission produced.

Non-anticipativity Constraints

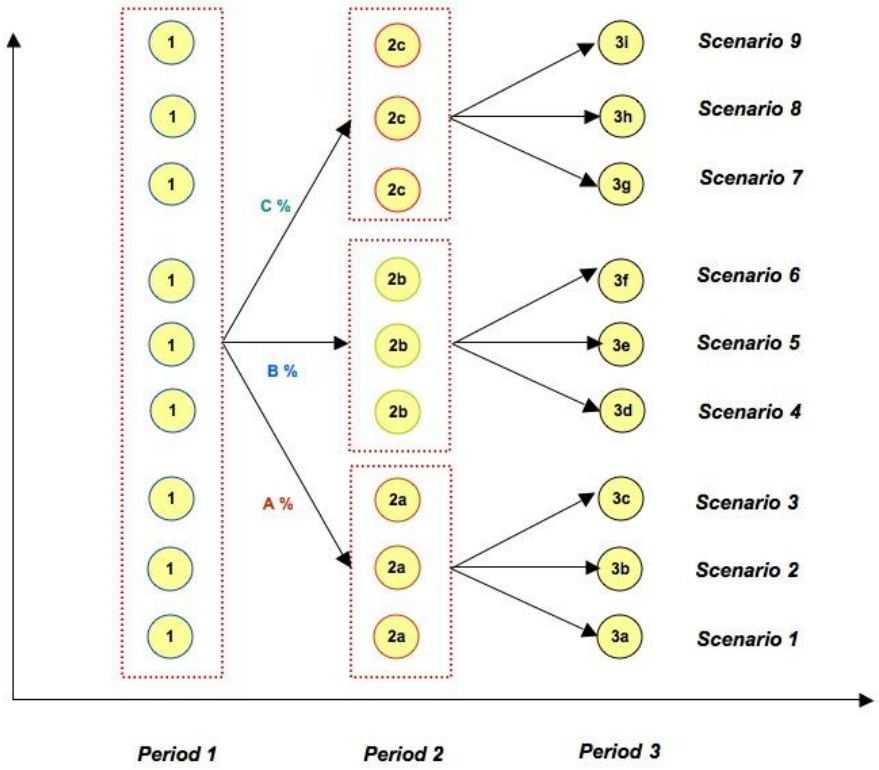


Figure 4.3: Non-anticipativity constraints for each time period

To capture the uncertainty in demand by using scenario-based approach, the non-anticipativity principle (Wets, 1975) was applied to all the decision variables. Wets states that "if a set of scenarios have the same available information up to time period t then the values of the variables corresponding to these scenarios are identical up to that time period".

The constraints for the three time periods considered in this model are as follows:

First time period:

$$Var_{xt_1c} = Var_{xt_1(c+1)} \qquad \forall x, c : c < 9 \tag{4.4}$$

where Var is any decision variable formulated in the model.

Index x stand for the indices presented in the model such as v and i.

In the first time period, all decision variables have the same values for all scenarios. This is due to the deterministic nature of the predicted demand. Therefore, all scenarios can be considered as one discrete scenario. The equation 4.4 ensures the condition.

Second time period:

$$Var_{xt_2c} = Var_{xt_2(c+1)} \qquad \forall x, c : 1 < c < 3 \tag{4.5}$$

$$Var_{xt_2c} = Var_{xt_2(c+1)} \qquad \forall x, c : 3 < c < 6 \tag{4.6}$$

$$Var_{xt_2c} = Var_{xt_2(c+1)} \qquad \forall x, c : 6 < c < 9 \tag{4.7}$$

In the second time period, the values of decision variable for the nine scenarios are constrained into three groups. This is because there are three different sets of scenarios in the structure of the demand scenario tree in the second time period. To ensure the similarity of these scenarios, the non-anticipativity constraints presented by the equations 4.5 to 4.7 above are enforced.

In the last time period, the values of decision variables of the nine scenarios are independent from each other. By imposing the aforementioned constraints, the stochastic nature of the energy system under uncertainty can be captured by a scenario-based approach to produce nine different energy supply chain network configurations.

4.4 Case Study: Thailand Energy System

The scenario-based stochastic programming approach described above is applied to the mathematical formulation of the previous multi-period deterministic energy system optimisation model to establish a multi-period stochastic energy system optimisation model which able to capture uncertainty in energy demand of Thailand. The reformulated stochastic model is tested with two scenarios which are explained in more detail below.

4.4.1 Description of scenario

The scenarios which are used to test the feasibility of the proposed stochastic model are similar to the scenarios generated for the previous deterministic model. Two scenarios are created which are described below.

1) Optimising the proposed stochastic model without consideration of the existing energy infrastructure of Thailand.
2) Same as scenario 1 but with the emission factor set equal to 0.9 to examine the effect of reducing the total emission by 10% to the energy planning strategy.

The input data required is the same as the previous deterministic model apart from the predicted demand. Instead of using the deterministic demand, a stochastic demand dataset is introduced and presented in the next section.

4.4.2 Input Data

The only additional data required by the proposed stochastic model is the stochastic demand and the probability of each scenario. The rest of the data input is the same as in the previous chapter.

Stochastic Demand

The planning horizon for the stochastic model is the same as the deterministic model. The first time period for the stochastic model also has the same energy demand as the deterministic model with the penetration factor of 0%, where the demand is assumed to be known. For the second time period, three different demand paths are created to represent the low, steady and high penetration factors. The steady case has the same penetration factor as the deterministic model which is 50%. Finally, for the third time period, nine different demand paths are implemented with three sets of low, steady and high penetration factors, continuing form the three paths of the second time period. The value of the fifth demand path (steady case) is the same as the penetration factor of the deterministic model which is 150%. The penetration factors are shown in Table 4.1.

Table 4.1: The penetration factor during each time period

Time Period		**Scenario c**	**Penetration Factor**
Year 1 to Year 3	*2007-2009*	c_1-c_9	0%
Year 4 to Year 10	*2010-2016*	c_1-c_3	30%
Year 4 to Year 10	*2010-2016*	c_4-c_6	50%
Year 4 to Year 10	*2010-2016*	c_7-c_9	70%
Year 11 to Year 20	*2017-2026*	c_1	80%
Year 11 to Year 20	*2017-2026*	c_2	100%
Year 11 to Year 20	*2017-2026*	c_3	120%
Year 11 to Year 20	*2017-2026*	c_4	130%
Year 11 to Year 20	*2017-2026*	c_5	150%
Year 11 to Year 20	*2017-2026*	c_6	170%
Year 11 to Year 20	*2017-2026*	c_7	180%
Year 11 to Year 20	*2017-2026*	c_8	200%
Year 11 to Year 20	*2017-2026*	c_9	220%

As described by equations 4.1 and 4.4 in the mathematical formulation, the probability of occurrence of each distinctive scenario is also required to capture the demand uncertainty. The probabilities of occurring for a three time period scenario tree with 9 distinct scenarios are presented in Table 4.2. The stochastic energy demand for Thailand is shown in Table 4.3. Furthermore, the energy demand scenario tree considers in this chapter is shown in Figure 4.4.

Table 4.2: The probabilities of occurrence of each scenario

	Scenario c								
	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
Probability (%)	6.25	12.50	6.25	12.50	25.00	12.50	6.25	12.50	6.25

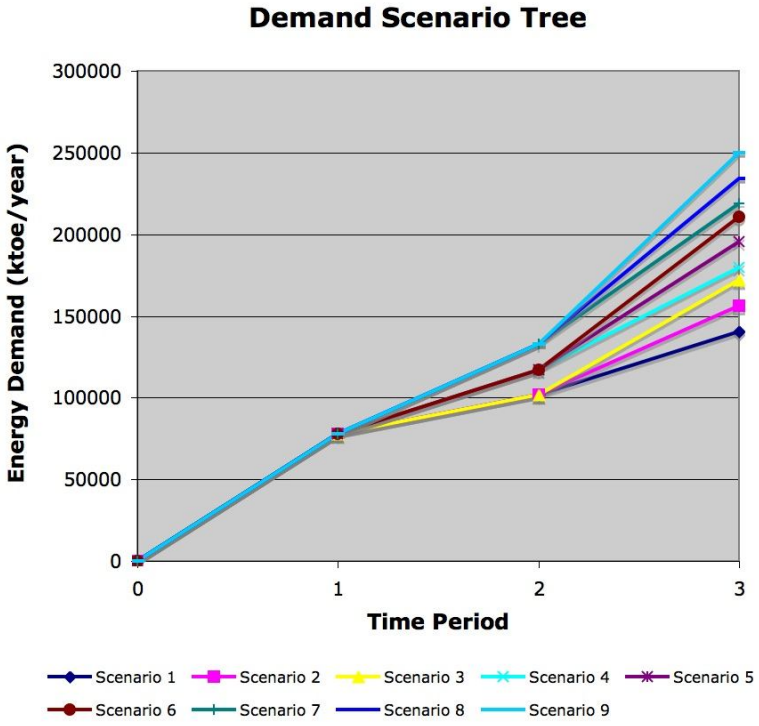


Figure 4.4: The demand scenario tree

Table 4.3: The stochastic energy demand for all scenarios

Time Period		Scenario c	Electricity Energy	Heat Energy	Petroleum Energy
Year 1 to 3	*2007-2009*	c_1-c_9	12,496	23,543	42,079
Year 4 to10	*2010-2016*	c_1-c_3	16,245	30,605	54,703
Year 4 to 10	*2010-2016*	c_4-c_6	18,744	35,314	63,118
Year 4 to 10	*2010-2016*	c_7-c_9	21,243	40,022	71,534
Year 11 to 20	*2017-2026*	c_1	22,493	42,377	75,742
Year 11 to 20	*2017-2026*	c_2	24,992	47,085	84,158
Year 11 to 20	*2017-2026*	c_3	27,491	51,794	92,574
Year 11 to 20	*2017-2026*	c_4	28,741	54,148	96,781
Year 11 to 20	*2017-2026*	c_5	31,240	58,857	105,197
Year 11 to 20	*2017-2026*	c_6	33,740	63,565	113,613
Year 11 to 20	*2017-2026*	c_7	34,989	65,919	117,821
Year 11 to 20	*2017-2026*	c_8	37,488	70,628	126,237
Year 11 to 20	*2017-2026*	c_9	39,988	75,336	134,652

4.4.3 Results and Discussion

Two cases have been implemented to examine the developed scenario-based stochastic energy system optimisation model. As in the previous chapter, the energy system of Thailand was also used as the case study. To reflect the two cases described in section 4.4.1, different values of emission factor have been used. The results from solving the two cases are presented and discussed below.

This first case used the same assumptions as the first case of the previous chapter where the existing energy system of Thailand was not considered. Based on the assumptions, the proposed stochastic model was able to suggest an optimal energy planning strategy for Thailand which consists of 9 different capacity expansion networks, according to the 9 different demand paths as shown in Figure 4.4. For the second scenario, the emission factor β was set at 0.9 to see the effect of reducing the total expected CO_2 emission by 10%.

The first feature from analysing the suggested networks is the similarity to the results of the previous deterministic model. The types of the suggested technologies were the same. However, the capacities were different to reflect the variations in demand. Moreover, 9 different networks were determined instead of just one network.

The suggested capacity of each technology for all scenarios throughout the planning horizon to meet the stochastic demand for case 1 and case 2 are shown in Figures 4.5 and 4.11 respectively.

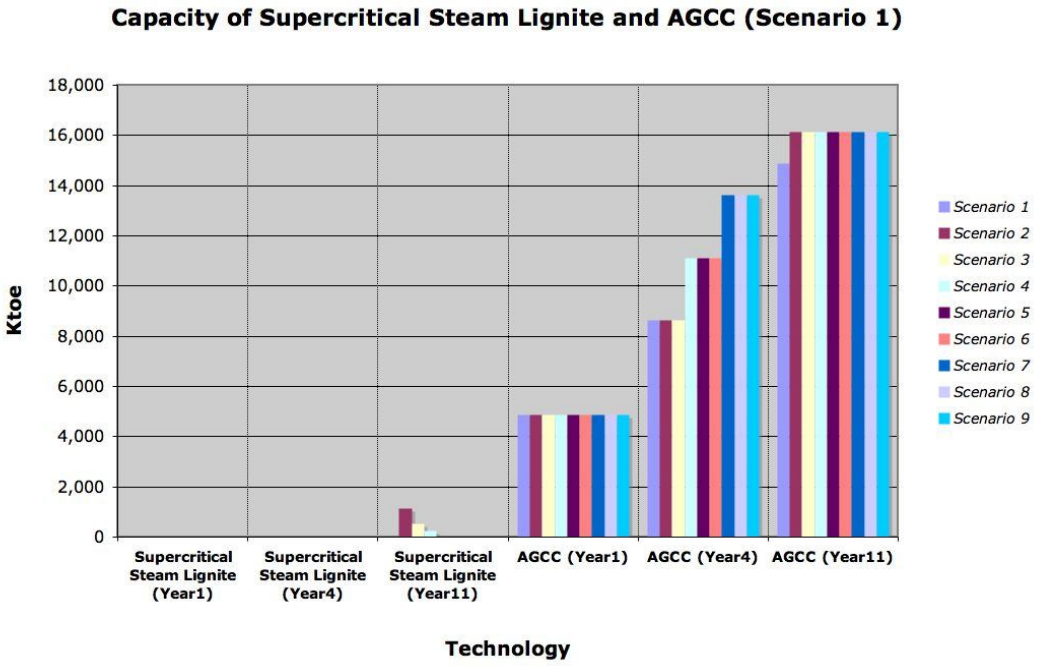


Figure 4.5: The suggested power plant capacity (β=1)

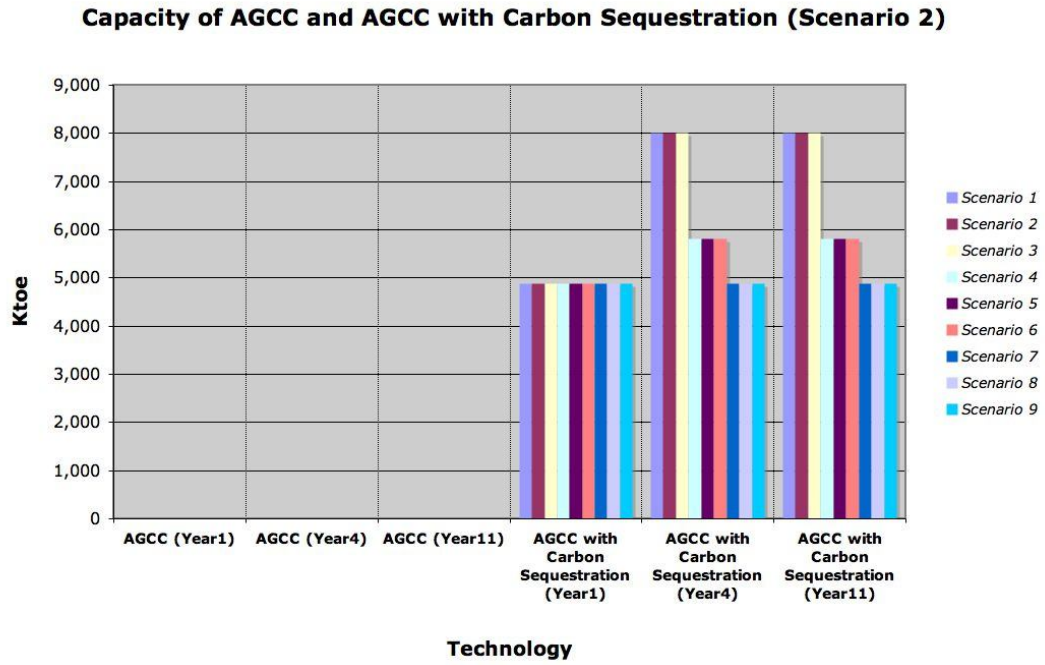


Figure 4.6: The suggested power plant capacity (β=0.9)

As mentioned earlier, the suggested networks for the stochastic model are similar to the deterministic one. The advanced gas combined cycle has been suggested as the main non-renewable power generation technology for case 1 where reduction of the CO_2 emission was not considered. The supercritical steam lignite was also suggested during the final time period. Similar to the previous chapter, the hydro, wind, solar thermal parabolic and geothermal were recommended as the renewable power generation technologies.

Considering case 2, the advanced gas combined cycle with carbon sequestration was suggested, to replace the advanced gas combined cycle and the supercritical steam lignite technologies suggested by case 1, in the attempt to reduce the expected emission by 10%. Figure 4.5 and 4.6, shows the capacity of suggested power generation technology for both scenarios. Moreover, similar to the results of the previous chapter, the combined heat and power (CHP) technology was also suggested. Figure 4.7 and 4.8, shows the capacity of suggested combined heat and power technology for the two cases over the planning horizon. Comparing the two figures, bituminous coal and natural gas were suggested as the main resources for the CHP power plants in the attempt to reduce the CO_2 emission.

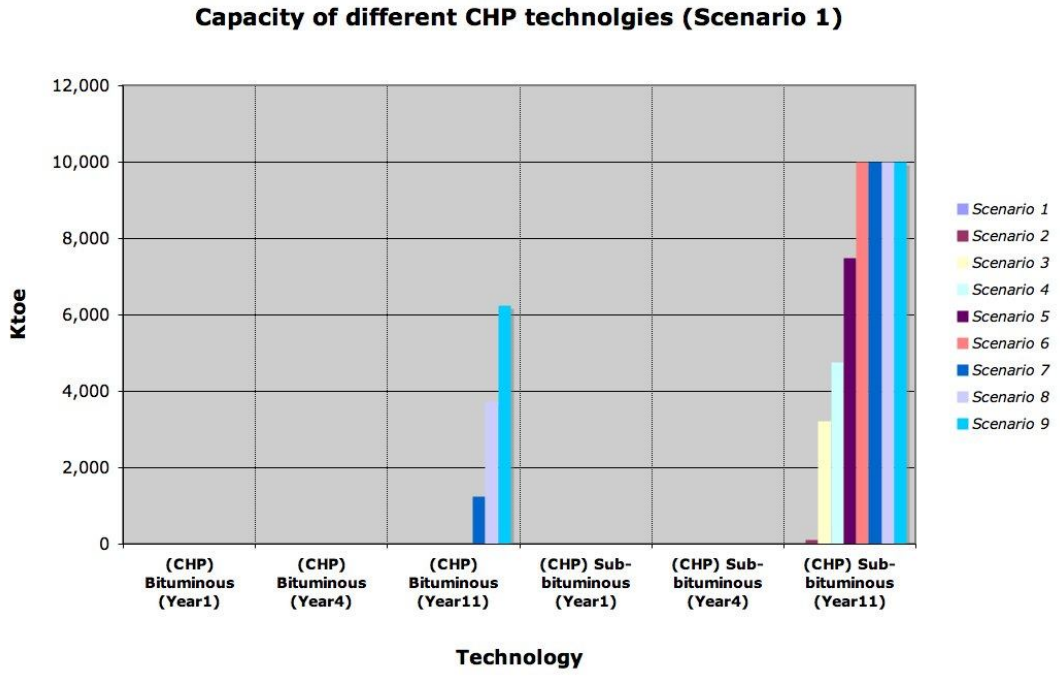


Figure 4.7: The suggested CHP capacity (β=1)

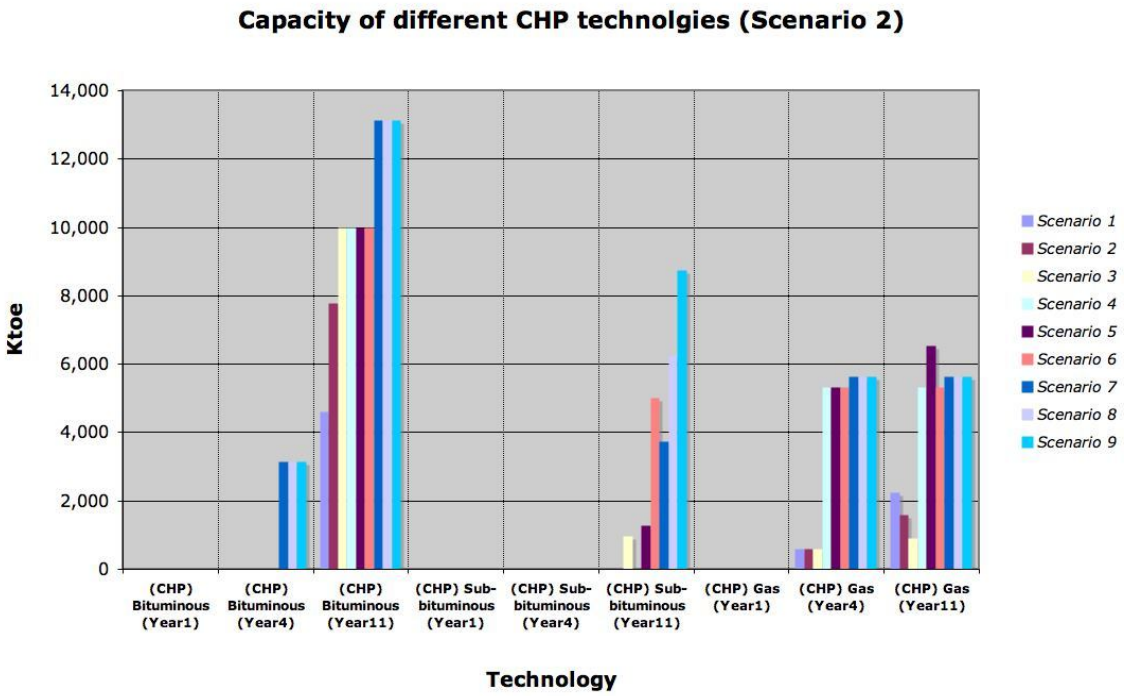


Figure 4.8: The suggested CHP capacity (β=0.9)

Furthermore, Figure 4.9 to 4.11 show the suggested capacity of direct usage of resources to meet the heat demand for both cases throughout the planning horizon.

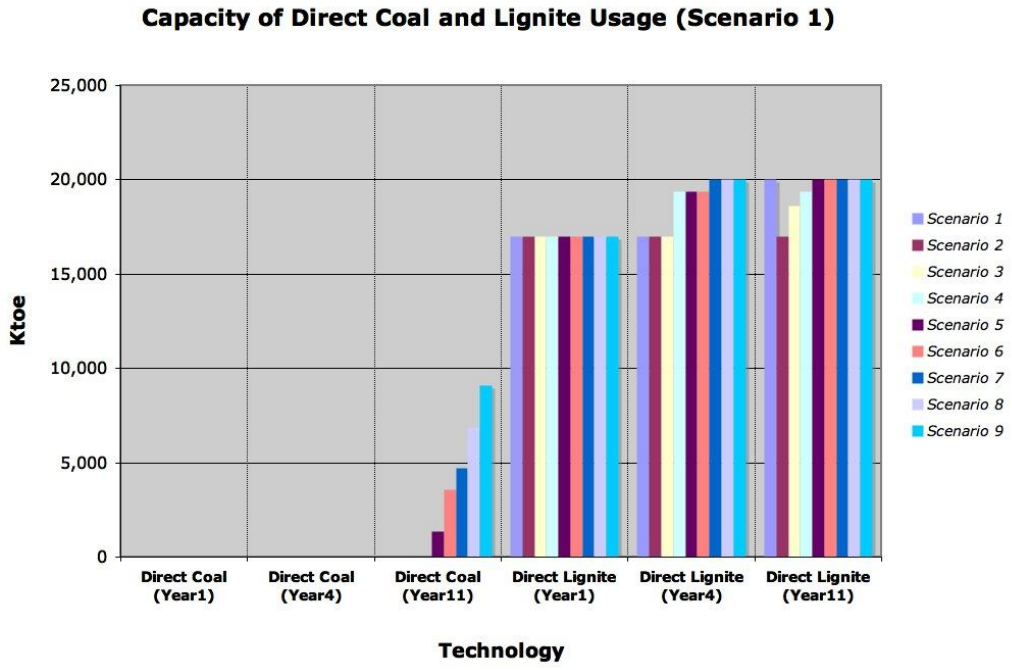


Figure 4.9: The suggested capacity of coal and lignite usage (β=1)

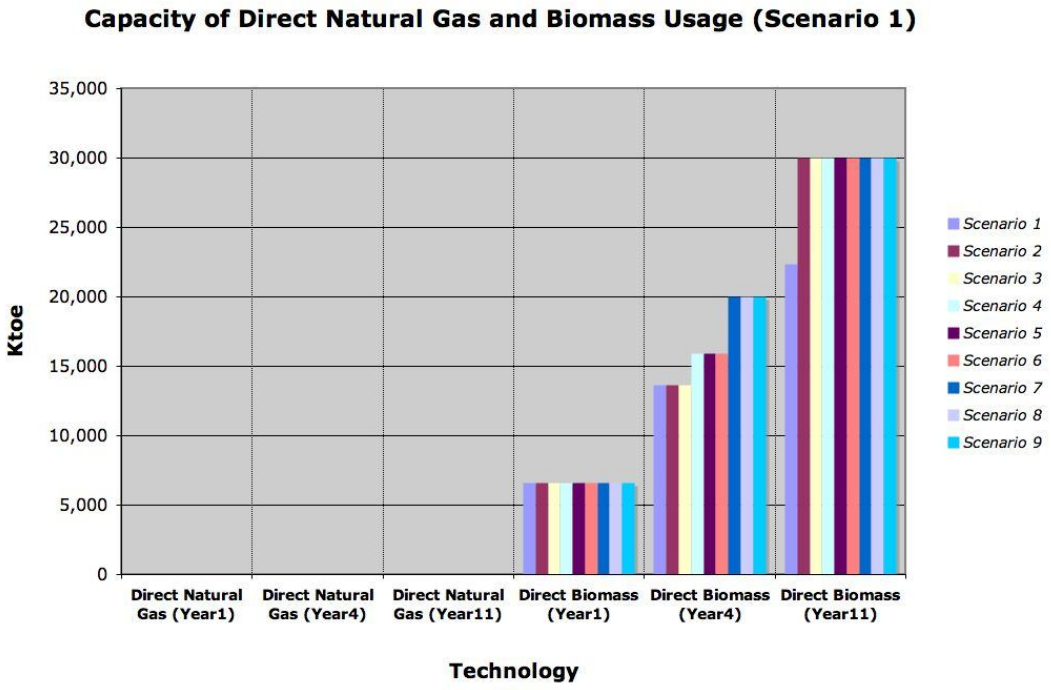


Figure 4.10: The suggested capacity of natural gas and biomass usage (β=1)

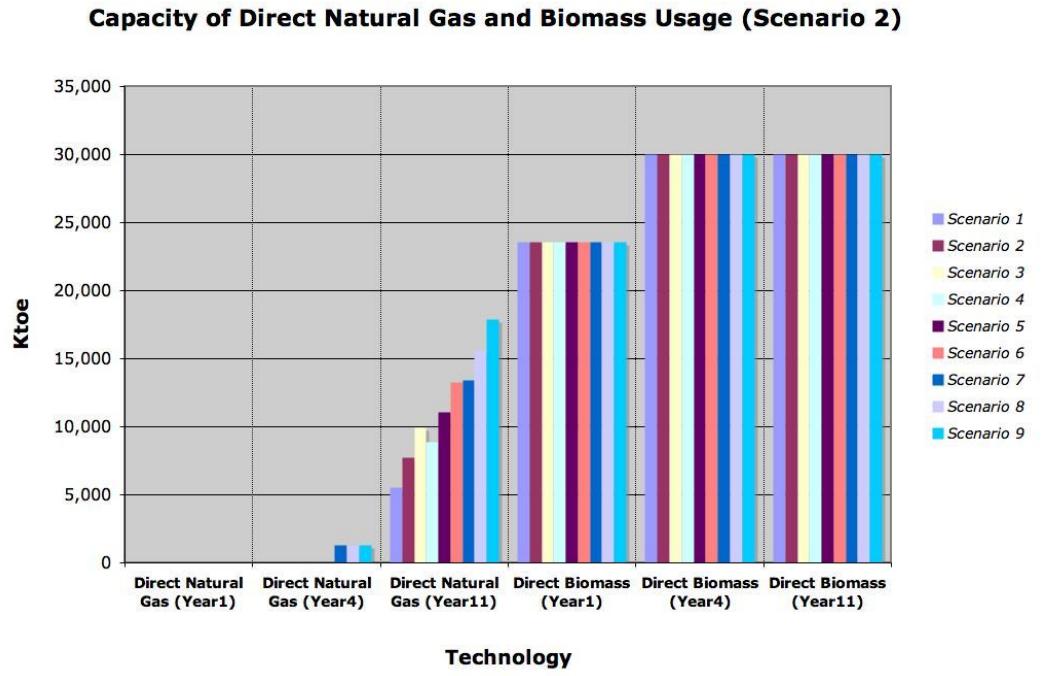


Figure 4.11: The suggested capacity of natural gas and biomass usage (β=0.9)

From analysing the three figures, it can also be summarised that to satisfy the stochastic heat demand, similar suggested types of direct resource usage with the previous deterministic model were suggested. Lignite, coal and biomass were the

suggested resources for case 1 as shown in Figure 4.9 and 4.10. In the attempt to reduce the CO_2 emission natural gas and biomass were recommended instead of lignite and coal as shown in Figure 4.11.

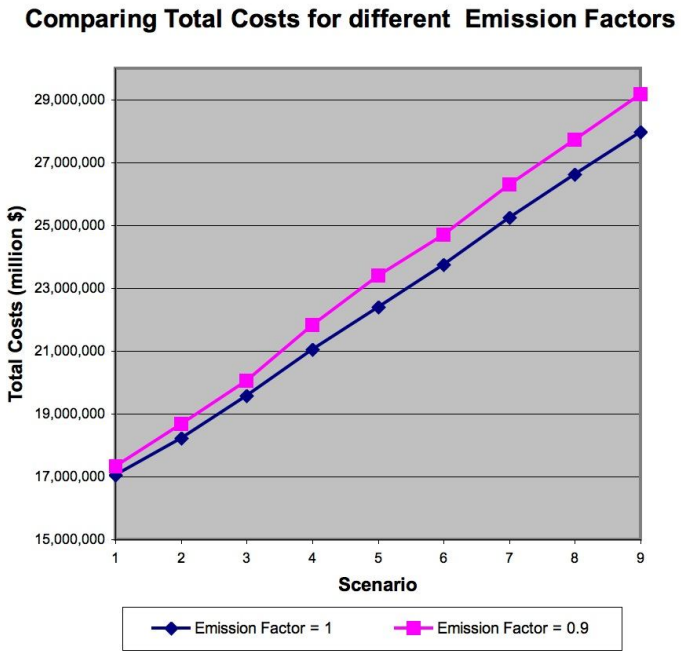


Figure 4.12: Comparison of the total costs for different values of β

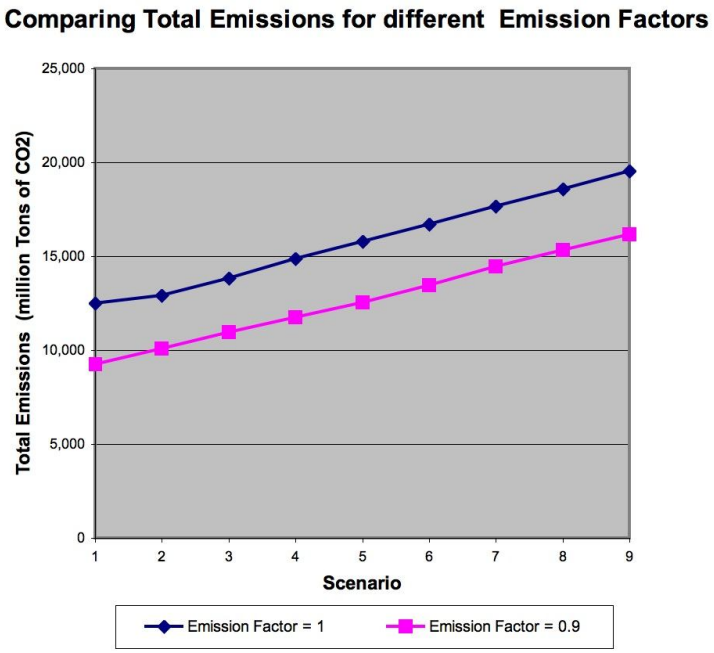


Figure 4.13: Comparison of the total emissions for different values of β

The comparison of total costs and total emissions of each scenario for both cases are shown in Figures 4.12 and 4.13 respectively. The expected total costs and expected total emissions for each case are also shown in Figure 4.14.

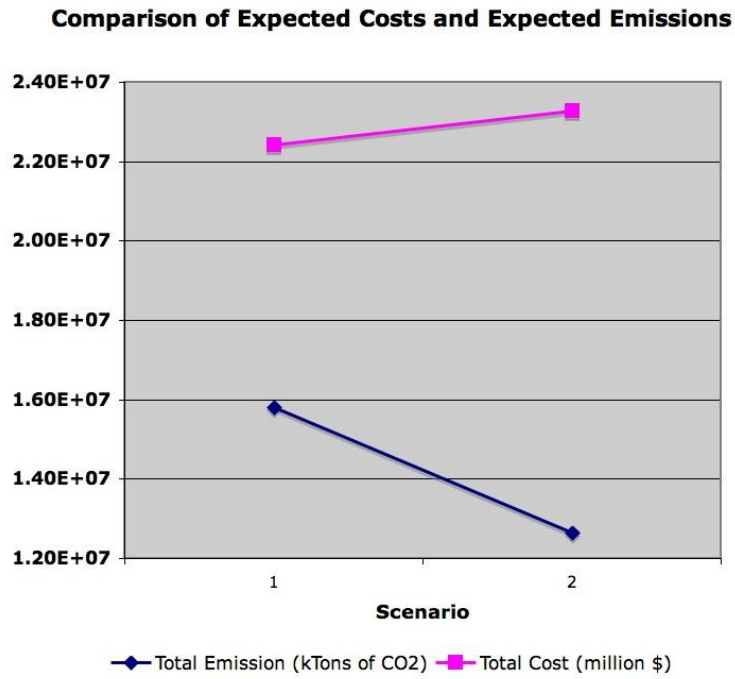


Figure 4.14: Comparison of the expected costs and expected emissions

The total costs and the total emissions of the suggested networks increase with increasing scenario number as shown in Figure 4.12 and 4.13. The increased in cost was due to the higher suggested capacity of power generation technology and direct resource usage to satisfy the stochastic demand.

To reduce the expected emissions, the expected costs were increased as a result selecting more expensive technologies and resources to reduce carbon dioxide emission. An example of such technology is the advanced gas combined cycle with carbon sequestration. The stochastic model also chose the use of natural gas as a substitute for lignite and coal. Moreover, because some of the demand paths of the stochastic demand scenario tree were higher than the deterministic demand, the results returned a wider range of technology options including the combustion gas turbine combined heat and power (CHP) as shown in Figure 4.8.

The results also show that to decrease the expected emissions by 10% or 4E+06 kTons of CO_2, it would cost approximately \$1E+06 million. In another words, \$1 million is required to reduce 4 kg of CO_2 based on the suggested networks.

As mentioned before that a Pentium 4, 1.8 GHz Dell machine was used to solve the stochastic model via the GAMS modelling tool and CPLEX v9.0. The corresponding computational statistics for solving the deterministic representative of the stochastic models in this chapter are summarised in Table 4.4. The results clearly show that the time required to solve the two cases are still minimal. These results show that the stochastic models are capable of identifying optimal energy planning strategies for Thailand under demand uncertainties.

Table 4.4: Summary of computational results for the stochastic model

	Case 1	**Case 2**
Number of variables	387137	387137
Number of equations	421921	421922
CPU time (sec)	7.227	7.166

4.4.4 Concluding Remarks

The work in the previous chapter described a multi-period deterministic energy system optimisation model at a national level. One of the drawbacks of the deterministic model for long-term energy planning was the assumption that the model has the perfect foresight of the future energy demand. In reality, the future demands are fraught with uncertainties. This chapter used the scenario-based stochastic programming approach to capture the uncertainty in demand by creating demand scenario tress with associated probability of occurring to generate nine distinct scenarios. As a result of optimising the nine scenarios with the objective function being the minimisation of the expected costs, the optimal solutions containing energy supply chain networks for 9 demand paths can be determined. From the results the decision-makers will be able to choose the most appropriate strategy to apply to the real-world.

For the case of Thailand's energy system, the suggested types of power generation technology and direct resource usage are similar to the results of the multi-period deterministic model. However, the suggested capacities of each technology are different from the previous chapter, according to the variation in stochastic demands of the nine scenarios. The wind, hydro, solar thermal parabolic and geothermal were recommended as the renewable power generation technologies. The advanced gas combined cycled was the most economical non-renewable power generation technology. However, with the consideration of environmental impact, the advanced gas combined cycled with carbon sequestration was recommended. Natural gas and biomass were suggested to be the substitute for coal and lignite while considering sustainability. The combined heat and power combustion gas turbine using bituminous coal, natural gas were also suggested to produce both electricity and heat energy to satisfy the stochastic demand.

The two models developed so far were able to determine optimal energy supply chain networks to meet both deterministic demand and stochastic demand. However, the proposed models did not take into account the spatially disaggregated nature of an energy system. In order to fully utilise the available resources and account for the energy demand in different geographical locations, the proposed model should also consider the spatial nature of an energy system. For these reasons, the next chapter investigates the modelling of a spatial energy system optimisation model.

Chapter 5

Spatial Energy System Modelling

5.1 Introduction

This chapter integrates the spatial nature of the real energy system of Thailand into the previous deterministic model. Before describing the modification to the previous deterministic model, the next sub section highlights the importance of incorporating spatial characteristics into energy system modelling.

5.1.1 Importance of spatial (space) in energy system modelling

The multi-period deterministic and stochastic optimisation models for Thailand's energy system developed and described in the previous chapters were based on the assumption that the whole country is considered as one unit which incorporated only one demand for each time period. By making that assumption, many crucial factors interlink with energy planning have been ignored.

It is undoubtedly true that within different regions of a country, the energy demands are different because of the variation in population density and the economic growth in that area. For example, the middle region of Thailand has the highest energy demand. This is because the middle region is the most populated region as the capital city of Thailand namely; Bangkok is located in the area.

Moreover, the amounts of resources in different regions are also different because of the differences in geographical location. Considering the amount of renewable resources in Thailand, the solar radiation is strongest in the north-east region, the wind speed is highest in the south region and the geothermal energy is found mostly in the north region. Considering the non-renewable resources, crude oil and condensate are located mostly in the south and middle regions.

Furthermore, the methods and costs for transporting resources and energy between each region were ignored. The transportation structure of the country is also an important factor. For example, the transmission line to transmit electricity or the pipeline to transport crude oil might not be readily available throughout the country. The structure of railway lines and roads must also be taken into account. These factors could potentially affect the costs and structure of any energy system. Therefore, in order to represent any energy system of a country, it is important to take into account its spatial characteristics.

As a result, a spatial multi-period deterministic mathematical model to determine the optimal structure of energy system of Thailand is developed. Similar to the previous models, the mathematical model is formulated as an MILP optimisation model.

The proposed MILP model aims to identify the optimal network of the energy system of Thailand throughout the planning horizon. The decisions determined by the model include: (1) the capacity of each type of energy production plants, (2) the location of those plants, (3) the quantity of resources used by each energy production plant in each location, and (4) the quantity of resources and energy being transported and their transportation mode. In order to implement the proposed model it is crucial to introduce new model structure which is described in the next section.

5.2 Model Structure

In addition to the model structure presented in Chapter 3, the important modifications to the structure are the introduction of grids and transportation modes. The grids

divide the total area into different regions. The transportation modes allow different ways of transporting both resources and energy between grids. The following subsections address the two components of the model structure in more detail.

5.2.1 Grids

As the case study for the proposed model is Thailand, the mainland has been divided into four grids depending on their geographical locations namely, “Middle, North, North-East and South”. In the mathematical formulation for the proposed model, the four grids are represented by index g.

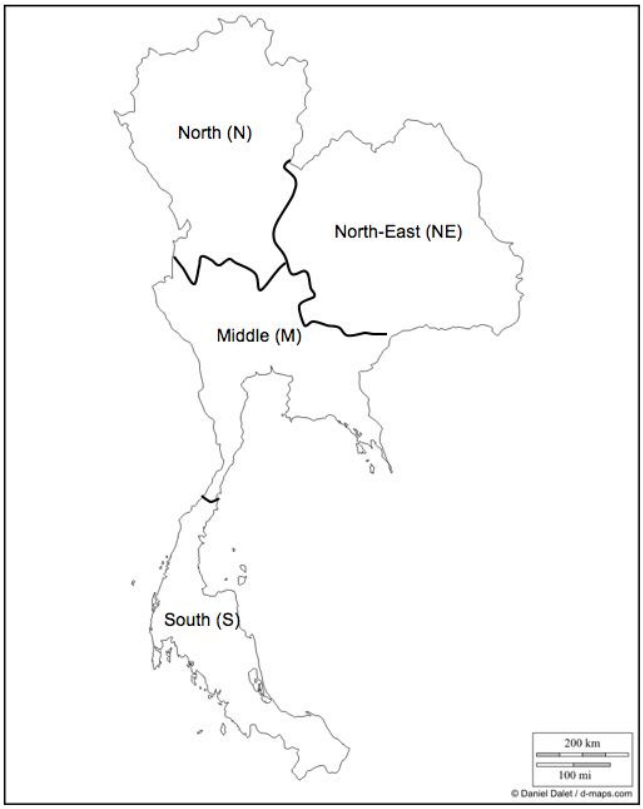


Figure 5.1: The grids

Each grid is allocated with associated demand, resources and existing energy production plants capacity for Thailand. All types of energy production plants can be built into all grids.

5.2.2 Transportation modes

As mentioned above both resources and energy can be transferred between grids. The transportation mode provides different ways of transporting the resources and energy. The transportation modes for resources are road, rail and pipeline. The transportation mode for electricity energy is transmission line. The transportation modes are represented by index m. The model allows all resources to be transported between grids. However, only electricity energy can be transferred between grids as heat energy and petroleum energy must be used locally.

The MILP optimisation model can then determine the optimal energy system for Thailand including the capacity of energy production plants in each grid and the amount of resources and energy to be transferred between grids to satisfy the demands of each grid.

It is also worth mentioning that the multi-period deterministic model described in chapter 3 is a special case of the spatial model described in this chapter. This is because when assigning the number of grid in the spatial model to 1, the mathematical formulation of the spatial model will be identical to the multi-period deterministic model as the flows of both resources and energy between grids will be ignored. The next section describes the mathematical formulation in more detail.

5.3 Mathematical Formulation

The mathematical formulation described in this section is the extension to the previous deterministic model. However, the formulation presented below also takes into account the spatial nature of the energy system by introducing grid index g and transportation mode index m. Moreover, as the emission constraints for this proposed model are identical to the deterministic model, the constraints will not be repeated in this section. Furthermore, the spatial model is formulated as a MILP model rather than a LP model. The mathematical formulation for the proposed spatial model is described below.

5.3.1 Notation

Indices

g	=	Grid
m	=	Transportation mode

Parameters

$CostFOM_{igt}$	=	Fixed operating and maintenance cost of process i in grid g during time period t ($/ktoe/year)
$CostVOM_{igt}$	=	Variable operating and maintenance cost of process i at grid g during time period t ($/ktoe)
$CostIV_{igt}$	=	Investment cost for newly-built capacity i in grid g during time period t ($/ktoe)
$CostR_{rgt}^{domestic}$	=	Cost of domestic resource r in grid g during time period t ($/ktoe)
$CostR_{rgt}^{import}$	=	Cost of imported resource r in grid g during time period t ($/ktoe)
$CostV_{vgt}^{import}$	=	Cost of imported energy v in grid g during time period t ($/ktoe)
$CostRT_{rm}$	=	Cost of transporting resource r by transportation mode m ($/ktoe)
$CostVT_{vm}$	=	Cost of energy v by transportation mode m ($/ktoe)
$gd_{gg'}$	=	Average distance between grid g and g' (km)
α_{vi}^{output}	=	Proportion of energy vector v produced per unit of process i
γ_{ri}^{input}	=	Proportion of resource r required for unit amount of process i
$conE_i$	=	Ratio for converting unit of energy vector e between MW and

		Ktoe (MW/ktoe)
$Capacity^{total}$	=	Total maximum capacity of power plant (MW)
DF_t	=	Discount factor at time period t
$R_{rg}^{\max}$	=	Amount of maximum reserve of resource r at grid g (ktoe)
$Ryear_{rg}^{\max}$	=	Amount of available resource r in grid g (ktoe)
$F_{vm}^{\min}$	=	Minimum flow of energy v by transportation model m (ktoe)
$F_{vm}^{\max}$	=	Maximum flow of energy v by transportation model m (ktoe)
$FR_{rm}^{\min}$	=	Minimum flow of resource r by transportation model m (ktoe)
$FR_{rm}^{\max}$	=	Maximum flow of resource r by transportation model m (ktoe)

Binary Variable

$VX_{vmgg'}$	=	1 if energy v is to be transported from grid g to g' by transportation model m, 0 otherwise
$RX_{rmgg'}$	=	1 if resource r is to be transported from grid g to g' by transportation model m, 0 otherwise
O_{vg}^{export}	=	1 if energy v is to be exported from grid g to g' by, 0 otherwise
O_{vg}^{import}	=	1 if energy v is to be imported from grid g to g' by, 0 otherwise
OR_{rg}^{export}	=	1 if resource r is to be exported from grid g to g' by , 0 otherwise
OR_{rg}^{import}	=	1 if resource r is to be imported from grid g to g' by , 0 otherwise

Variables

dvi_{vgt}	=	Decision variable for importing energy v into grid g at time period t (ktoe)

$dvi_{vgt}^{oversea}$	=	Decision variable for importing energy v at grid g in time period t from neighbouring countries (ktoe)
dve_{vgt}	=	Decision variable for exporting energy v at grid g in time period t to neighbouring countries (ktoe)
dl_{vgt}	=	Decision variable for local demand of energy v at grid g during time period t (ktoe)
dri_{rgt}	=	Decision variable for importing resource r into grid g at time period t (ktoe)
$dri_{rgt}^{oversea}$	=	Decision variable for importing resource r into grid g at time period t from neighbouring countries (ktoe)
Dem_{vgt}^{all}	=	Decision variable for total demand of energy v at grid g during time period t (ktoe)
dp_{rgt}	=	Decision variable for using potential domestic resource r at grid g during time period t (ktoe)
EP_{bgt}	=	Production of output b of process i in grid g during time period t (ktoe)
EP_{vgt}	=	Production of energy vector v of process i at grid g during time period t (ktoe)
EP_{vgt}^{net}	=	Net production of energy vector v of process i at grid g during time period t (ktoe)
RP_{rgt}	=	Production of resource r (petroleum product) at grid g during time period t (ktoe)
UE_{rigt}	=	Usage of resource r of process i at grid g at time period t (ktoe)
C_{igt}	=	Capacity of process i at grid g during time period t (ktoe)
C_{igt}^{MW}	=	Capacity of process i at grid g during time period t (MW)
TC_{t}^{MW}	=	Total capacity during time period t (MW)
E_{igt}	=	Expansion of process i at grid g at time period t (ktoe)
E_{igt}^{MW}	=	Expansion of process i at grid g at time period t (MW)

AU_{rgt}	=	Total usage of resource r at grid g during time period t (ktoe)
$F_{vmg'gt}$	=	Flow rate of energy vector v from grid g' to grid g at time period t by transportation mode m (ktoe)
$F_{vmgg't}$	=	Flow rate of energy vector v from grid g to grid g' by l at time period t by transportation mode m (ktoe)
$FR_{rmg'gt}$	=	Flow rate of resource r from grid g' to grid g at time period t by transportation mode m (ktoe)
$FR_{rmgg't}$	=	Flow rate of resource r from grid g to grid g' at time period t by transportation mode m (ktoe)
$OMCost_{it}$	=	Operating and Maintenance cost of process i at time period t ($)
$FOMCost_{it}$	=	Fixed O&M cost of process i at time period t ($)
$VOMCost_{it}$	=	Variable O&M cost of process i at time period t ($)
$RCost_{rt}^{domestic}$	=	Cost of domestic resource r used at time period t ($)
$RCost_{rt}^{import}$	=	Cost of importing resource r at time period t ($)
$EtCost_{vt}^{total}$	=	Total cost for transporting energy v at time period t ($)
$EtCost_{vg'gt}$	=	Cost for transporting energy v between grid g and g' at time period t ($)
$RtCost_{rt}^{total}$	=	Total cost for transporting resource r at time period t ($)
$RtCost_{rg'gt}$	=	Cost for transporting resource r between grid g and g' at time period t ($)
$InvCost_{it}$	=	Investment cost for new process i at time period t ($)
$Cost^{total}$	=	Total cost ($)

The spatial optimisation model formulation consists of two types of entities; constraints and objective functions, which are described below.

5.3.2 Objective Function

The objective function for this spatial deterministic model is similar to the one in chapter 3. However, instead of minimising the total cost of the network, the total discounted cost is minimised. The objective function can be expressed as:

$$\textbf{\textit{Minimise}} \quad Cost^{total} \tag{5.1}$$

The cost equations proposed for this model are similar to the deterministic model. However, there are some differences due to the additional transportation costs between grids.

- **Investment costs**

The total investment cost of process i during time period t ($InvCost_{it}$) can be expressed in terms of capacity of newly-built processes i at grid g (E_{igt}) and the investment cost of each newly-built capacity i as follows:

$$InvCost_{it} = DF_t \cdot \sum_g \left(E_{igt} \cdot CostIV_{igt} \right) \qquad \forall i,t \tag{5.2}$$

where

DF_t is the discount factor during time period t

- **Operation and Maintenance (O&M) costs**

The O&M costs of process i during time period t ($OMCost_{it}$) can be expressed as the sum of Fixed O&M costs ($FOMCost_{it}$) and Variable O&M ($VOMCost_{it}$) of each process i during time period t. The variable $OMCost_{it}$ is given in the form:

$$OMCost_{it} = FOMCost_{it} + VOMCost_{it} \qquad \forall i,t \qquad (5.3)$$

$$FOMCost_{it} = DF_t \cdot \sum_g \left(C_{igt} \cdot CostFOM_{igt} \right) \qquad \forall i,t \qquad (5.4)$$

$$VOMCost_{it} = DF_t \cdot \sum_g \left(C_{igt} \cdot CostVOM_{igt} \right) \qquad \forall i,t \qquad (5.5)$$

- **Domestic Raw material cost**

The cost of domestic raw material r used during time period t ($RCost_{rt}^{domestic}$) can be described in term of amount of domestic raw material r used in grid g during time period t (dp_{rgt}) and the domestic cost of each raw material r ($CostR_{rt}^{domestic}$) as follows:

$$RCost_{rt}^{domestic} = DF_{t\cdot} \sum_g \left(dp_{rgt} \cdot CostR_{rgt}^{domestic} \right) \qquad \forall r,t \qquad (5.6)$$

- **Imported Raw material cost**

The cost of imported raw material r used from neighbouring countries during time period t ($RCost_{rt}^{import}$) can be described in terms of amount of imported raw material r used in grid g during time period t (dri_{rgt}) and the imported cost of each raw material r ($CostR_{rt}^{import}$) as follows:

$$RCost_{rt}^{import} = DF_t \sum_g \left(dri_{rgt} \cdot CostR_{rgt}^{import} \right) \qquad \forall r,t \qquad (5.7)$$

- **Imported Energy cost**

The cost of imported energy v during time period t ($VCost_{vt}^{import}$) can be described in term of the amount of imported energy v in grid g during time period t (dvi_{vgt}) and the imported cost of each energy v ($CostV_{vt}^{import}$) as follows:

$$VCost_{vt}^{import} = DF_t \cdot \sum_{g} \left(dvi_{vgt} \cdot CostV_{vgt}^{import} \right) \qquad \forall v,t \qquad (5.8)$$

- **Raw Material Transportation costs**

The following equations define the total transportation cost of resource r during time period t ($RtCost_{rt}^{total}$):

$$RtCost_{rt}^{total} = DF_t \cdot \sum_{gg'} RtCost_{rg'gt} \qquad \forall r,t \qquad (5.9)$$

$$RtCost_{rg'gt} = FR_{rg'gt} \cdot CostRT_{rm} \cdot gd_{gg'} \qquad \forall r,g,g',t : g \neq g' \qquad (5.10)$$

where

$CostRT_{rm}$ is the cost of transporting resource r by transportation mode m per km

$gd_{gg'}$ is the distance between grid g and grid g'

- **Energy Transportation costs**

It is assumed that the transportation of energy v between grids is carried out by sending electricity through a transmission line which is the only one transportation mode for transporting energy in this model. The following equations define the total transportation cost of energy v during time period t ($EtCost_{vt}^{total}$):

$$EtCost_{vt}^{total} = DF_t \cdot \sum_{gg'} EtCost_{vg'gt} \qquad \forall v,t \qquad (5.11)$$

$$EtCost_{vg'gt} = F_{vg'gt} \cdot CostTE_{vm} \cdot gd_{gg'} \qquad \forall v,g,g',t : g \neq g' \qquad (5.12)$$

where

$CostVT_{vm}$ is the cost of transporting energy v by transportation mode m per km

$gd_{gg'}$ is the distance between grid g and grid g'

The total cost can be expressed as the following equation.

$$Cost^{total} = \sum_{t} \left(\begin{array}{l} \sum_{i} InvCost_{it} + \sum_{i} OMCost_{it} \\ \sum_{r} RtCost_{rt}^{total} + \sum_{v} EtCost_{vt}^{total} \\ \sum_{r} RCost_{rt}^{domestic} + \sum_{r} RCost_{rt}^{import} \\ + \sum_{v} VCost_{vt}^{import} \end{array} \right) \quad (5.13)$$

5.3.3 Constraints

Energy Production Constraints

Production variables and production constraints are formulated to describe the processes and conversion technologies of each model. Annual production of output b (both energy v and raw material r) from each process i in grid g, which is represented by EP_{bigt} can be described by parameter α_{bi}^{output} and variable C_{igt}, where α_{bi}^{output} is the proportion of output b produced by process i. The expression for EP_{bit} is given in the form:

$$EP_{bigt} = \alpha_{bi}^{output} \cdot C_{igt} \qquad \forall b, i, g, t \quad (5.14)$$

The production of output b for each process i in time period t can then be either used to supply the energy demand or can be exported. Moreover, electricity energy is influenced by the load factor (LF) and also the transmission lost (TL). The net electricity energy production v in grid g during time period t (EP_{vgt}^{net}) is given in the form:

$$EP_{vgt}^{net} + dve_{vgt} = LF \cdot \left((1 - TL) \cdot \sum_{i} EP_{vigt} \right) \qquad \forall v, g, t : v = electricity \qquad (5.15)$$

The net heat and petroleum energy production v in grid g during time period t (EP_{vgt}^{net}) is given in the form:

$$EP_{vgt}^{net} + dve_{vgt} = \sum_{i} EP_{vigt} \qquad \forall v, g, t, : v \neq electricity \qquad (5.16)$$

The second term of the left hand side of the equation is the decision variable for exporting or safe stock keeping of energy v in grid g during time period t.

The production of raw material r in grid g during time period t RP_{rgt} can be expressed as:

$$RP_{rgt} = \sum_{i} EP_{rigt} \qquad \forall r, g, t \qquad (5.17)$$

Resource Usage Constraints

The total resource usage r required by process i at grid g (UE_{rigt}) can be described in term of process capacity, as the proportion of resource r required for process i, which is represented by γ_{ri}^{input} multiplied by the capacity of process i, which is represented by C_{igt}. The expression for UE_{rigt} is given in the form:

$$UE_{rigt} = \gamma_{ri}^{input} \cdot C_{igt} \qquad \forall r, i, g, t \qquad (5.18)$$

The total resource usage in grid g, which is represented by, AU_{rgt} can be expressed as sum of resource usage r for all processes i in grid g. The variable is described in the form:

$$AU_{rgt} = \sum_{i} UE_{rigt} \qquad \forall r, g, t \tag{5.20}$$

Energy Balance Constraints

The energy balance between the net production rate of energy v at grid g and the total demand required by grid g itself can be expressed as follows:

$$EP_{vgt}^{net} = Dem_{vgt}^{all} + \sum_{mg'} \left(F_{vmgg't} - F_{vmg'gt} \right) - dvi_{vgt}^{oversea} \qquad \forall v, g, t \tag{5.21}$$

The equation above stated that the net production rate of energy v at grid g during time period t (EP_{vgt}^{net}) must be equal to the total demand in grid g during time period t that can be supplied by the biomass energy (Dem_{vgt}^{all}) plus the sum of the total flow rate exporting from this grid g ($F_{vmgg't}$) less the sum of the total flow rate of energy v imported to grid g ($F_{vmg'gt}$) and less the imported energy (from neighbouring countries) v in grid g during time period t ($dvi_{vgt}^{oversea}$).

Resource Balance Constraints

The decision variable for using the available resource r in grid g can be described by five terms. These are the total resource usage r required by grid g, the import and export of resource r between grids, the import of resource r from neighbouring countries and the domestic production of resource r (petroleum products). The relationship can be described by the following equation:

$$dp_{rgt} = AU_{rgt} + \sum_{mg'} \left(FR_{rmgg't} - FR_{rmg'gt} \right) - dri_{rgt}^{oversea} - RP_{rgt} \qquad \forall r, g, t \qquad (5.22)$$

Energy Demand Constraints

The total demand of energy v in grid g during time period t (Dem_{vgt}^{all}) can be defined by two terms. The first term is the local demand of energy v in grid g (dl_{vgt}). The second part is the imported demand of energy v into the same grid g during time period t (dvi_{vgt}). The total demand is given in the form:

$$Dem_{vgt}^{all} = dl_{vgt} + dvi_{vgt} \qquad \forall v, g, t \qquad (5.23)$$

The variable dl_{vgt} is constrained to be less than or equal to the net production of energy v in the same grid g (EP_{vgt}^{net}). The constraint is given in the form:

$$dl_{vgt} \leq EP_{vgt}^{net} \qquad \forall v, g, t \qquad (5.24)$$

From equation 5.21, the local demand (dl_{vgt}) can also be described as the net production less the amount exported to neighbouring grids, plus the imported energy from neighbouring countries, which is given in the form :

$$dl_{vgt} = EP_{vgt}^{net} - \sum_{mg'} F_{vmgg't} + dvi_{vgt}^{oversea} \qquad \forall v, g, t \qquad (5.25)$$

Moreover, the variable dvi_{vgt} is equal to the sum of the total flow rate of energy v imported to grid g ($F_{vmg'gt}$). The imported demand is expressed as:

$$dvi_{vgt} = \sum_{mg'} F_{vmg'gt} \qquad \forall v, g, t \qquad (5.26)$$

Raw Material Demand Constraints

The imported demand of raw material r at grid g during time period t (dri_{rgt}) is equal to the sum of the total flow rate of raw material r imported to grid g ($FR_{rmg'gt}$). The imported demand is expressed as:

$$dri_{rgt} = \sum_{mg'} FR_{rmg'gt} \qquad \forall r, g, t \tag{5.27}$$

On the other hand, the decision variable for using the available resource r at the same grid g (dp_{rgt}) is less than or equal to the amount of available resource r at grid g during time period t ($Ryear_{rg}^{\max}$). The constraint is given in the form:

$$dp_{rgt} \leq Ryear_{rg}^{\max} \qquad \forall r, g, t \tag{5.28}$$

The total usage of resource r in grid g must also be less than or equal to the maximum reserves of each resource in grid g ($R_{rg}^{\max}$). The statement can be defined as follows:

$$\sum_{t} dp_{rgt} \leq R_{rg}^{\max} \qquad \forall r, g \tag{5.29}$$

Unit Conversion Constraints

In general the unit for the capacity of power plant is in MW. The following equations is formulated to convert capacity of process i at grid g during time period t in ktoe (C_{igt}) to capacity in MW (C_{igt}^{MW}).

$$C_{igt}^{MW} = C_{igt} \cdot conE_i \qquad \forall i, g, t \tag{5.30}$$

The total energy production capacity of all power plants during time period t can be then expressed as:

$$TC_t^{MW} = \sum_g \sum_i C_{igt}^{MW} \qquad \forall t \tag{5.31}$$

The same applies to converting units for expansion of capacity of process i at grid g during time period t in ktoe (E_{igt}) to expanded capacity in MW (E_{igt}^{MW}).

$$E_{igt}^{MW} = E_{igt} \cdot conE_i \qquad \forall i, g, t \tag{5.32}$$

Capacity Constraints

For this proposed multi-period model, the capacity of process i in grid g during year t (C_{igt}) can be expressed as the previous period's capacity of process i plus an expansion of process i in period t (E_{igt}) which is given by:

$$C_{igt} = C_{ig}^0 + E_{igt} \qquad \forall i, g, t : t = 1 \tag{5.33}$$

$$C_{igt} = C_{ig,t-1} + E_{igt} \qquad \forall i, g, t : t \neq 1 \tag{5.34}$$

The maximum power plant capacity during time period t can be controlled by the following constraint.

$$TC_t^{MW} \leq Capacity^{total} \qquad \forall t \tag{5.40}$$

Transportation Constraints

If a particular grid cannot satisfy the energy demand from converting its own resources into energy then there is a need for flow of either resources or moreover energy between different grids. The optimal transportation types for each flow of

resource or energy between grids also have to be chosen. Similar to the transportation constraints proposed by Almansoori, 2006 to reflect the above statement, the flow of both energy and resources between grids must be bound by the maximum and minimum allowable flow rates ($F_{vm}^{\min}, F_{vm}^{\max}, FR_{rm}^{\min}$ *and* $FR_{rm}^{\max}$). For example, the constraints will ensure that only the flow of electricity energy by transmission line is allowed between grids, not other energy types. The constraints can be expressed as:

$$F_{vm}^{\min} \cdot VX_{vmgg'} \le F_{vmgg'} \le F_{vm}^{\max} \cdot VX_{vmgg'} \qquad \forall v, m, g, g' : g \ne g' \qquad (5.41)$$

$$FR_{rm}^{\min} \cdot RX_{rmgg'} \le FR_{rmgg'} \le FR_{rm}^{\max} \cdot RX_{rmgg'} \qquad \forall r, m, g, g' : g \ne g' \qquad (5.42)$$

Flow of a resource or an energy type such as electricity between grids must be constrained into only direction. This is due to the concept that it would not be sensible for a grid to export to other grids while that grid needs to import from other grids in the first place. Therefore, a grid can only export resource or energy to other grids or import them from neighbouring grids, or neither but not both. To control the flow of both energy and resources between grids into only one direction, the following constraints are imposed.

$$O_{vg}^{export} \ge VX_{vmgg'} \qquad \forall v, m, g, g' : g \ne g' \qquad (5.43)$$

$$O_{vg}^{import} \ge VX_{vmg'g} \qquad \forall v, m, g, g' : g \ne g' \qquad (5.44)$$

$$O_{vg}^{import} + O_{vg}^{export} \le 1 \qquad \forall v, g \qquad (5.45)$$

$$OR_{rg}^{export} \ge RX_{rmgg'} \qquad \forall r, m, g, g' : g \ne g' \qquad (5.46)$$

$$O_{rg}^{import} \ge RX_{rmg'g} \qquad \forall r, m, g, g' : g \ne g' \qquad (5.47)$$

$$OR_{rg}^{import} + OR_{rg}^{export} \le 1 \qquad \forall r, g \qquad (5.48)$$

5.3 Case Study: Thailand's Energy System

In order to examine the feasibility of the proposed spatial model, the scenarios considered in this chapter have been generated using the same structure as the scenarios in chapter 3. The scenarios are described below.

1) Optimising the proposed spatial model without considering the existing energy infrastructure of Thailand.
2) Optimising the proposed spatial model with consideration of the existing energy infrastructure of Thailand.
3) Same as scenario 2 but with the emission factor equal to 0.9 to see the effect of reducing the total emission by 10% to the energy planning strategy.

5.3.1 Input Data

The input data required for this spatial model is based on the data used in the deterministic model. However, additional data related to geographical location is required. The data is divided into five categories including technology data, resource data, financial data, demand data and grid data. The date is presented below.

5.3.1.1 Technology Data

The only modification to the technology data used in this proposed spatial model is the capacity of existing technologies in Thailand which is shown in Table 3.9. The capacities of existing technologies in the considered grids are required, instead of the capacity for the whole country. The data is shown in Table 5.1 below.

Table 5.1: Capacity of existing technologies in each grid in ktoe

Technology	M	N	NE	S
Geothermal	0.00	0.23	0.00	0.00
Hydro	812.12	970.40	560.69	236.01
Wind Onshore	0.00	0.00	0.00	0.15
Solar Thermal Parabolic	0.02	0.39	0.00	0.01
Supercritical Steam Pulverized Coal (Bituminous)	1,014.39	0.00	0.00	0.00
Supercritical Steam Pulverized Coal (Lignite)	0.00	1,808.05	0.00	0.00
Biomass Steam Cycle	187.66	50.77	169.73	32.02
Oil Steam Turbine	0.00	0.00	0.00	256.14
Gas Steam Turbine	1,084.83	0.00	0.00	0.00
Oil/Gas Steam Turbine	2,704.55	0.00	0.00	105.54
Gas Internal Combustion Engine (Diesel)	0.00	4.07	0.00	0.00
Combustion Gas Turbine Combined Heat Power (Sub-bituminous)	128.07	0.00	0.00	0.00
Combustion Gas Turbine Combined Heat Power (Bituminous)	135.60	0.00	0.00	0.00
Combustion Gas Turbine Combined Heat Power (Gas)	1,143.59	0.00	0.00	0.00
Conventional Gas Combined Cycle	7,600.43	0.00	555.34	510.77
Conventional Combustion Gas Turbine (Petroleum Products)	275.73	0.00	0.00	183.82
Conventional Combustion Gas Turbine	0.00	178.54	0.00	0.00
Petroleum Refinery	5,831.72	1,000.00	1,000.00	31,000.00

[DEDE, 2005a] [DMF, 2005a] [DEDE 2004b] [DEDE 2003e] [DEDE 1999] [DEDE, 2009a] [DEDE, 2009b] [DEDE, 2009c] [PDP, 2007] [EIA, 2007] [EIA, 2009].

5.3.1.2 Resource Data

The resource data required by the proposed model include the estimated availability of each resource per year and the estimated reserve of each resource in each grid. The two data types are shown in Table 5.2 and Table 5.3.

Table 5.2: Availability per year of each resource in each grid

Resource per Year	**M**	**N**	**NE**	**S**
Crude-Oil	0.00	0.00	0.00	10,000.00
Condensate	0.00	0.00	0.00	5,000.00
Uranium	0.00	0.00	0.00	0.00
Geo-Energy	0.00	164.41	0.00	0.00
Water-Energy	2,394.90	2,394.90	2,394.90	798.30
Wind-Energy	0.00	0.00	0.00	3,628.89
Solar-Energy	1,701.04	1,701.04	6,804.17	1,134.03
Natural-Gas	0.00	0.00	0.00	30,000.00
Petroleum-Product	0.00	0.00	0.00	0.00
Bituminous	0.00	0.00	0.00	0.00
Lignite	0.00	20,000.00	0.00	0.00
Sub-Bituminous	0.00	0.00	0.00	0.00
Wood	7,500.00	7,500.00	7,500.00	7,500.00

Table 5.3: Total reserves of each resource in each grid

Total Reserves	**M**	**N**	**NE**	**S**
Crude Oil	0.00	0.00	0.00	47,797.00
Condensate	0.00	0.00	0.00	89,639.00
Uranium	0.00	0.00	0.00	0.00
Underground Heat	0.00	∞	0.00	0.00
Water	∞	∞	∞	∞
Wind	0.00	0.00	0.00	∞
Solar	∞	∞	∞	∞
Natural Gas	0.00	0.00	0.00	753,199.00
Petroleum Product	0.00	0.00	0.00	0.00
Bituminous	0.00	0.00	0.00	0.00
Lignite	0.00	745,382.00	0.00	0.00
Sub-Bituminous	0.00	0.00	0.00	0.00
Wood	∞	∞	∞	∞

[Shrestha, 2006] [Jaimsin, 2005] [DEDE, 2003e] [DEDE, 1999] [DEDE, 2003d] [Limjeerajarus et al., 2004] [DEDE, 2004a] [Wongsapai, 2004c] [Szwarc, 2004] [DEDE, 2004c] [Keawsompong et al., 2002] [DEDE, 2004b] [Limjeerajarus et all, 2004b] [World Bank, 2001] [Raksaskulwong, 2004] [Ramingwong et al., 2000] [Raksaskulwong and Chaturongkawanich, 2001] [CMU, 2004] [Pacudan, 2003] [Greacen, 2004] [DMF, 2005a] [MOE, 2008] [MOE, 2007] [DEDE, 2009a] [DEDE, 2009b] [DEDE, 2009c] [Sajjakulnukit, 2005]

5.3.1.3 Financial Data

Transportation cost

The additional financial data required for this spatial model is the costs to transport resources and energy by different transportation mode. In Thailand the estimated cost for road and rail transport are $0.231 and $0.028 per ton-km respectively. The two transportation modes can be used to transport natural gas, different types of coal, lignite, wood, crude oil, condensate, and petroleum products.

Moreover, natural gas, crude oil, condensate, and petroleum can also be transported by pipeline. However, the pipeline structure of Thailand is not well established. It is therefore difficult to estimate the transportation cost by this mode. The transportation cost by pipeline is assumed to be $10 per ktoe for this proposed model. The electricity transmission cost is also assumed to be $10 per km-ktoe. The transportation costs in $ per km-ktoe is shown in Table 5.4.

Table 5.4: Transportation costs ($ per km per ktoe)

Resources and Energy	**Road**	**Rail**	**Pipeline**	**Transmission line**
Crude Oil	190	19	10	-
Condensate	190	19	10	-
Uranium	5	-	-	-
Underground Heat	-	-	-	-
Water	-	-	-	-
Wind	-	-	-	-
Solar	-	-	-	-
Natural Gas	230	23	-	-
Petroleum Product	190	19	10	-
Bituminous	300	30	-	-
Lignite	800	80	-	-
Sub-Bituminous	320	32	-	-
Wood	730	73	-	-
Electricity Energy	-	-	-	10

[TBOI, 2008]

Discount Factor

The objective function of the proposed spatial model is to minimise the total discounted costs of an energy system. As the proposed model is formulated as an MILP model, the discount factor has to be put in as a parameter. Assuming the interest rate and the inflation rate are 4% and 0% respectively, the discount factor for 20 years planning horizon is shown in Table 5.5.

Table 5.5: Discount Factor (Interest rate = 4%)

Year	Discount Factor	Year	Discount Factor
1	1.00000	11	0.67556
2	0.96154	12	0.64958
3	0.92456	13	0.62460
4	0.88900	14	0.60057
5	0.85480	15	0.57748
6	0.82193	16	0.55526
7	0.79031	17	0.53391
8	0.75992	18	0.51337
9	0.73069	19	0.49363
10	0.70259	20	0.47464

5.2.1.4 Demand Data

For this proposed spatial model, the demand is assumed to be proportional to the population density. The demand for the four grids was calculated from the total demand for the whole country used in Chapter 3 and the population density of each grid. The population density is shown in Table 5.6. The estimated energy demands for the three time periods are shown in Table 5.7 to Table 5.9 respectively.

Table 5.6: Estimated population density of in different region of Thailand

	M	N	NE	S
Population Density%	31.50	16.45	29.36	11.59

[MOE, 2008]

Table 5.7: Estimated energy demand of the first time period

Energy Type	Time Period 1 (0% penetration factor)			
	M	N	NE	S
Electricity Energy	3,936.20	2,055.26	3,668.52	1,446.95
Heat Energy	7,415.77	3,872.10	6,911.46	2,726.05
Petroleum Energy	13,254.58	2,055.26	12,353.20	4,872.41

Table 5.8: Estimated energy demand of the second time period

Energy Type	Time Period 2 (50% penetration factor)			
	M	N	NE	S
Electricity Energy	5,904.30	3,082.89	5,502.78	2,170.43
Heat Energy	11,123.66	5,808.15	10,367.19	4,089.08
Petroleum Energy	19,881.87	3,082.89	18,529.80	7,308.62

Table 5.9: Estimated energy demand of the third time period

Energy Type	Time Period 3 (150% penetration factor)			
	M	N	NE	S
Electricity Energy	5,904.30	3,082.89	5,502.78	2,170.43
Heat Energy	11,123.66	5,808.15	10,367.19	4,089.08
Petroleum Energy	19,881.87	3,082.89	18,529.80	7,308.62

5.3.1.5 Grid Data

The grid data required by this model is the estimated distance between each grid which is shown in Table 5.10.

Table 5.10: The distances between grids

Distance (km)	M	N	NE	S
M	0	366	379	695
N	366	0	322	998
NE	379	322	0	1011
S	695	998	1011	0

5.3.2 Results and Discussion

The proposed multi-period spatial optimisation model was formulated as a MILP model which takes into account the geographical location of both resources and demands in an energy system. The model was applied to the energy system of Thailand with additional input data related to the spatial nature of the energy system which is described in the previous section. The proposed spatial model was able to determine the optimal energy supply chain network for different regions of Thailand, identifying the type, scale, and location of each energy production plant. The flow of resources and energy between grids were also suggested.

Scenario I: without existing capacities

The optimal energy supply chain network structure of scenario I for the three time periods are shown in Figure 5.2 to 5.4 respectively.

First time period

From Figure 5.2, it can be seen that to satisfy the electricity energy demand in the middle region of Thailand, solar thermal parabolic and hydro power plants were suggested to be constructed with their maximum capacities which are 565 and 830 ktoe respectively. However, to satisfy the demand, the model suggested that import of electricity energy through transmission line from the north and the south regions are required. For the north-east region, the solar thermal parabolic was the main power plant to be built with capacity of 2,259 ktoe. Import of electricity energy was also required from the north region. For the north region, the supercritical steam lignite was recommended as all the lignite available in Thailand is located in that region. Considering renewable energy power plant, hydro, solar thermal parabolic and geothermal power plants were also suggested at their maximum potential capacities. Furthermore, nearly 3,500 ktoe of electricity energy from this region is exported to the middle and the north-east regions. The model suggested that it is cheaper to construct the supercritical steam lignite power plant with higher capacity than the regional demand and transmit the excess electricity to the middle and north-east regions.

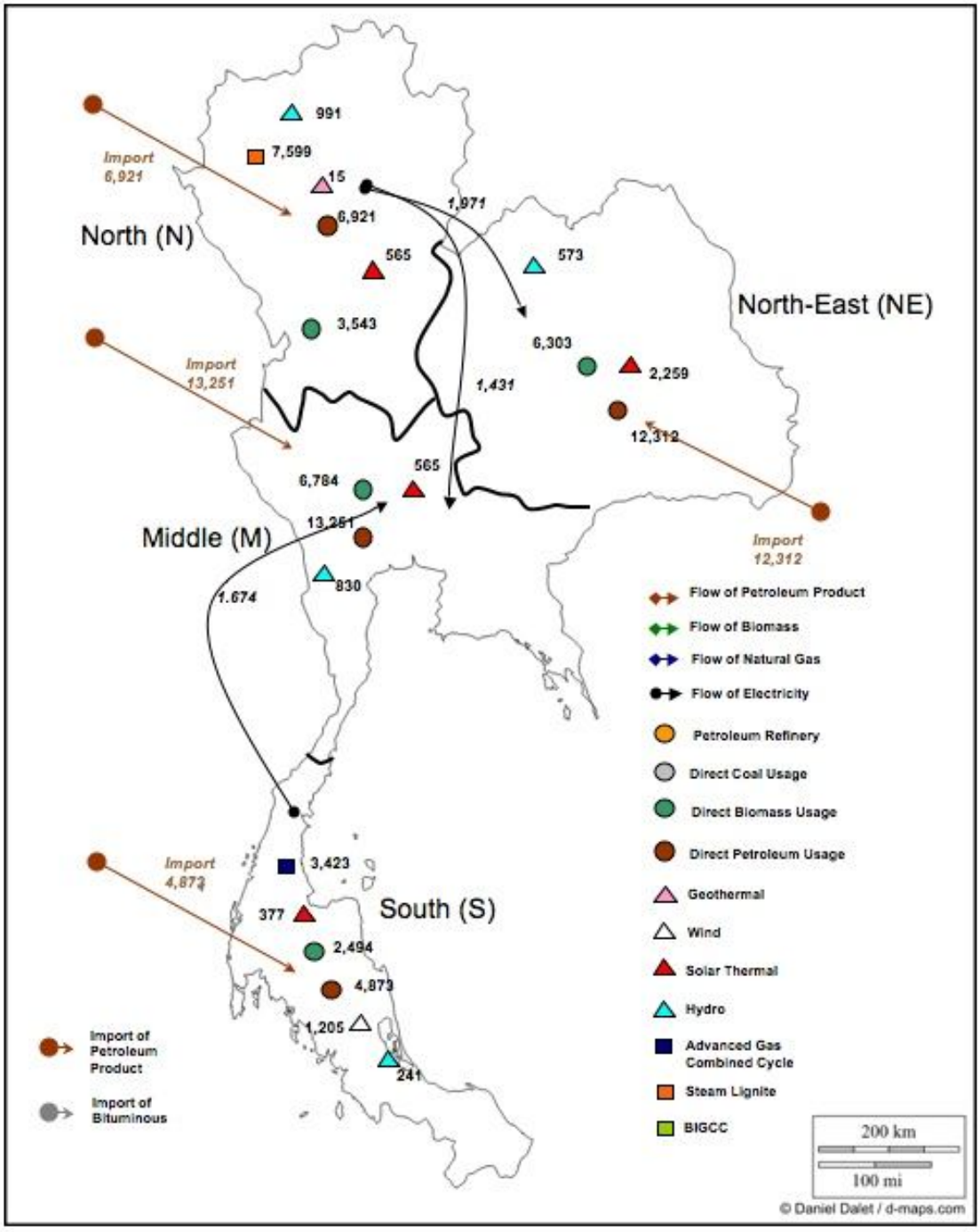


Figure 5.2: The suggested network structure of spatial energy supply chain for Scenario I during the first time period

For the south region, the advanced gas combined cycle was the main power generation technology suggested for the region with the capacity of 3,423 ktoe. The model suggested that the best strategy is to develop the power plant in the south of Thailand where natural gas is available to be utilised with no extra transportation required. The excess generated electricity can then be transmitted through the transmission line to the middle region of the country. As the wind speed in the south region of Thailand is the highest, the model suggested that 1,205 ktoe of wind power plant to be built in the region. The hydro and solar thermal parabolic power plants were also suggested.

For all regions, the heat energy demands were satisfied by using biomass as fuel. However, the petroleum energy demands were met by importing petroleum products from overseas which is different from the optimal network of the multi-period deterministic model described in chapter 3. When considering the geographical location of resources and the transportation of both resource and energy, the model suggested that it is more economical to import petroleum products directly from overseas. Even though the import method was chosen by the model, the results might be changed, depending on the variation in price of the petroleum products and the quantity that can be imported from overseas.

Second time period

Additional to the suggested capacity for the first time period, the biomass integrated gasification combined cycle (BIGCC) power plants were suggested in the north and the north-east regions. The capacity of the advanced gas combined cycle power plant in the south region has been increased to 18,955 ktoe to cover the increase in electricity energy demands in the middle, the north-east and also the south regions. Extra flow of biomass from the north to the middle and the north-east regions were also established as shown in Figure 5.3. Furthermore, to satisfy the increased in heat demand for the second time period, import of bituminous coal to the middle region is required.

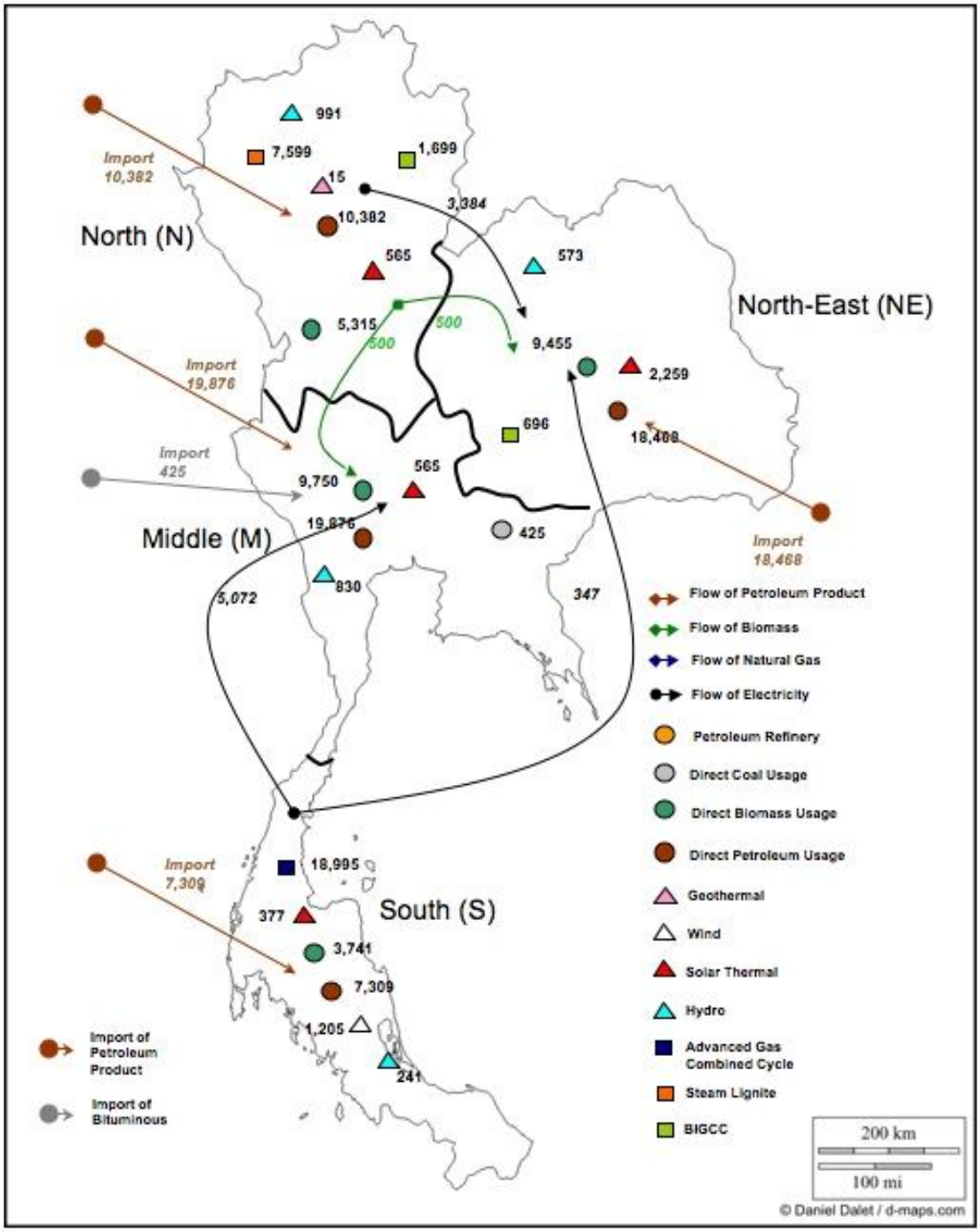


Figure 5.3: The suggested network structure of spatial energy supply chain for Scenario I during the second time period

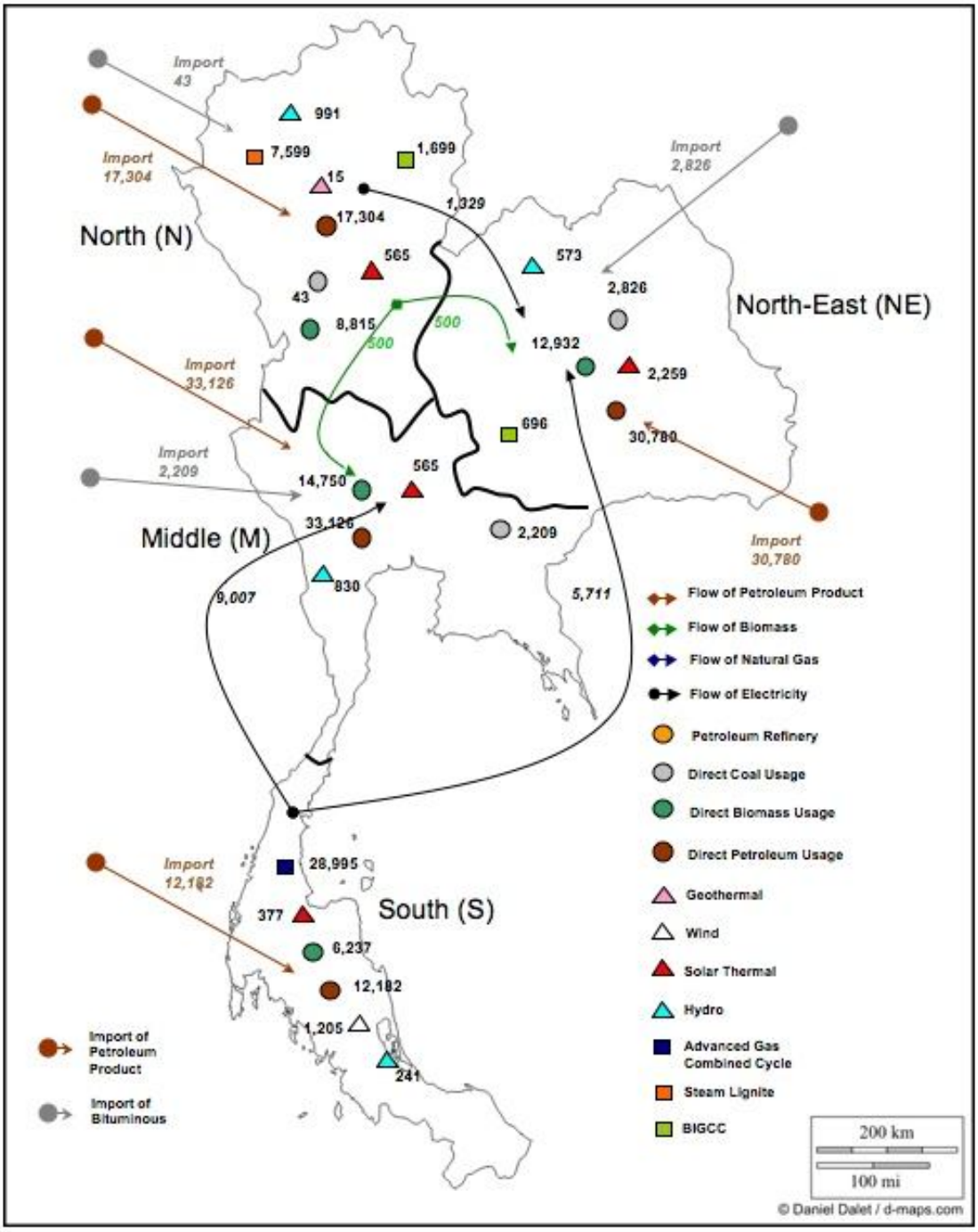


Figure 5.4: The suggested network structure of spatial energy supply chain for Scenario I during the last time period

Third time period

From Figure 5.4, it can be summarised that no additional power generation technology has been suggested in the last period. However, the capacity of the advanced gas combined cycle power plant significantly increased to 28,995 ktoe. The import of petroleum products and bituminous coal were also suggested for all regions.

Scenario II: with existing capacities (β=1)

When the existing capacities of the power plants in Thailand have been included, similar to the results of the previous scenario and the results of the multi-period deterministic model, the capacity expansion of advanced gas combined cycle power plant has been suggested as shown in Figure 5.5. The renewable power generation technologies including hydro, solar thermal parabolic, wind turbine and geothermal were also recommended at their maximum capacities. The biomass and lignite also have been suggested as the two main fuels for heat energy demand as shown in Figure 5.6.

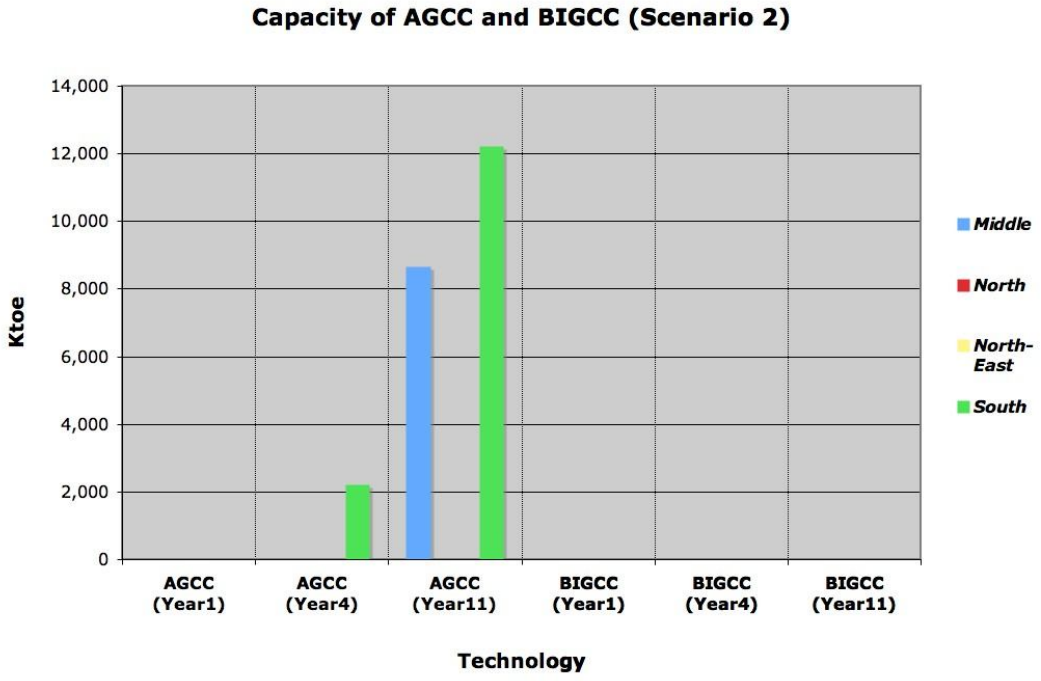


Figure 5.5: The capacity of AGCC and BIGCC *(β=1)*

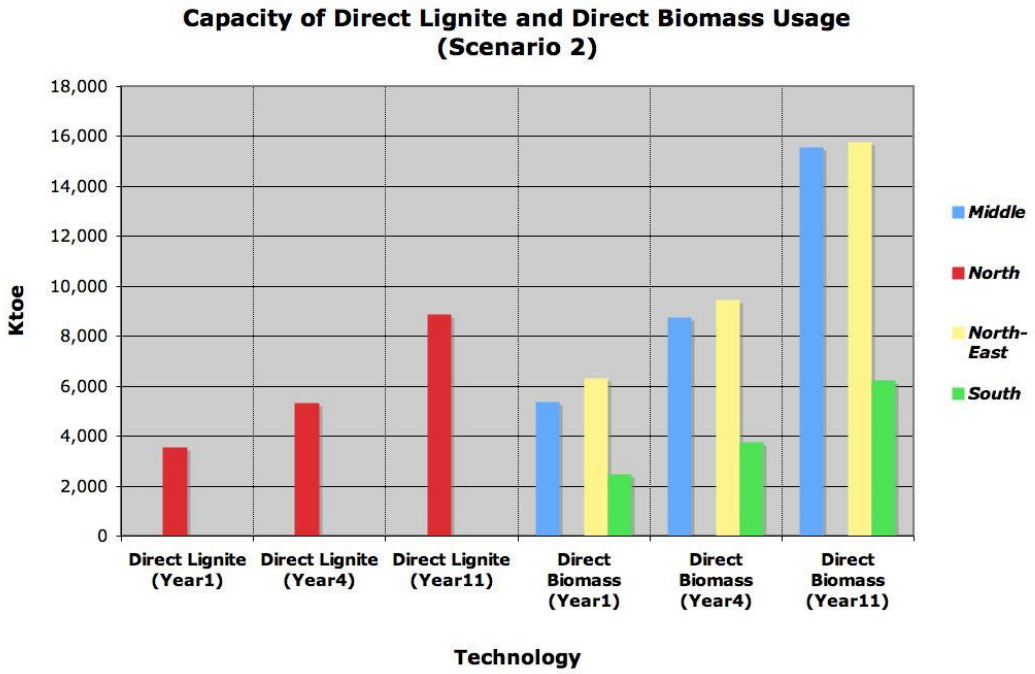


Figure 5.6: The capacity of direct lignite and biomass usage *(β=1)*

Furthermore, the existing petroleum refineries were built in the south and the middle regions to account for the crude oil and condensate that are locally available. The petroleum products can then be transported by pipeline and rail to other regions of Thailand. However, it is also suggested that in the later time period the petroleum products should be imported directly, instead of importing crude oil.

Scenario III: with existing capacities (β=0.9)

When the emission factor is decreased to 0.9, it is as expected that capacity of the advanced gas combined cycle power plant will be replaced by a technology with lower CO2 emission. The technology is biomass integrated gasification combined cycle for this scenario. The capacity of the AGCC and BIGCC are shown in Figure 5.7. The direct usage of lignite as fuel was also replaced by biomass as shown in Figure 5.8.

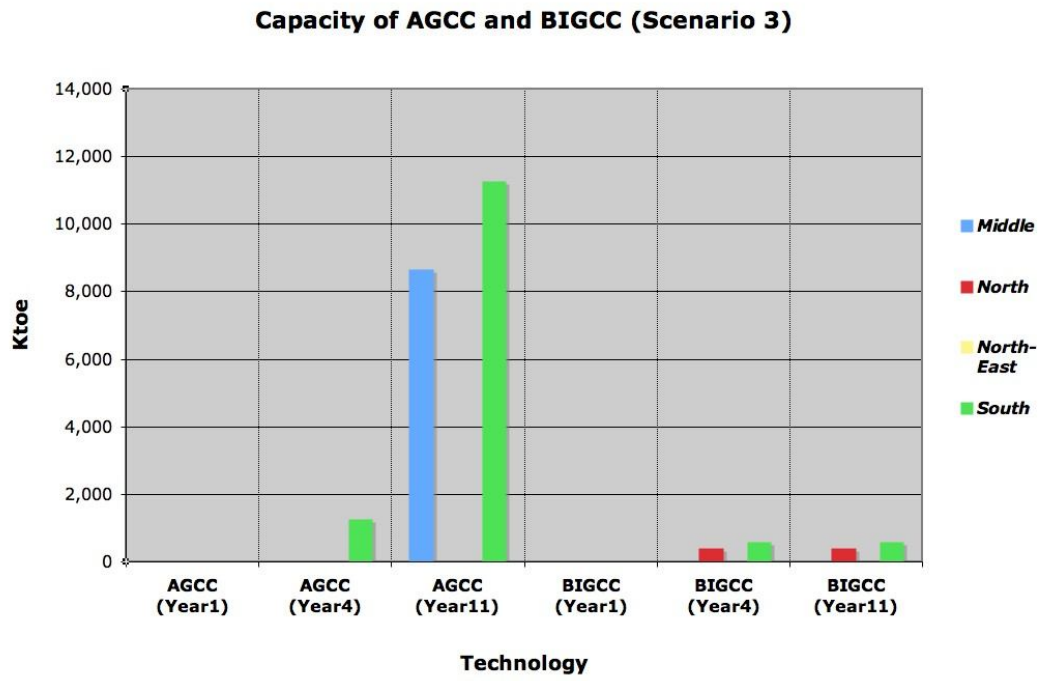


Figure 5.7: The capacity of AGCC and BIGCC *(β=0.9)*

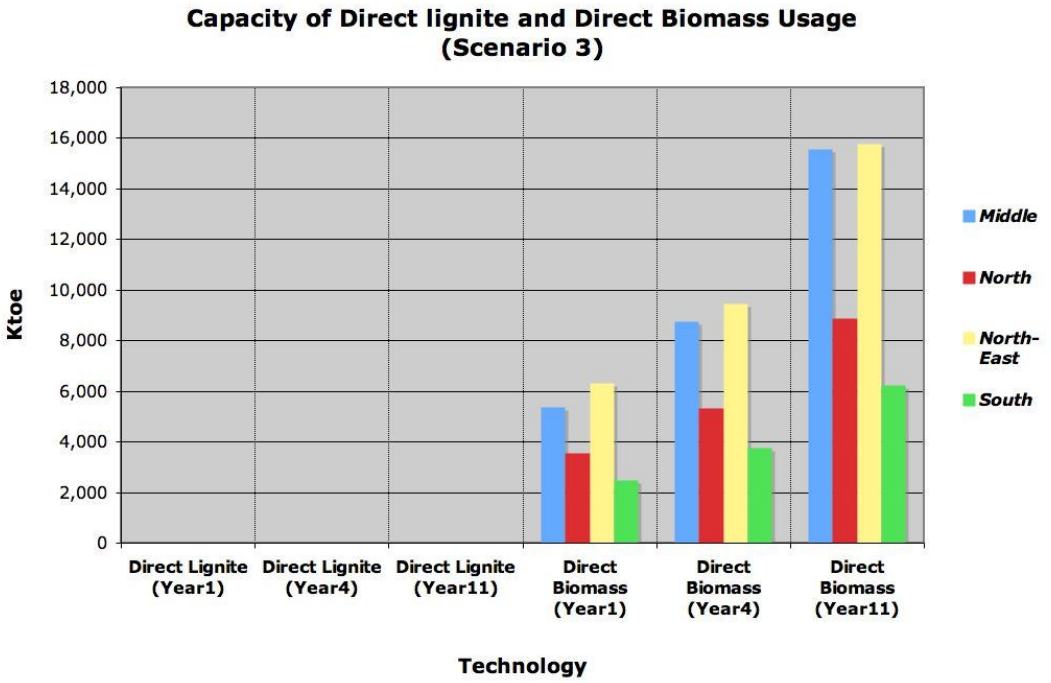


Figure 5.8: The capacity of direct lignite and biomass usage *(β=0.9)*

As mentioned before, a Pentium 4, 1.8 GHz Dell machine was used to solve the MILP model via the GAMS modelling tool and CPLEX v9.0. The corresponding computational statistics for solving the MILP models in this chapter are summarised

in Table 5.11. The table clearly shows that the time required to solve the three scenarios are minimal in comparison with the number of variables and equations involved in both scenarios. The optimality gaps are also very low which prove to be satisfactory. These results show that the MILP models are capable of identifying optimal energy planning strategies for Thailand in a very short time.

Table 5.11: Summary of computational results for the multi-period spatial model

	Scenario 1	**Scenario 2**	**Scenario 3**
Number of single variables	200722	200722	200722
Number of discrete variables	17920	17920	17920
Number of equations	245094	245042	245043
Optimality gap (%)	0.015	0.015	0.015
CPU time (sec)	4.13	4.83	4.019

5.3.3 Concluding Remarks

The aim of the work in this chapter is to develop a multi-period spatial deterministic model which incorporates the geographical location of the country of interest into consideration in determining the optimal energy supply chain network to satisfy the future energy demand. The proposed spatial model was based on the multi-period deterministic model developed in chapter 3. However, in order to capture the spatial nature, a few tasks have been completed including, (1) dividing the mainland area of the country of interest into grids, (2) collecting the necessary data such as the amount of resources and demands in each grid, and (3) modifying the deterministic mathematical formulation to include the necessary indices, variables and constraints to capture the spatial nature, such as the flow of resources and electricity energy between grids. The proposed model has been formulated as a MILP model. The spatial model was able to determine optimal energy supply chain networks by identifying scale and type of energy production capacity, scale and type of resource usage in each grid. The model was also able to discover the optimal flow of resources and energy between grids to satisfy the energy demand throughout the planning horizon.

For this chapter Thailand was again used as the case study with the mainland area being divided into 4 grids, named M, N, NE and S, representing middle, north, north-east and south regions of Thailand. The feasibility of the proposed model was analysed with 3 scenarios. The generated results demonstrate the usefulness of the spatial optimisation model in the context of long-term energy planning at the national level.

The advanced gas combined cycle and other power generation power plants from renewable energy were once again chosen for the suggested network. However, finer details of locations of each power plant were determined according the location of the resources. In the case of the advanced gas combined cycle power plant, the model suggested that the best strategy is to develop most of the power plants in the south of Thailand where natural gas is available to be utilised with no extra transportation required. Most of the hydro power plants were suggested to be developed in the north and middle regions of Thailand. The wind power plants were suggested to be built in the south region of Thailand as these areas are close to the sea with high wind speed. The solar thermal parabolic power plants were recommended for the north-east region of Thailand where the strength of the sun was predicted to be strongest throughout the year. The geothermal power plants were also recommended to be developed in the north region of Thailand where most hot springs are found. As for heat energy the lignite and biomass resources were also chosen as before. The lignite was replaced by only biomass resource in the attempt to reduce the carbon dioxide emission. From the results it can be implied that the trend of the energy planning strategy was the same as the previous model but with higher details of interactions and locations between resources, energy production technologies and demands.

From the results, it can be concluded that the geographical location and the scale of production of energy depend heavily on the local availability of resources in each grid. However, the energy demand in each grid and the cost of energy production technologies were also influential to the structure of an energy supply chain network. Furthermore, the transportation costs for both resources and energy are also important factors as the costs vary between different resources.

The spatial model described in this chapter only divides the country's total area into four main grids. However, to fully represent the geographical location of an energy system, higher numbers of grids are required. As the Ministry of energy of Thailand is currently promoting the development of power production from renewable sources, the next chapter investigates the modelling of a Biomass-to-Energy supply chain network with application to Thailand.

Chapter 6

Biomass-to-Energy Spatial Energy System Modelling

6.1 Introduction

In the previous chapter, a spatial deterministic multi-period optimisation model has been developed to determine the optimal network structure of energy system for Thailand throughout the planning horizon. The model takes into account various energy production technologies that use different kinds of resources as raw materials. The model divided the total mainland area of Thailand in to 4 grids to capture the spatial nature of a real energy system.

However, in order to develop a model that fully reflects the energy system for the whole country, a large amount of real data on all types of energy production technology is required. With the increasing interest in promoting renewable energy by the government of Thailand, the proposed model developed and described in this chapter is focused only on energy production technologies using "***biomass***" as a raw material.

Moreover, as there are many kinds of biomass available in Thailand. Instead of considering all types of biomass as one resource, the proposed model takes into account various biomass with different heat value as different raw materials. The types of biomass that are available in Thailand include bagasse, cane trash, palm fibre, palm shell, palm bunch, palm frond, rice husk, rice straw, corncob, cornstalk, tapioca, parawood and wood.

Furthermore, with the intention of capturing the spatial nature of real energy systems, the total mainland area of Thailand should be divided into girds with a smaller area. The smaller the area of each grid means the higher detail of the network. In this chapter, instead of representing the energy system with four grids, the total mainland area has been divided to seventy. The grids are divided according to the location of each province in Thailand. As there are seventy provinces in Thailand, the number of grids becomes seventy as stated above.

6.2 Model Structure

The Thailand spatial biomass to energy model is a special version of the previous spatial energy system model for Thailand. The previous model considered various types of available resources that can be converted to energy that supply electricity and heat demands of all four regions of Thailand. This model only investigates using biomass as a raw material to produce electricity for Thailand. However, this model has a higher complexity than the previous model in number of ways including:

- The numbers of grids as the four regions of Thailand have been divided further into 76 provinces.
- The biomass resource has been modified to include many types of biomass such as rice husk, rice straw and corncob.
- The technology for converting biomass into electricity has also been updated.

Although the model structure of the proposed model is the same as the spatial model presented in the previous chapter the elements contained in each component are different to reflect the new biomass-to-energy spatial optimisation model. The new elements for each component are described below.

6.2.1 Technology

As this proposed model focuses on the Biomass-to-Energy supply chain network, only the biomass thermal conversion technologies will be taken into account in this model.

Similar to the previous model, the technology type is represented by index i.

The technologies for converting biomass into energy considered in this model are the Biomass Integrated Gasification Combined Cycle (BIGCC) and Biomass-fired steam turbine (BST). As different biomass has different heat value, the power generation capacity of each biomass type using the same quantity will be different. Therefore, BIGCC using rice straw as raw material will be counted as one type of technology and BIGCC using corncob will also be counted as another type of technology in this model. As this model considers 13 types of biomass, therefore, a total of 26 biomass thermal conversion technology types are taken into account in this model.

6.2.2 Raw Material

The only raw material considered in this model is the biomass. However, as there are many kinds of biomass available in Thailand, each type of the biomass will also be taken into account in this model. Also similar to the previous model, the raw material type is characterised by index r. The list of each type of biomass is shown in Table 6.1.

Table 6.1: Type of Biomass

Biomass Type
Bagasse
Cane Trash
Palm Fibre
Palm Shell
Pam Empty Bunch
Palm Oil Frond
Rice Husk
Rice Straw
Corncob
Corn Stalk
Tapioca rhizome
Parawood
Wood

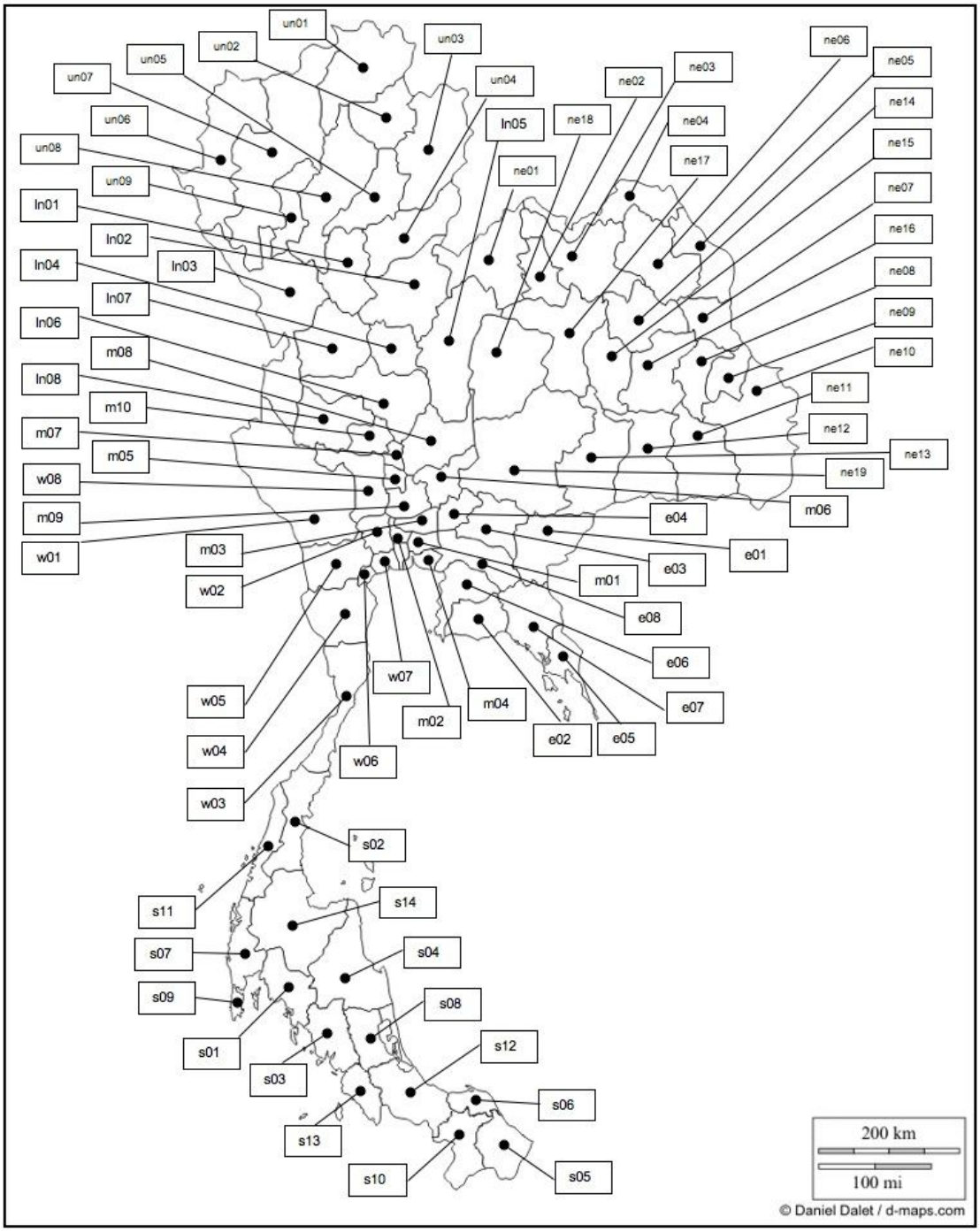


Figure 6.1: The provinces

6.2.3 Grid

As mentioned above that the number of grid cells considered in this model has been increased to 76 grids from the 4 grids used in the previous model to represent each of the provinces in Thailand. It is worth mentioning that the size of each grid is different

according to the actual size of each province in Thailand. The same index g is also used to signify each grid in this model. The new grids are shown in Figure 6.1.

6.2.4 Transportation Mode

The only transportation mode used in this model is by road (truck), therefore the index l which represents the transportation mode in the previous model has been discarded.

6.3 Mathematical Formulation

The mathematical formulation described in this section is similar to the one for the previous model in many ways. The model is formulated as a MILP model. However, the main difference is the change to the objective function. In this model the objective function is to maximise the profit instead of minimising the cost of the supply chain network. Moreover, because of the increase in complexity from the number of grids considered in this model, this proposed model will not taken into account the uncertainty in demand. The reformulated mathematical formulation is described below. However, as the capacity constraints and the energy and raw material transport constraints are similar to the previous model, the two constraints are not described in this section.

6.3.1 Notation

Indices

i	=	Process of energy production
r	=	Resource for energy production (Raw material)
t	=	Time period
v	=	Energy vector
g	=	Grid

Parameters

$CostFOM_{ig}$	=	Fixed operating and maintenance cost of process i at grid g ($/ktoe/year)
$CostVOM_{ig}$	=	Variable operating and maintenance cost of process i at grid g ($/ktoe)
$CostIV_{ig}$	=	Investment cost for newly-built capacity i at grid g ($/ktoe)
$CostR_{rg}$	=	Cost of resource r at grid g ($/ktoe)
$CostOE_{rg}$	=	Average cost of other energy at grid g ($/ktoe)
$CostTE_{gg'}$	=	Cost to transport energy v from grid g to g' ($/ktoe/km)
FP	=	Fuel price ($/Litre)
TFR	=	Truck fuel rate (Litre/km)
TC	=	Truck capacity (Ton)
$gd_{gg'}$	=	Average distance between grid g and g' (km)
α_{vi}^{output}	=	Proportion of energy vector v produced per unit of process i
γ_{ri}^{input}	=	Proportion of resource r required for unit amount of process i
LF	=	Load factor
TL	=	Percentage of transmission loss
Dem_{vgt}^{all}	=	Demand of energy v at grid g during time period t (ktoe)
BR_{rgt}^{ton}	=	Amount of available biomass residue r at grid g during time period t (Ton)
$conR_{r}$	=	Ratio for converting unit of resource r between Ton and ktoe (Ton/ktoe)
$conE_{v}$	=	Ratio for converting unit of energy vector v between MW and ktoe (MW/ktoe)
DF_{t}	=	Discount factor at time period t
$Rdis^{\max}$	=	The maximum distance that resource r can be transported (km)
$Edis^{\max}$	=	The maximum distance that energy v can be transported (km)
$Capacity^{total}$	=	Total maximum capacity of power plant (MW)

$Capacity^{\min}$	=	Total minimum capacity of power plant per grid (MW)
PP	=	Peak electricity value (Baht/kWh)
OPP	=	Off-peak electricity value (Baht/kWh)
FT	=	Ft rate (Baht/kWh)
$Adder$	=	Subsidy Adder (Baht/kWh)
$bigM$	=	Large number
$smallm$	=	Small number

Binary Variable

$E_{igt}^{establish}$	=	Active capacity expansion of process i at grid g during time period t

Variables

di_{vgt}	=	Decision variable for importing energy v into grid g at time period t (ktoe)
dl_{vgt}	=	Decision variable for local demand of energy v at grid g during time period t (ktoe)
doe_{vgt}	=	Decision variable for using other energy v at grid g in time period t (ktoe)
dp_{rgt}	=	Decision variable for using potential domestic resource r at grid g during time period t (ktoe)
dri_{rgt}	=	Decision variable for importing resource r into grid g at time period t (ktoe)
dpl_{rgt}	=	Decision variable for local demand of resource r at grid g during time period t (ktoe)
dp_{rgt}^{unuse}	=	Decision variable for unused resource r at grid g during time period t (ktoe)

Dem_{vgt}^{chosen}	=	Decision variable for chosen demand of energy v at grid g during time period t to be supplied by biomass energy v (ktoe)
EP_{vigt}	=	Production of energy vector v of process i at grid g during time period t (ktoe)
EP_{vgt}^{net}	=	Net production of energy vector v of process i at grid g during time period t (ktoe)
UE_{rigt}	=	Usage of resource r of process i at grid g at time period t (ktoe)
C_{igt}	=	Capacity of process i at grid g during time period t (ktoe)
C_{igt}^{MW}	=	Capacity of process i at grid g during time period t (MW)
TC_{t}^{MW}	=	Total capacity during time period t (MW)
$NetC_{gt}^{MW}$	=	Net Capacity of all processes at grid g during time period t (MW)
E_{igt}	=	Expansion of process i at grid g at time period t (ktoe)
E_{igt}^{MW}	=	Expansion of process i at grid g at time period t (MW)
AU_{rgt}	=	Total usage of resource r at grid g during time period t (ktoe)
AU_{rgt}^{Ton}	=	Total usage of resource r at grid g during time period t (Ton)
$F_{vg'gt}$	=	Flow rate of energy vector v from grid g' to grid g at time period t (ktoe)
$F_{vgg't}$	=	Flow rate of energy vector v from grid g to grid g' by l at time period t (ktoe)
$FR_{rg'gt}$	=	Flow rate of resource r from grid g' to grid g by at time period t (ktoe)
$FR_{rgg't}$	=	Flow rate of resource r from grid g to grid g' at time period t (ktoe)
BR_{rgt}^{ktoe}	=	Amount of available biomass residue r at grid g during time period t (ktoe)
$OMCost_{it}$	=	Operating and Maintenance cost of process i at time period t ($)
$FOMCost_{it}$	=	Fixed O&M cost of process i at time period t ($)

$VOMCost_{it}$	=	Variable O&M cost of process i at time period t ($)
$RCost_{rt}$	=	Cost of resource r used during time period t ($)
$OECost_{rt}$	=	Cost of other energy v used during time period t ($)
$EtCost_{vt}^{total}$	=	Total cost for transporting energy v at time period t ($)
$EtCost_{vg'gt}$	=	Cost for transporting energy v between grid g and g' ($)
$RtCost_{rt}^{total}$	=	Total cost for transporting resource r at time period t ($)
$RtCost_{rg'gt}$	=	Cost for transporting resource r between grid g and g' ($)
$CostPT_{gg'}$	=	Cost of transporting resource r per truck from grid g to g' ($)
$InvCost_{it}$	=	Investment cost for new process i at time period t ($)
$Cost^{total}$	=	Total cost ($)
$Rdis_{rgg't}$	=	Distance travel of resource r from grid g to g' at time period t (km)
$Edis_{vgg't}$	=	Distance travel of energy v from grid g to g' at time period t (km)
$PeakE_{vgt}$	=	Generated electricity during peak hour (kWh)
$OffPeakE_{vgt}$	=	Generated electricity during off-peak hour (kWh)
$E\,\mathrm{Re}v_{vgt}^{peak}$	=	Revenue from selling electricity during peak hour at grid g during time period t ($)
$E\,\mathrm{Re}v_{vgt}^{offpeak}$	=	Revenue from selling electricity during off-peak hour at grid g at time period t ($)
$E\,\mathrm{Re}v_{vgt}^{adder}$	=	Extra revenue from adder in selling electricity at grid g during time period t ($)
$E\,\mathrm{Re}v_{gt}^{total}$	=	Total annual revenue from selling electricity at grid g during time period t ($)
$\mathrm{Re}v^{total}$	=	Total annual revenue ($)

The Biomass-To-Energy spatial optimisation model formulation consists of two types of entities; constraints and objective functions, which are described below.

6.3.2 Objective Function

As mentioned above the objective function for this model is to maximise the overall profit for the Biomass-to-Energy supply chain network. Therefore, the objective function is to maximise profit defined as the total revenue less the total cost. Thus the objective function is given in the form:

$$Maximise \quad \mathrm{Re}v^{total} - Cost^{total} \tag{6.1}$$

The two components are described in more detail below.

6.3.2.1 Cost Equations

The cost equations proposed for this model are similar to the pervious spatial model. However, there are some differences due to the assumptions made for this model. In this model, to only consider the quantity of biomass resource available in Thailand, it was assumed that biomass cannot be imported from outside Thailand. Therefore, the cost for importing from neighbouring countries can be ignored.

Moreover, because the objective of this model has been changed to maximising the profit rather than minimising the costs, the cost for unused energy can also be ignored. Furthermore, as additional data on fixed and variable O&M costs for each biomass thermal conversion technologies has been obtained, the O&M costs equations now include both fixed and variable costs.

- **Investment costs**

The total investment cost of process i during time period t ($InvCost_{it}$) can be expressed in terms of capacity of newly-built processes i at grid g (E_{igt}) and the investment cost of each newly-built capacity i as follows:

$$InvCost_{it} = DF_t \cdot \sum_g \left(E_{igt} \cdot CostIV_{ig} \right) \qquad \forall i,t \qquad (6.2)$$

where

DF_t is the discount factor during time period t

- **Operation and Maintenance (O&M) costs**

The O&M costs of process i during time period t ($OMCost_{it}$) can be expressed as the sum of Fixed O&M costs ($FOMCost_{it}$) and Variable O&M ($VOMCost_{it}$) of each process i during time period t. The variable $OMCost_{it}$ is given in the forms:

$$OMCost_{it} = FOMCost_{it} + VOMCost_{it} \qquad \forall i,t \qquad (6.3)$$

$$FOMCost_{it} = DF_t \cdot \sum_g \left(C_{igt} \cdot CostFOM_{ig} \right) \qquad \forall i,t \qquad (6.4)$$

$$VOMCost_{it} = DF_t \cdot \sum_g \left(C_{igt} \cdot CostVOM_{ig} \right) \qquad \forall i,t \qquad (6.5)$$

- **Raw material cost**

The raw material cost of total raw material used r during time period t ($RCost_{rt}$) can be described in term of total usage of raw material r at grid g during time period t (AU_{rgt}) and the cost of each raw material r ($CostR_{rt}$) as follow:

$$RCost_{rt} = DF_t \cdot \sum_g \left(AU_{rgt} \cdot CostR_{rt} \right) \qquad \forall r,t \qquad (6.6)$$

- **Raw Material Transportation costs**

It is assumed that the transportation of resource r from grid g to g' is carried out by truck which is the only one transportation mode to transport resource r in this model. The following equations define the total transportation cost of resource r during time period t ($RtCost_{rt}^{total}$):

$$RtCost_{rt}^{total} = DF_t \cdot \sum_{gg'} RtCost_{rg'gt} \qquad \forall r,t \qquad (6.7)$$

$$RtCost_{rg'gt} = \frac{FR_{rg'gt} \cdot conR_r \cdot CostPT_{gg'}}{TC} \qquad \forall r,g,g',t \qquad (6.8)$$

$$CostPT_{gg'} = FP \cdot TFR \cdot 2gd_{gg'} \qquad \forall g,g' \qquad (6.9)$$

where

$CostPT_{gg'}$	is the cost of transporting resource r per truck from grid g to grid g’
$conR_r$	is the conversion ratio for converting unit ktoe to tonne
$gd_{gg'}$	is the distance between grid g and grid g’
FP	is the fuel price
TFR	is the truck fuel rate
TC	is the truck capacity

- **Energy Transportation costs**

It is assumed that the transportation of energy v between grids is carried out by sending electricity through a transmission line which is the only one transportation mode for transporting energy in this model. The following equations define the total transportation cost of energy v during time period t ($EtCost_{vt}^{total}$):

$$EtCost_{vt}^{total} = DF_t \cdot \sum_{gg'} EtCost_{vg'gt} \qquad \forall v,t \qquad (6.10)$$

$$EtCost_{vg'gt} = F_{vg'gt} \cdot CostTE_{gg'} \cdot gd_{gg'} \qquad \forall v,g,g',t \qquad (6.11)$$

The total cost can be expressed as the following equation.

$$Cost^{total} = \sum_{t} \left(\begin{array}{l} \sum_{i} InvCost_{it} + \sum_{i} OMCost_{it} \\ \sum_{r} RtCost_{rt}^{total} + \sum_{v} EtCost_{vt}^{total} \\ + \sum_{r} RCost_{rt} \end{array} \right) \quad (6.12)$$

6.3.2.2 Revenue Equations

The revenue considered for this biomass to energy model comes from the sales of electricity produced by the network.

Electricity

It is important to realise that the revenue from selling electricity will vary between different countries. The following equations are based on the data currently used in Thailand. The amount of electricity generated during peak hours and off-peak hours at each grid e during time period t in kWh are given in the form:

$$PeakE_{vgt} = EP_{vgt} \cdot conE_{v} \cdot PeakHour \cdot 1000 \qquad \forall v, g, t \qquad (6.13)$$

$$OffPeakE_{vgt} = EP_{vgt} \cdot conE_{v} \cdot OffPeakHour \cdot 1000 \qquad \forall v, g, t \qquad (6.14)$$

The revenues from selling electricity during peak ($E\,\mathrm{Re}v_{vgt}^{peak}$) and off-peak ($E\,\mathrm{Re}v_{vgt}^{offpeak}$) hours are calculated using the following equations where PP is the peak electricity price, OPP is the off-peak electricity price and FT is the additional expenditure that is set by the Thai government which is altered by the oil price.

$$E\,\mathrm{Re}v_{vgt}^{peak} = 0.98 \cdot PeakE_{vgt} \cdot (PP + FT) \qquad \forall v, g, t \qquad (6.15)$$

$$E\,\mathrm{Re}v_{vgt}^{offpeak} = 0.98 \cdot OffPeakE_{vgt} \cdot (OPP + FT) \qquad \forall v, g, t \qquad (6.16)$$

In Thailand, the additional value of electricity which is called Adder is added to both peak and off-peak power generation to promote investment in biomass-to-energy power plant. The Adder is also formulated in this model by the following expression:

$$E\,\mathrm{Re}v_{vgt}^{adder} = Adder \cdot \left(PeakE_{vgt} + OffPeakE_{vgt}\right) \qquad \forall v,g,t \qquad (6.17)$$

Therefore, the total revenue from selling electricity at grid g during time period t can be expressed as:

$$E\,\mathrm{Re}v_{gt}^{total} = DF_t \cdot \sum_{v}\left(E\,\mathrm{Re}v_{vgt}^{peak} + E\,\mathrm{Re}v_{vgt}^{offpeak} + E\,\mathrm{Re}v_{vgt}^{adder}\right) \quad \forall g,t \qquad (6.18)$$

Furthermore, the total revenue can be expressed as:

$$\mathrm{Re}v^{total} = \sum_{t}\sum_{g} E\,\mathrm{Re}v_{gt}^{total} \qquad (6.19)$$

6.3.3 Constraints

Energy Production Constraints

Production variables and production constraints are formulated to describe the processes and conversion technologies of each model. Annual production of energy v for each process i, which is represented by EP_{vigt} can be described by parameter α_{vi}^{output} and variable C_{igt}, where α_{vi}^{output} is the proportion of energy vector v produced by process i. The expression for EP_{vigt} is given in the form:

$$EP_{vigt} = \alpha_{vi}^{output} \cdot C_{igt} \qquad \forall v,i,g,t \qquad (6.20)$$

As the only energy vector in this model is electricity, the net electricity production to meet the demand has to take into account the load factor (LF) and also the

transmission lost (TL). The net energy production v at grid g during time period t (EP_{vgt}^{net}) is given in the form:

$$EP_{vgt}^{net} = LF \cdot \left((1-TL) \cdot \sum_{i} EP_{vigt} \right) \qquad \forall v, g, t \qquad (6.21)$$

Resource Usage Constraints

The total resource usage r required by process i at grid g (UE_{rigt}) can be described in term of process capacity, as the proportion of resource r required for process i, which is represented by γ_{ri}^{input} multiply by capacity of process i, which is represented by C_{igt}. The expression for UE_{rigt} is given in the form:

$$UE_{rigt} = \gamma_{ri}^{input} \cdot C_{igt} \qquad \forall r, i, g, t \qquad (6.22)$$

The total resource usage at grid g, which is represented by, AU_{rgt} can be expressed as sum of resource usage r for all process i at grid g. The variable is described in the form:

$$AU_{rgt} = \sum_{i} UE_{rigt} \qquad \forall r, g, t \qquad (6.23)$$

Energy Balance Constraints

The energy balance between the net production rate of energy v at grid g and the total demand required by grid g itself can be expressed as follows:

$$EP_{vgt}^{net} = Dem_{vgt}^{chosen} + \sum_{g'} \left(F_{vgg't} - F_{vg'gt} \right) \qquad \forall v, g, t \qquad (6.24)$$

The equation above states that the net production rate of energy v at grid g during time period t (EP_{vgt}^{net}) must be equal to the chosen demand in grid g during time period t that can be supplied by the biomass energy (Dem_{vgt}^{chosen}) plus the sum of the total flow rate exporting from this grid g ($F_{vgg't}$) less the sum of the total flow rate of energy v imported to grid g ($F_{vg'gt}$).

Material Balance Constraints

The material balance between the decision variable for using the available biomass r at grid g and the total resource usage r required by grid g itself is given in the form:

$$dp_{rgt} = AU_{rgt} + \sum_{g'} \left(FR_{rgg't} - FR_{rg'gt} \right) \qquad \forall r, g, t \qquad (6.25)$$

The total mass balance on grid g must be written to determine the total amount of raw material usage r and therefore demand of raw material r in grid g.

Unit Conversion Constraints

In general the unit for the capacity of power plant is in MW. The following equations is formulated to convert capacity of process i at grid g during time period t in ktoe (C_{igt}) to capacity in MW (C_{igt}^{MW}).

$$C_{igt}^{MW} = C_{igt} \cdot conE_i \qquad \forall i, g, t \qquad (6.26)$$

The total energy production capacity of all power plants during time period t can be then expressed as:

$$TC_t^{MW} = \sum_g \sum_i C_{igt}^{MW} \qquad \forall t \qquad (6.27)$$

The same applies to converting units for expansion of capacity of process i at grid g during time period t in ktoe (E_{igt}) to expanded capacity in MW (E_{igt}^{MW}).

$$E_{igt}^{MW} = E_{igt} \cdot conE_i \qquad \forall i,g,t \qquad (6.28)$$

On the other hand, the unit for biomass is in Ton. The following equation is formulated to convert the availability of biomass residue r at grid g during time period t in Ton (BR_{rgt}^{ton}) to biomass in ktoe (BR_{rgt}^{ktoe}).

$$BR_{rgt}^{ktoe} = \frac{BR_{rgt}^{ton}}{conR_r} \qquad \forall r,g,t \qquad (6.29)$$

where

$conR_r$ is the ratio for converting unit of resource r between Ton and ktoe

The total usage of biomass r at grid g during time period t in Ton (AU_{rgt}^{Ton}) can also be expressed as:

$$AU_{rgt}^{Ton} = AU_{rgt} \cdot conR_r \qquad \forall r,g,t \qquad (6.30)$$

Energy Demand Constraints

As the objective function has been changed to maximising the profit, and because the energy produced from biomass only cannot fully supply the energy demand in each area of Thailand. The following demand constraint has been formulated in this model.

$$Dem_{vgt}^{chosen} \leq Dem_{vgt}^{all} \qquad \forall v,g,t \qquad (6.31)$$

The above constraint states that the chosen demand of energy v that can be supplied from biomass energy at grid g during time t (Dem_{vgt}^{chosen}) is less than or equal to the total demand of energy v at grid g during time t (Dem_{vgt}^{all})

The variable Dem_{vgt}^{chosen} can be separated into two parts. The first part is the local demand of energy v at grid g (dl_{vgt}). The second part is the imported demand of energy v into the same grid g during time t (di_{vgt}). The total demand is given in the form:

$$Dem_{vgt}^{chosen} = dl_{vgt} + di_{vgt} \qquad \forall v, g, t \qquad (6.32)$$

The variable dl_{vgt} is constrained to be less than or equal to the net production of energy v in the same grid g (EP_{vgt}^{net}). The constraint is given in the form:

$$dl_{vgt} \leq EP_{vgt}^{net} \qquad \forall v, g, t \qquad (6.33)$$

Moreover, the variable di_{vgt} is equal to the sum of the total flow rate of energy v imported to grid g ($F_{vg'gt}$). The imported demand is expressed as:

$$di_{vgt} = \sum_{g'} F_{vg'gt} \qquad \forall v, g, t \qquad (6.34)$$

Finally, the total demand of energy v in grid g at time period t that cannot be supplied by the energy from biomass is given in the form:

$$Dem_{vgt}^{unmet} = Dem_{vgt}^{all} - Dem_{vgt}^{chosen} \qquad \forall v, g, t \qquad (6.35)$$

Raw Material Demand Constraints

Applying a similar formulation as for the energy demand constraints, the total resource usage must also be equal to the local demand and the imported demand of raw material r at grid g during time period t (dpl_{rgt}, dri_{rgt}).

$$AU_{rgt} = dpl_{rgt} + dri_{rgt} \qquad \forall r, g, t \qquad (6.36)$$

The imported demand of raw material r at grid g during time period t (dri_{rgt}) is equal to the sum of the total flow rate of raw material r imported to grid g ($FR_{rg'gt}$). The imported demand is expressed as:

$$dri_{rgt} = \sum_{g'} FR_{rg'gt} \qquad \forall r, g, t \qquad (6.37)$$

On the other hand, the local demand of raw material r at grid g during time period t (dpl_{rgt}) is constrained to be less than or equal to the decision variable for using the available biomass r at the same grid g (dp_{rgt}) which also less than or equal to the amount of available biomass residue r at grid g during time period t (BR_{rgt}^{ktoe}). The constraint is given in the form:

$$dpl_{rgt} \leq dp_{rgt} \leq BR_{rgt}^{ktoe} \qquad \forall r, g, t \qquad (6.38)$$

The unused amount of biomass r at grid g during time period t (dp_{rgt}^{unuse}) is equal to the amount of available biomass residue r at grid g during time period t (BR_{rgt}^{ktoe}) less the decision variable for using the available biomass residue r at the same grid g (dp_{rgt}).

$$dp_{rgt}^{unuse} = BR_{rgt}^{ktoe} - dp_{rgt} \qquad \forall r, g, t \qquad (6.39)$$

Capacity Constraints

The maximum power plant capacity during time period t can be controlled by the following constraint.

$$TC_t^{MW} \leq Capacity^{total} \qquad \forall t \qquad (6.40)$$

The minimum capacity expansion of process i in grid g during time period t in MW can be expressed as:

$$E_{igt}^{MW} \leq E_{igt}^{establish} \cdot Capacity^{\min} \qquad \forall i,g,t \tag{6.41}$$

The binary variable $E_{igt}^{establish}$ is equal to 1 when a capacity expansion of process i in grid g during time period t is suggested and 0 otherwise. The following equations justify the establishment of the capacity expansion of process i in grid g during time period t.

$$E_{igt}^{MW} - bigM \cdot E_{igt}^{establish} \leq 0 \qquad \forall i,g,t \tag{6.42}$$

$$E_{igt}^{MW} - smallm \cdot E_{igt}^{establish} \geq 0 \qquad \forall i,g,t \tag{6.43}$$

Transportation Constraints

The transportation constraints to control the flows of resource and energy between different grids are identical to equations 5.41 to 5.48 of the previous chapter.

6.4 Description of scenarios

Three scenarios have been created to examine the proposed spatial energy optimisation model of biomass in Thailand. In Thailand there are already many existing biomass power plants utilising various biomass types. Moreover, most of the total biomass residues have been used by many industries including the energy sector. The three scenarios investigate different network possibilities according to those factors. The scenarios are described below:

1) Optimising only the unused biomass available in Thailand without considering the existing biomass power plants.
2) Optimising the total generated biomass in Thailand without consideration of the existing biomass power plants.
3) Optimising the unused biomass if the yield of generated biomass has been double with consideration of the existing biomass power plants.

The first scenario is considered to suggest the optimal structure of a possible expansion plan to the existing network of biomass power plants in Thailand. Only the unused biomass will be utilised in this scenario to reflect the real-world situation.

The second scenario is created to determine the optimal structure for biomass power plants network when all generated biomass are available. Or in other words, the second scenario is when the development is started at the beginning.

Finally, the third scenario explores the case when the yield of total generated biomass becomes double and therefore there is a higher amount of unused biomass to utilise. This case represents a possible real-word situation, as power from biomass has been receiving increasing attention, therefore diversion from others uses or from energy crops to increase the yield might be a possible scenario in the future. The additional input data is presented in the next section. For all scenarios, the minimum expansion capacity is set to be 5 MW as a smaller capacity might not be economical because of the economy of scale.

6.4.1 Input Data

6.4.1.1 Technology Data

The technology data required by the proposed model are the input and output factors, and the capacities of existing biomass power plant in each grid.

The input and output factors are similar to the previous model. However, the only relevant technology data is the amount of input raw material and output product factors of each biomass thermal conversion technology. The factors are calculated from the expected heat rate of each technology. The heat rate for BIGCC and BSC are assumed to be 8,911 and 13,000 Btu/kWh respectively [CERI, 2005] [Breeze, 2005]. Therefore, the conversion efficiencies for the two technologies are 38.31% and 26.26%. The factors are given in Table 6.2. The capacities of existing biomass power plants in Thailand are shown in Table 6.3. All of the power plants are using BSC technology. None of the BIGCC power plant has been established [DEDE, 2005a] [DEDE, 1999] [DEDE, 2008] [MOE, 2008] [Demirbas, 2001] [Bain, 1998] [Sajjakulnukit, 2005] [EIA, 2007].

Table 6.2: Input and Output factors of each technology

Technology Type	Input	Output
BIGCC	2.6101	1
BSC	3.8079	1

[CERI, 2005] [Breeze, 2005]

Table 6.3: Capacity of existing biomass power plants in MW in each grid (Part I)

	BSC Bagasse	BSC PalmShell	BSC PalmBunch	BSC RiceHusk	BSC RiceStraw	BSC Corncob	BSC Tapioca	BSC Wood
M1	0	0	0	0	0	0	0	0
M2	0	0	0	0	0	0	0	0
M3	0	0	0	0	0	0	0	0
M4	0	0	0	0	0	0	0	0
M5	0	0	0	8	0	0	0	0
M6	8	0	0	0	0	0	0	0
M7	4	0	0	0	0	0	0	0
M8	8	0	0	16	0	0	6	10.5
M9	0	0	0	8	1	0	0	0
M10	0	0	0	8.8	0	0	0	0
E1	8	8	0	0	0	0	0	0
E2	0	0	0	0	0	0	0	0
E3	0	0	0	0	0	8	0	0
E4	0	0	0	0	0	0	0	0
E5	0	0	0	0	0	0	0	0
E6	9	0	0	0	0	0	0	0
E7	0	0	0	0	0	0	0	0
E8	0	0	0	1.8	0	0	0	0
LN1	8	0	0	0	0	0	0	10.5
LN2	5	0	0	0	0	0	0	0
LN3	8	0	0	24	0	0	0	0
LN4	0	0	0	19.45	0	0	0	0
LN5	0	0	0	0	0	0	0	29.5
LN6	2.5	0	0	45.2	0	0	0	0
LN7	5	0	0	8	0	0	2.8	0
LN8	4	0	0	8	0	0	4	0
UN1	0	0	0	16	0	0.135	0	0
UN2	0	0	0	0	0	0	0	0
UN3	0	0	0	0	0	0	0	0
UN4	3	0	0	8	0	0	0	0
UN5	0	0	0	8	0	0	0	0
UN6	0	0	0	0	0	0	0	0
UN7	0	0	0	0	0	0	0	0
UN8	0	0	0	0	0	0	0	0
UN9	0	0	0	0	0	0	0	8

Table 6.3: Capacity of existing biomass power plants in MW each grid (Part II)

	BSC Bagasse	BSC PalmShell	BSC PalmBunch	BSC RiceHusk	BSC RiceStraw	BSC Corncob	BSC Tapioca	BSC Wood
NE1	0	0	0	0	0	0	0	0
NE2	16	0	0	0	0	0	0	0
NE3	12	0	0	8	0	0	0	8
NE4	0	0	0	0	0	0	0	0
NE5	0	0	0	0	0	0	0	0
NE6	0	0	0	0	0	0	0	5.25
NE7	16	0	0	0	0	0	0	0
NE8	0	0	0	0	0	0	0	0
NE9	0	0	0	0	0	0	0	0
NE10	0	0	0	15	0	0	0	8
NE11	0	0	0	0	0	0	0	2.5
NE12	8	0	0	8	0	0	0	8
NE13	8	0	0	32	0	0	0	18.75
NE14	10.5	0	0	0	0	0	0	0
NE15	0	0	0	0	0	0	0	0
NE16	0	0	0	28	0	0	0	5.25
NE17	0	0	0	8	0	0	0	0
NE18	0	0	0	0	0	0	0	14.2
NE19	22	0	0	22.7	0	0	0	0
W1	26	0	0	16	0.85	0	0	0
W2	0	0	2.5	0.5	0.75	0	0	0
W3	3	2	1	0	0	0	0	8
W4	0	0	0	0	0	0	0	0
W5	9.8	0	0	0	0.3	0	4.8	0
W6	0	0	0	0	0	0	0	0
W7	0	0	0	0	0	0	0	0
W8	0	0	0	46.5	0	0	0	0
S1	0	8.5	21	0	0	0	0	0
S2	0	0	10.4	0	0	0	0	0
S3	0	0	0	0	0	0	0	0
S4	0	0	0	0	0	0	0	0
S5	0	0	0	0	0	0	0	0
S6	0	0	0	0	0	0	0	0
S7	0	0	0	0	0	0	0	0
S8	0	0	0	0	0	0	0	0
S9	0	0	0	0	0	0	0	0
S10	0	0	0	0	0	0	0	0
S11	0	0	1	0	0	0	0	0
S12	0	0	0	0	0	0	0	0
S13	0	0	0	0	0	0	0	0
S14	0	0	3.5	0	0	0	0	0

[DEDE, 2005a] [DEDE, 1999] [DEDE, 2008] [MOE, 2008] [Demirbas, 2001] [Bain, 1998] [Sajjakulnukit, 2005] [EIA, 2007]

6.4.1.2 Raw material Data

The main raw material used in this model is the biomass listed in Table 6.1. The data related to the biomass which is required for this model is listed below.

- The estimated total generated quantity of each type of biomass in each grid.
- The estimated unused quantity of each type of biomass in each grid.
- The heat value of each type of biomass

The first two data types are shown in Table A6.1 and Table A6.2 respectively. The heat values are shown in Table 6.4 below.

Table 6.4: The heat value of each type of biomass

Biomass Type	**Heat Value MJ/Kg**	**Tonne/ ktoe**	**ktoe/ MMTonne**
Bagasse	16.21	2,582.85	387.17
Cane Trash	16.42	2,549.82	392.18
Palm Fibre	19.94	2,099.70	476.26
Palm Shell	21.13	1,981.45	504.68
Pam Empty Bunch	19.41	2,157.03	463.60
Palm Oil Frond	17.87	2,342.92	426.82
Rice Husk	15.51	2,699.42	370.45
Rice Straw	15.56	2,690.75	371.64
Corncob	16.63	2,517.62	397.20
Corn Stalk	13.38	3,129.15	319.58
Tapioca rhizome	10.61	3,946.09	253.42
Parawood	16.85	2,484.75	402.46
Wood	16.85	2,484.75	402.46

[MOE, 2008] [Sajjakulnukit, 2005].

6.4.1.3 Financial Data

The financial data required can be divided into revenue streams data and costs data which are presented below

Revenue Data

The revenue stream considered in this Biomass-to-Energy spatial model is the revenue from selling electricity from converting biomass.

At present the electricity price is fixed at 2.93 baht/kWh at peak hour and 1.12 baht/kWh at off-peak hour. The government also includes the subsidy adder of 0.8 bath/kWh for using biomass as fuel for power production. Furthermore, an additional Ft rate is also added to the electricity price to compensate for the additional expenditure, which is altered by the oil price. The value of Ft was 0.773 baht in December 2008 and 0.9089 baht in January 2009. The electricity prices in $/kWh are summarised in Table 6.5 below.

Table 6.5: Electricity prices

Electricity Revenue Streams	Prices ($/kWh)
Peak Electricity	0.08872
Off-peak Electricity	0.03380
Ft rate	0.02727
Subsidy Adder	0.02424

[PEA, 2010] [EGAT, 2010]

Cost Data

The costs data include biomass conversion technology costs, transportation cost of biomass between grids, transmission cost of electricity between grids, and cost of each type of biomass which are described below.

Technology costs

The estimated capital and O&M costs for Biomass Integrated Gasification Combined Cycle (BIGCC) and Biomass Steam Combustion (BSC) power plants used in this model are shown in Table 6.6 and Table 6.7 respectively. The costs are derived from CERI, 2005 and Breeze, 2005. The costs in $/ktoe are shown in Table 6.8 and Table 6.9.

Table 6.6: Capital costs of selected Biomass-to-Energy technologies

Technology Types	Capital Costs	Unit
BIGCC	1,757,000	$/MW
BSC	1,510,000	$/MW

Table 6.7: O&M costs of selected Biomass-to-Energy technologies

Technology Types	Fixed O&M Costs ($/kW)	Variable O&M Costs ($/MWh)
BIGCC	47.18	2.96
BSC	50.00	1.50

Table 6.8: Capital costs of selected Biomass-to-Energy technologies

Technology Types	Capital Costs	Unit
BIGCC	2,332,638	$/ktoe
BSC	2,004,714	$/ktoe

Table 6.9: O&M costs of selected Biomass-to-Energy technologies

Technology Types	Fixed O&M Costs	Variable O&M Costs	Unit
BIGCC	62,637	33,324	$/ktoe
BSC	66,381	17,445	$/ktoe

[CERI, 2005] [Breeze, 2005]

Raw material Transportation cost

In this model, the proposed method for biomass transportation is by truck. The transportation costs are calculated by the distance travelled by the truck and the fuel cost as described by equations 6.7 to 6.9. The data required to calculate the transportation cost are given in Table 6.10.

Table 6.10: Transportation cost data

Transportation cost data	Value	Unit
Truck Capacity	8	Ton
Truck Fuel Rate	2.35	Litre/km
Truck Fuel Price	0.7879	$/Litre

[TBOI, 2008] [MOE, 2008].

Electricity Transmission cost

The transmission cost is the same as the previous model, for ease of reference the cost is assumed to be $10 per km.

Raw material cost

The estimated cost of each type of biomass considered in this model is given in Table 6.11.

Table 6.11: The estimated cost of biomass

Biomass Type	**Value**	**Unit**
Bagasse	14.29	$/Ton
Cane Trash	1.43	$/Ton
Palm Fibre	1.14	$/Ton
Palm Shell	60	$/Ton
Pam Empty Bunch	1.86	$/Ton
Palm Oil Frond	1.29	$/Ton
Rice Husk	31.43	$/Ton
Rice Straw	51.43	$/Ton
Corncob	20	$/Ton
Corn Stalk	1.71	$/Ton
Tapioca rhizome	22.86	$/Ton
Parawood	17.14	$/Ton
Wood	15.71	$/Ton

[DEDE, 2005a] [DEDE, 2009a][DEDE, 2009b] [DEDE, 2009c] [EGAT, 2010] [Sajjakulnukit, 2005]

6.4.1.4 Grid Data

Two types of important data are grouped into this section. The first set of data is the distances between each grid. The distances are required for the calculation of transportation costs. The distances are given in Table A1 [TBOI, 2008]. The second set of data is the demand of electricity in each grid. As the demand is assumed to be proportional to the population density, the demand for each grid was calculated from the total demand for the whole country used in Chapter 3 and the population density of each province (grid). The population density and the demand for each grid are shown in Table 6.12 and Table 6.13 respectively.

Table 6.12: The estimated % of population density in each grid

Middle and West Provinces	Population Density %
m01	11.1170
m02	1.4247
m03	1.2600
m04	1.0073
m05	0.3962
m06	0.3034
m07	0.8522
m08	1.0469
m09	1.0234
m10	0.4744
w01	1.0862
w02	1.1067
w03	0.6709
w04	0.6290
w05	1.1358
w06	0.2779
w07	0.6106
w08	1.1834

South and East Provinces	Population Density %
s01	0.5237
s02	0.6500
s03	0.8283
s04	2.0858
s05	0.9648
s06	0.8645
s07	0.3279
s08	0.6874
s09	0.3794
s10	0.6341
s11	0.2226
s12	1.7634
s13	0.3729
s14	1.2744
e01	0.5237
e02	0.6500
e03	0.8283
e04	2.0858
e05	0.9648
e06	0.8645
e07	0.3279
e08	0.6874

North-East Provinces	Population Density %
ne01	0.8576
ne02	0.6798
ne03	2.0154
ne04	1.2448
ne05	0.9267
ne06	1.5172
ne07	0.4619
ne08	0.7533
ne09	0.5100
ne10	2.5448
ne11	1.9997
ne12	1.9162
ne13	2.1170
ne14	1.2474
ne15	1.2865
ne16	1.8015
ne17	2.4057
ne18	1.5453
ne19	3.5265

Lower and Upper North Provinces	Population Density %
ln01	0.8417
ln02	1.1787
ln03	0.6794
ln04	0.8093
ln05	1.4335
ln06	1.5173
ln07	1.0547
ln08	0.4625
un01	1.6551
un02	0.6832
un03	0.6569
un04	0.6764
un05	0.6569
un06	0.3246
un07	2.1709
un08	1.0889
un09	0.5572

[MOE, 2008] [MOE, 2007]

Table 6.13: The estimated demand of electricity in each grid

Middle and West Provinces	Demand (ktoe)
m01	1389
m02	178
m03	157
m04	126
m05	50
m06	38
m07	106
m08	131
m09	128
m10	59
w01	136
w02	138
w03	84
w04	79
w05	142
w06	35
w07	76
w08	148

South and East Provinces	Demand (ktoe)
s01	65
s02	81
s03	104
s04	261
s05	121
s06	108
s07	41
s08	86
s09	47
s10	79
s11	28
s12	220
s13	47
s14	159
e01	92
e02	95
e03	77
e04	43
e05	38
e06	193
e07	87
e08	111

North-East Provinces	Demand (ktoe)
ne01	107
ne02	85
ne03	252
ne04	156
ne05	116
ne06	190
ne07	58
ne08	94
ne09	64
ne10	318
ne11	250
ne12	239
ne13	265
ne14	156
ne15	161
ne16	225
ne17	301
ne18	193
ne19	441

Lower and Upper North Provinces	Demand (ktoe)
ln01	105
ln02	147
ln03	85
ln04	101
ln05	179
ln06	190
ln07	132
ln08	58
un01	207
un02	85
un03	82
un04	85
un05	82
un06	41
un07	271
un08	136
un09	70

6.4.2 Results and Discussion

The first important result from solving the proposed model using the CPLEX solver with GAMS as modelling language is that, with the number of grids considered in this model (76 grids) and the time period being more than one, the size of the file containing the results from solving the model became too large for the CPLEX solver memory. Therefore, only one time period with the duration of 10 years has been considered in this case to examine the proposed model. However, with a higher memory of the CPLEX solver, the proposed multi-period Biomass-to-Energy spatial model is expected to be functional and is able to generate an optimal solution. The results obtained from each scenario with one time period are described below.

6.4.2.1 Scenario 1: without existing capacity, utilise only unused biomass

The proposed model aims to generate the optimal expansion strategy of a Biomass-to-Energy supply chain network which utilises all the unused biomass in Thailand. The proposed model was able to determine the optimal quantities and locations of the chosen raw materials, the flows of each type of the raw material between grids, the locations of each type of the chosen biomass power plants, the capacities of the biomass power plants, the quantities of the electricity produced from each of the power plants, and the flows of electricity to satisfy the electricity demand of each grid. The financial data derived from the suggested network including the costs and the revenues and therefore the total profit of the network were also revealed.

According to the results, a further 6,380 MW of biomass power plant was suggested to be established from the unused amount of biomass available in Thailand. The suggested expansion of Biomass-to-Energy supply chain network is shown in Figure 6.2 to 6.6.

The first feature to notice form analysing the results is that the biomass integrated gasification combined cycle (BIGCC) technology was chosen rather than the traditional biomass steam cycle (BSC) technology. From figure 6.2, it can be seen that for the middle provinces, only four types of biomass were suggested as raw material

for the BIGCC power plant which are rice straw, cane trash, tapioca rhizome and corn stalk. The suggested capacity of BIGCC from rice straw has the highest capacity, followed by cane trash, corn stalk and tapioca rhizome. The total suggested capacity for the middle provinces was approximately 490 MW.

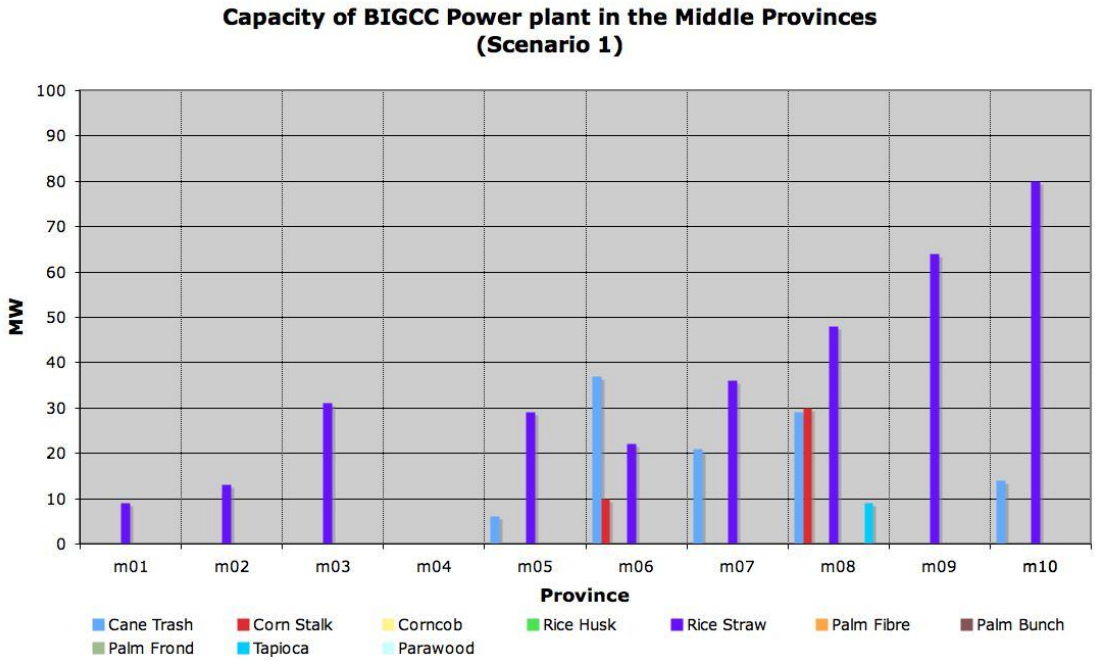


Figure 6.2: The middle provinces (Scenario 1)

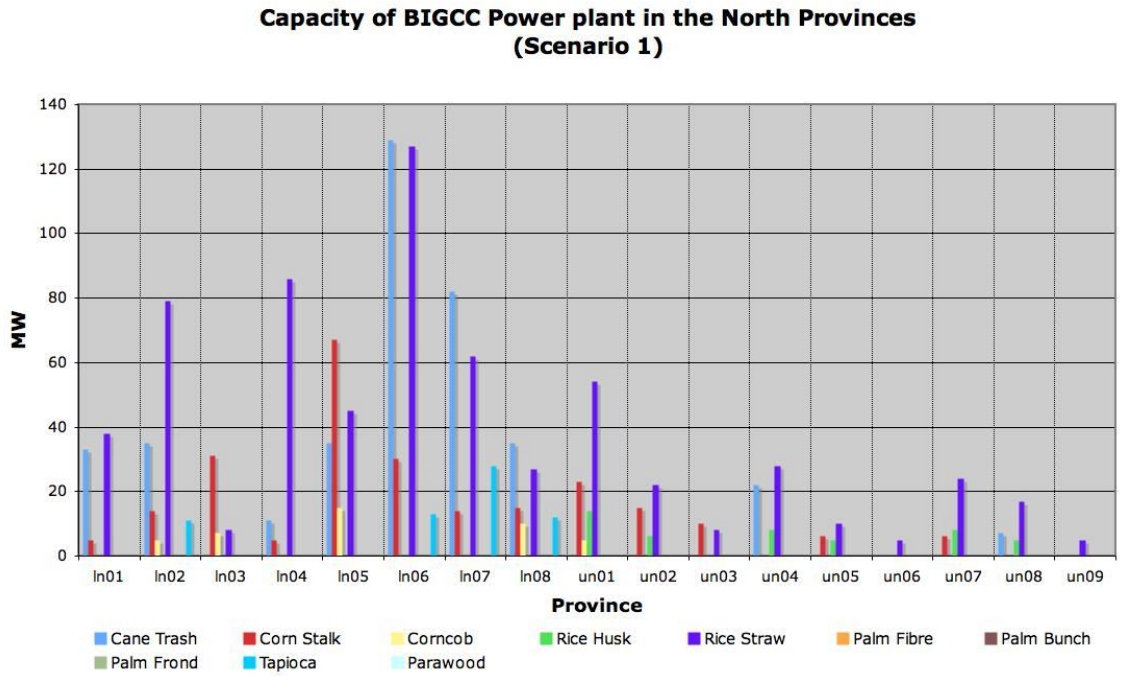


Figure 6.3: The north provinces (Scenario 1)

Approximately 1,400 MW of BIGCC power plants were suggested to be built using various biomass as resource as shown in Figure 6.3. Cane trash, rice straw and corn stalk were the main resources.

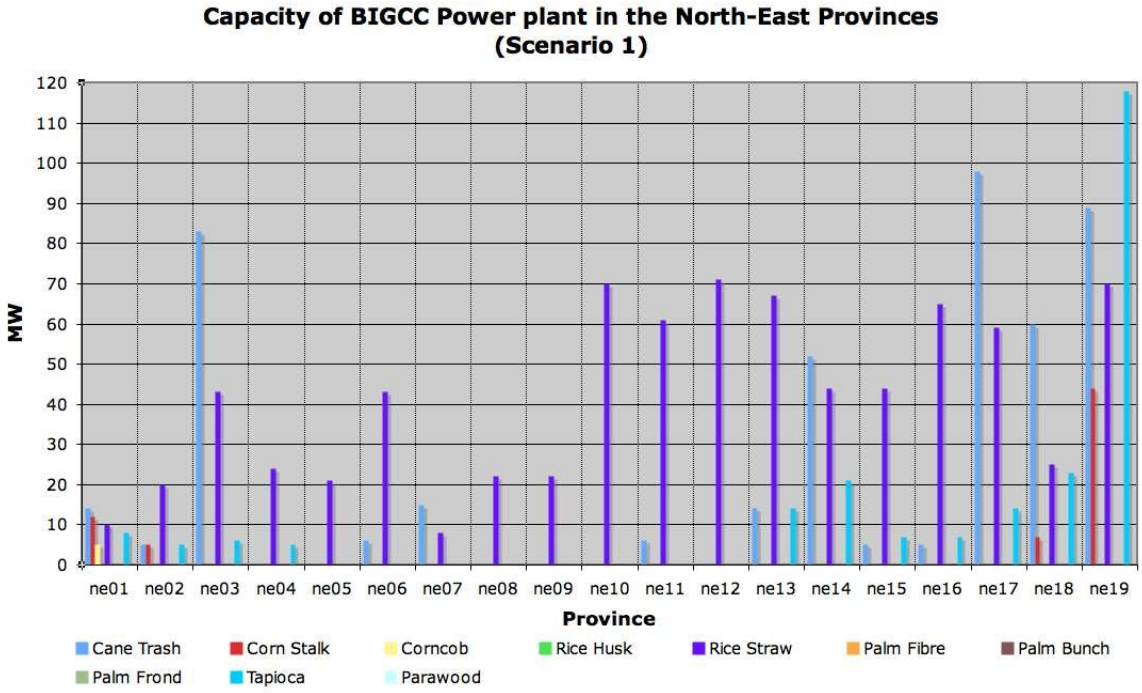


Figure 6.4: The north-east provinces (Scenario1)

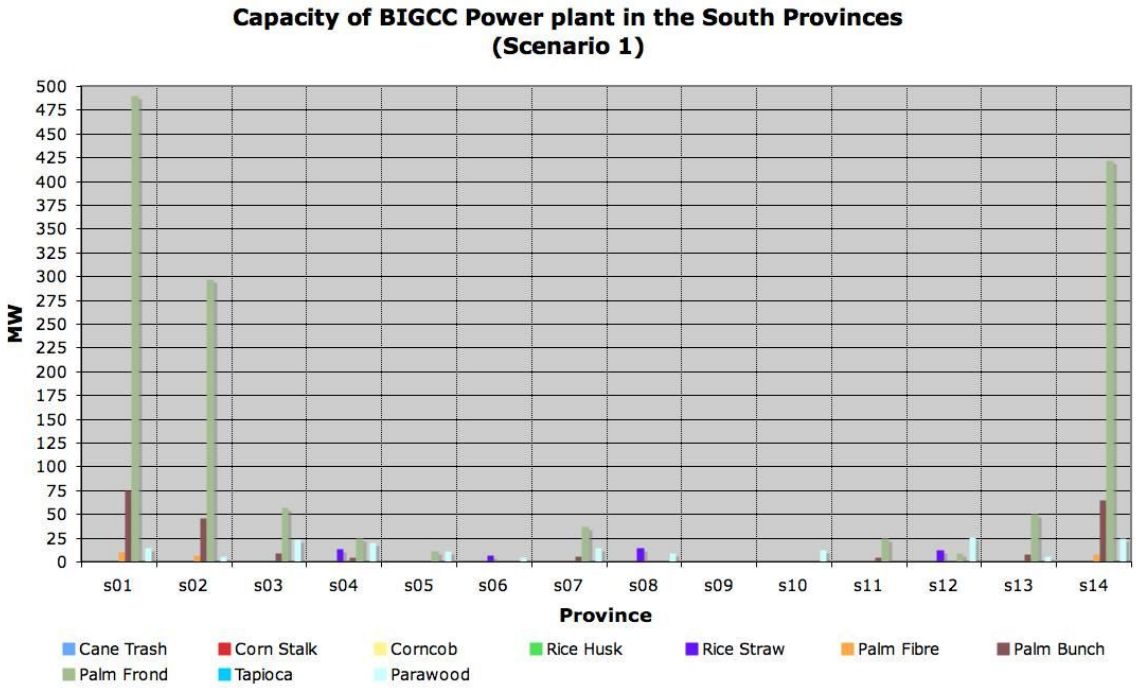


Figure 6.5: The south provinces (Scenario 1)

For the north-east provinces, more than 1,500 MW of BIGCC power plants using cane trash, rice straw and tapioca rhizome as raw materials as shown in Figure 6.4. Considering the south provinces, as there are many palm trees available in the region, more than 1,900 MW of BIGCC power plants were recommended. From the total suggested capacity, 1,426 MW use palm frond as raw material. The capacity of BIGCC power plants in the south provinces are shown in Figure 6.5. Around 400 MW of BIGCC power plants were located to be constructed in the East provinces. Rice straw and tapioca rhizome were the main resources. The model suggested that more than 600 MW of BIGCC power plants to be established in the west provinces. Cane trash and rice straw were the two main resources for the west region. The capacity of BIGCC power plants in the west and the east provinces are shown in Figure 6.6.

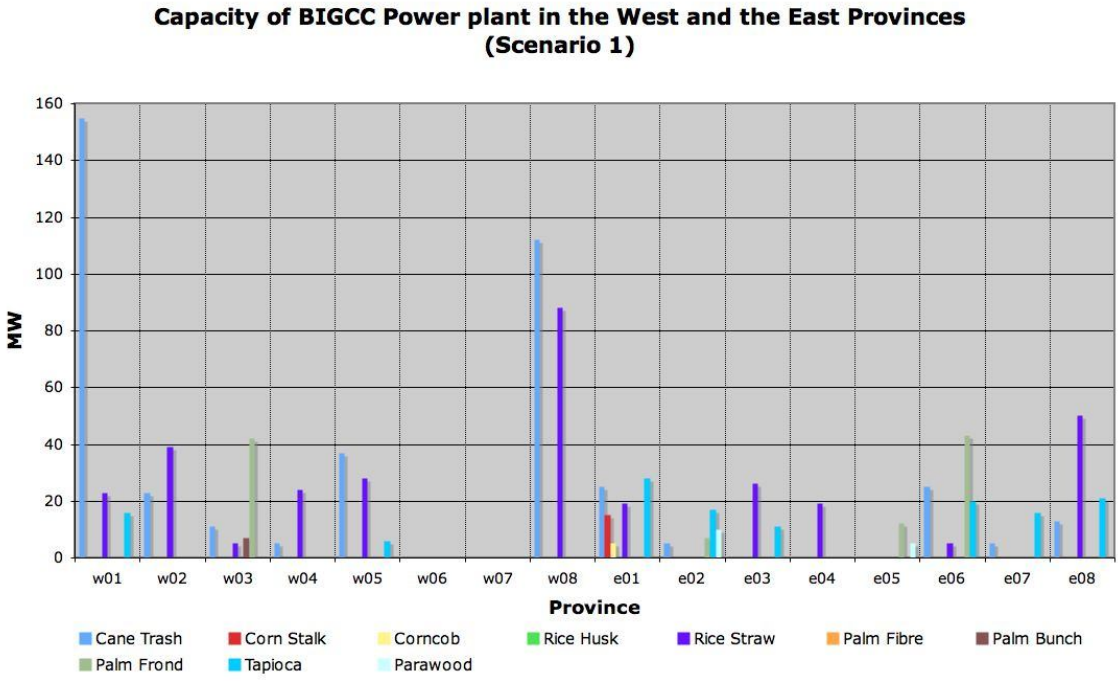


Figure 6.6: The west and the east provinces (Scenario 1)

One of the features to notice from the results is that the suggested biomass power plants are located in the grids which are rich with biomass not with the highest demand. It can be seen that the grid with the highest demand does not contain the highest amount of capacity expansion. For example in grid M01 which represents Bangkok, the capital city of Thailand, the demand of electricity is the highest, but only 21 % was suggested to be fulfilled by the electricity generated from biomass. This was because it is more economical to develop biomass power plants in the areas

(grid) that are abundant with raw material to reduce the transportation and transmission costs. The results can be implied that for the Biomass-to-Energy case, the model suggested a distributed power development plan rather than a centralised one. The flows of electricity between provinces are shown in Table. 6.14. From the table it can be seen that from the total of 76 provinces, only 16 flows between provinces were established. These results show that the current availability of biomass available to be utilised for power generation is enough to meet the demand of local provinces but still not high enough to satisfy the demand of the whole country.

Table 6.14: Flow of electricity between grids in ktoe (Scenario 1)

Flow of Electricity	m07	m08	w02	w03	w04	w05	s03	s04	s06	s08	s09	s11	S12	ln03
m06		12.2												
m10	8.5													
w01			7.1											
s01							41.8		15.2	73.1	49.8		195.7	
s02				39.3	60.7	74.7						7.2		
s14								225.6						
ln06	25.4													
ln07														0.8
ln08	13.5													

Table 6.15: Flow of biomass between grids in ktoe (Part 1)

		m08	w01	w03	e01	e05	e06	e07	s01	s02	s03	s04	s06	s11
Cane Trash	**e02**							2.0						
Palm Fibre	**s07**								1.4					
Palm Fibre	**w03**									1.6				
Palm Fibre	**s11**									0.9				
Palm Oil Frond	**e07**					2.4								
Palm Oil Frond	**e08**						3.3							
Palm Oil Frond	**s08**										1.2			
Palm Empty Bunch	**s02**													2.5
Palm Empty Bunch	**s12**											2.2		
Rice Straw	**w04**			0.7										
Rice Straw	**e02**						2.0							
Rice Straw	**s02**			2.9										
Rice Straw	**s10**												3.4	
Corncob	**e03**				0.7									
Corncob	**e07**				1.1									
Corncob	**e08**				0.6									
Corncob	**ne18**				0.5									
Corn Stalk	**w05**		0.7											
Tapioca Rhizome	**m06**	3.0												
Parawood	**s10**												0.3	
Parawood	**s11**									4.7				

Table 6.16: Flow of biomass between grids in ktoe (Part 2)

		un04	un05	un06	un07	un08	ln01	ln02	ln04	ln07	ln08
Cane Trash	**un05**	1.5									
Cane Trash	**ln03**									3.9	
Rice Husk	**un03**		4.1								
Rice Husk	**un04**		0.2								
Rice Husk	**un09**				2.5	1.0					
Rice Straw	**un09**			2.3							
Corncob	**un04**							1.1			
Corncob	**ln01**							2.0			
Corncob	**ln06**										13.3
Corn Stalk	**m10**										1.7
Corn Stalk	**un04**						0.9				
Corn Stalk	**un08**				4.5						
Corn Stalk	**ln02**								3.1		
Tapioca Rhizome	**ln04**							0.4			

Table 6.17: Flow of biomass between grids in ktoe (Part 3)

		ne01	ne02	ne03	ne04	ne06	ne13	ne16
Cane Trash	**ne04**			3.1				
Cane Trash	**ne05**					4.0		
Cane Trash	**ne15**							3.2
Corncob	**ne02**	1.3						
Corncob	**ne03**	0.5						
Corncob	**ne18**	2.6						
Corn Stalk	**ne01**		0.9					
Corn Stalk	**ne03**		2.0					
Corn Stalk	**ne04**		0.3					
Corn Stalk	**ne17**		0.8					
Tapioca Rhizome	**ne03**		4.6		4.6			
Tapioca Rhizome	**ne12**						4.5	

The Table 6.15 to 6.17 show the suggested flows of biomass between grids. It can be seen that the quantities of biomass to be transported between grids are not very high. It is more economical to utilise the local biomass in each province then transmit the excess electricity generated to other provinces. The results also show that the flow of biomass only occurs between neighbouring grids to minimise the transportation cost.

Another interesting feature of the results is the amount of unused biomass left after being used by the suggested capacity expansion. The results show that not all the considered amount of biomass has been used. This was because the distances between the grids of unused biomass and the unfulfilled demand were too far apart which

made the transportation costs too high for the suggested network. The financial data of the suggested network is shown in Table 6.18.

Table 6.18: Breakdown of financial details of the suggested network (Scenario 1)

Financial Detail ($)	**Scenario 1**
Revenue	5.1726E+10
Investment Cost	8.3895E+09
Fixed Cost	2.2528E+09
Variable Cost	1.2381E+09
Raw Material Cost	7.1464E+09
Raw Material Transportation Cost	1.2268E+08
Electricity Transmission Cost	1.8909E+07
Total Profit	3.2557E+10

In order to find out the most financially attractive type of biomass power plant, the maximum capacity expansion has been set to 500 MW. From analysing the results, the BIGCC power plant using palm fibre is the most financially attractive option of biomass power plant, followed by BIGCC of palm fibre and BIGCC of palm empty bunch when enough raw materials are available in the same grid as the power plant. With the same thermal conversion technology, the amount of electricity produced is proportional to the heat value of the biomass. As presented in Table 6.4 that the heat value is the highest for palm shell followed by palm fibre and palm empty bunch, therefore it is not surprising that the most financially attractive type of biomass power plant is the BIGCC of palm fibre. As palm fibres are mostly allocated in the southern region of Thailand, all of the suggested BIGCC power plants are in the southern provinces of Thailand. Furthermore, the results also suggested that the BIGCC technology is more financially attractive than the BSC technology.

As biomass is considered as a source of renewable energy which does not produce GHG, it can be stated that if the suggested Biomass-to-Energy network with a capacity expansion of 4810 MW was implemented then an estimated value of 2.80E+13 g of CO_2 could be reduced per year assuming that a normal coal steam power plant produce 664 g of CO_2 per kWh.

6.4.2.2 Scenario 2: without existing capacity, utilise all biomass available

The suggested capacity expansion for scenario 2 is shown in Figure 6.7 to 6.11. It can be seen from the figures that a similar pattern of Biomass-to-Energy supply chain network was suggested. However, the total suggested biomass power plant capacity from all biomass available in Thailand became 13,320 MW. The estimated electricity demand used in this proposed model for the whole country is 14,746 MW. Therefore, based on the model assumptions, nearly 90% of the total electricity demand could be fulfilled by energy from the total generated biomass in Thailand.

The increase in capacity mainly came from utilising bagasse, and rice husk residues which were not available in the previous scenario. Comparing to the availability of rice straw, the quantity also increased a lot too. The suggested capacities of BIGCC power plants using bagasse as raw material were nearly 3,000 MW. The bagasse residues are available throughout the country. However they are currently used in the manufacture of pulp, paper products and building materials. Moreover, more than 1,000 MW of BIGCC power plants with rice husk as fuel were recommended. It is also worth mentioning that only the capacity expansion of BIGCC power plants are shown in Figure 6.7 to 6.11. The existing BSC power plants are not included.

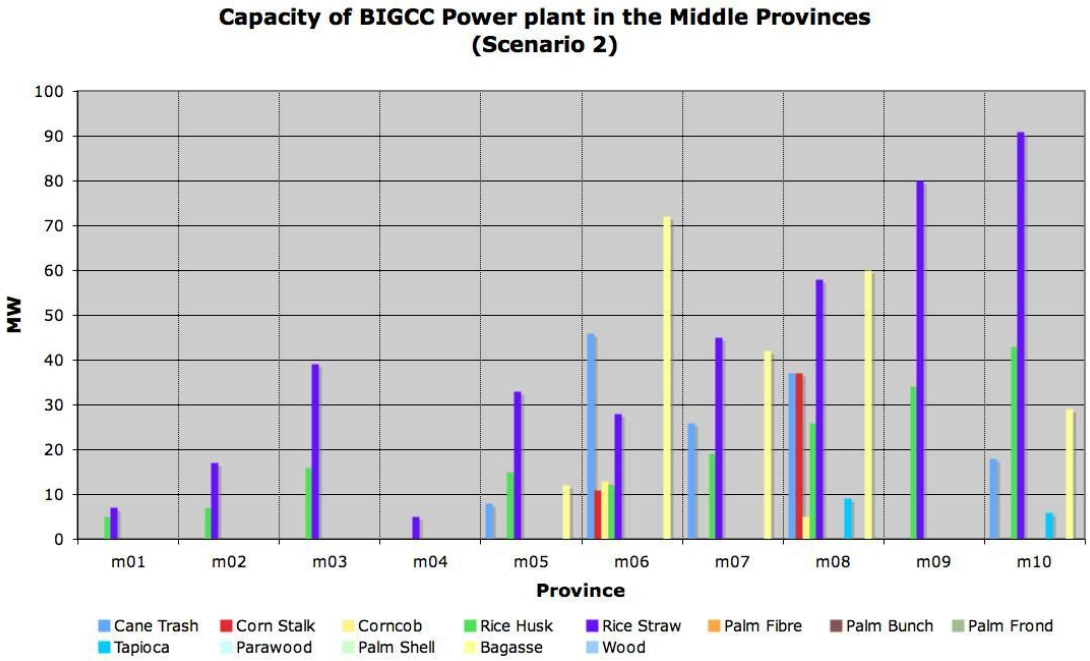


Figure 6.7: The middle provinces (Scenario 2: all biomass)

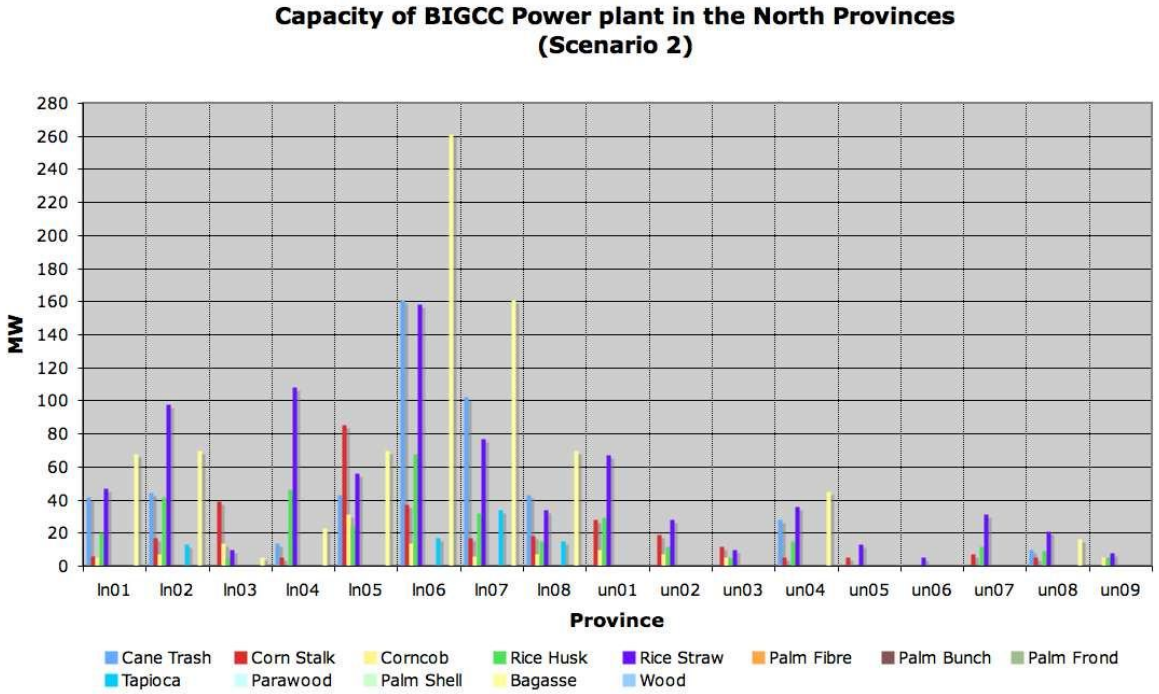


Figure 6.8: The north provinces (Scenario 2: all biomass)

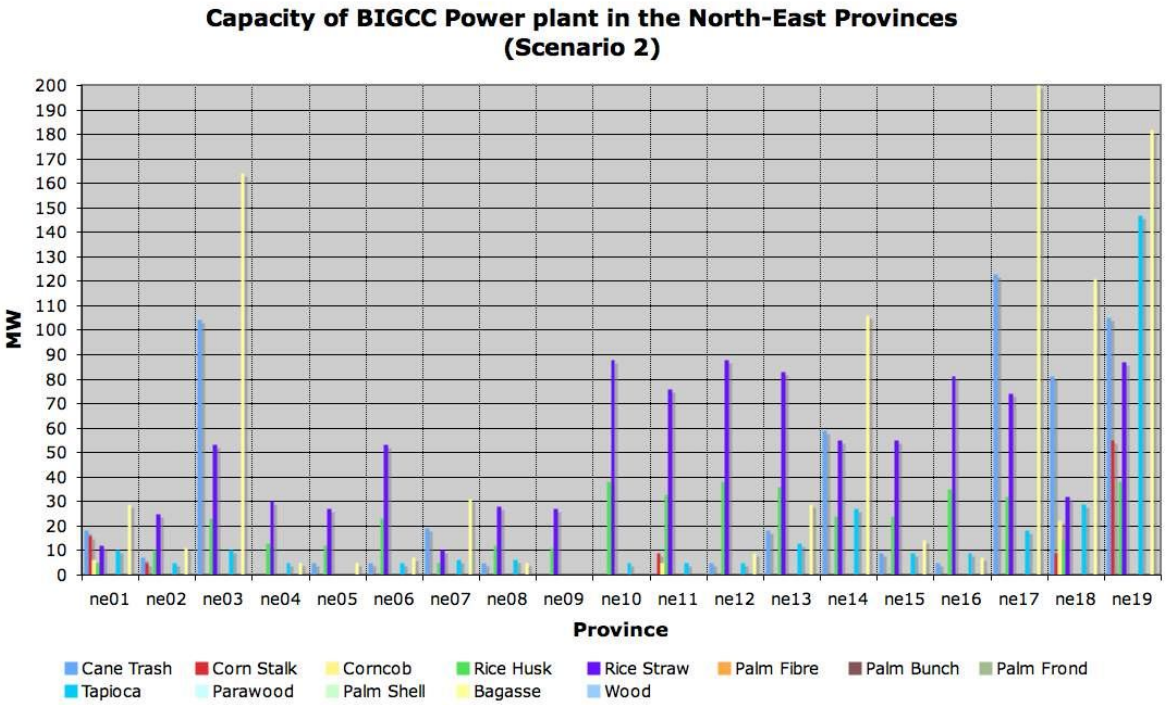


Figure 6.9: The north-east provinces (Scenario 2: all biomass)

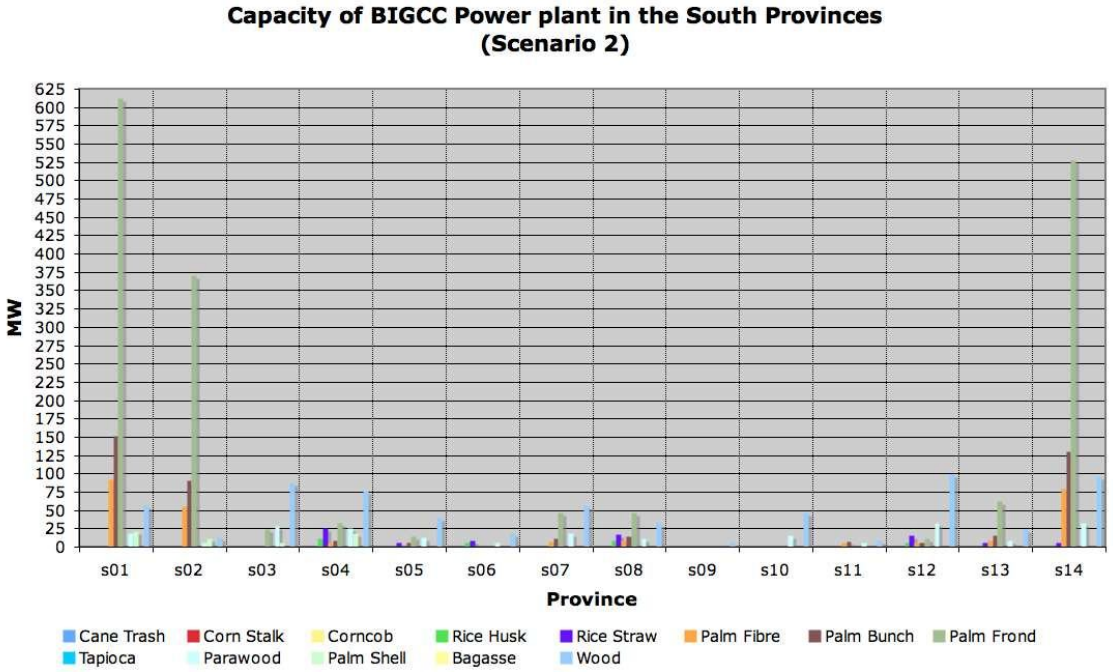


Figure 6.10: The south provinces (Scenario 2: all biomass)

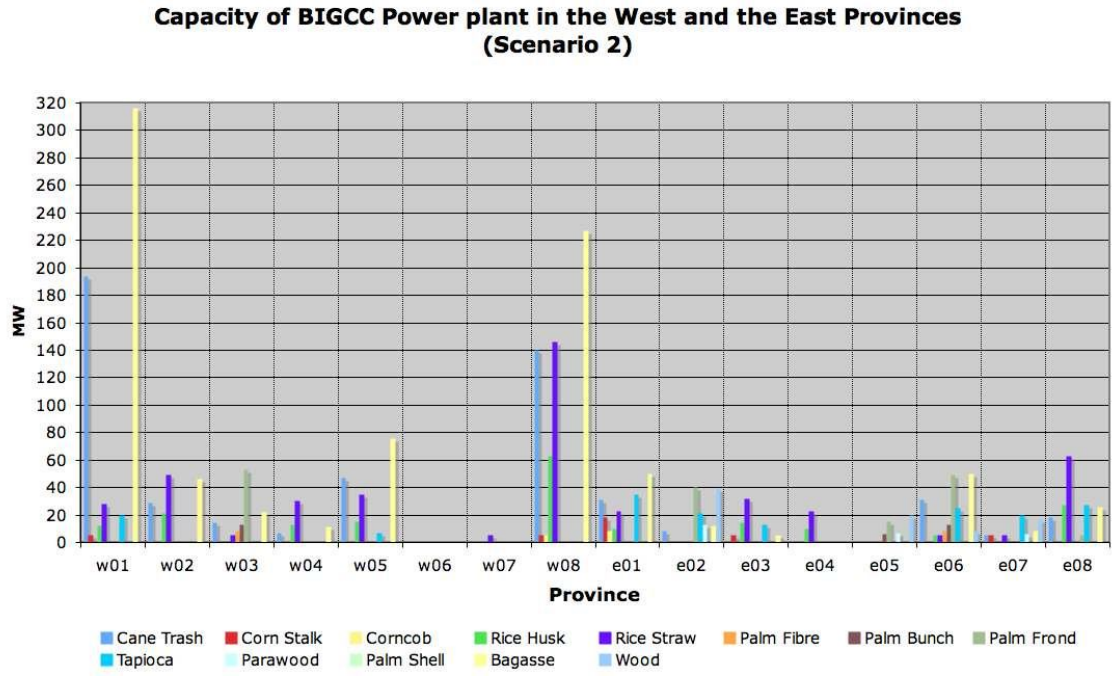


Figure 6.11: The west and the east provinces (Scenario 2: all biomass)

Table 6.19 shows the flow of electricity between grids for scenario 2. Comparing the flow of electricity for this scenario with the previous scenario, it can be seen that higher numbers of flow have been established.

Table 6.19: Flow of electricity between grids in ktoe (Scenario 2)

Flow of Electricity	m01	m02	m03	m04	m07	m09
m10		19.2			11.9	47.8
w01	254.4					
w08	108.3			128.4		
s01	258.3					
s02	278.2					
s14	502.2					
ln06	48.0	58.0	123.6			
ln08		92.0				

Flow of Electricity	w02	w03	w04	w05	w06	w07
w01	36.1					
s01		1.8			30.1	76.3
s02			37.2	13.1		
s07					6.4	

Flow of Electricity	e03	e04	e06	e07
w08			49.0	
e01				34.3
e02				0.4
e08			7.7	
ln06	29.1	20.1		

Flow of Electricity	s04	s05	s09	s10	s11	s12
s01	135.2	8.4		36.7		100.4
s07			46.0		9.3	
s08		15.0				
s13		44.7				

Flow of Electricity	un02	un03	un05	un07	un08	un09
un04		7.9				
ln01				25.9		4.9
ln02		54.6	11.4			
ln04	40.3					
ln06			61.1			
ln07					97.6	54.7

Flow of Electricity	ne01	ne02	ne04	ne13	ne15	ne16
m06				97.5		
m08		37.6				
ln04	1.1					
ln05	40.0	4.3				
ne03			1.9			
ne14					35.8	4.5
ne17					21.1	
ne18					28.9	

As the demand of electricity of province m01 (Bangkok) is the highest in the country, the model suggested that nearly 2,000 MW should be imported from other provinces. Moreover, when considering the total availability of biomass in Thailand before any industrial uses, many provinces have enough biomass residues to convert into electricity to meet their demands and also to transmit to other provinces.

Furthermore, an estimated value of 5.84E+13 g of CO_2 could be reduced per year from the suggested Biomass-to-Energy capacity expansion. The financial data for the suggested network is shown in Table 6.20.

Table 6.20: Breakdown of financial details of the suggested network (Scenario 2)

Financial Detail ($)	**Scenario 2**
Revenue	1.0788E+11
Investment Cost	1.7710E+10
Fixed Cost	4.7556E+09
Variable Cost	2.6136E+09
Raw Material Cost	1.3822E+10
Raw Material Transportation Cost	4.5496E+08
Electricity Transmission Cost	1.2022E+08
Total Profit	6.8404E+10

6.4.2.3 Scenario 3: with existing capacity, utilised unused biomass when the yield of generated biomass becomes double

The first feature to notice from the suggested capacity expansion of this scenario is that the total estimated electricity demand for Thailand could be met from converting the considered amount of biomass into electricity. The total suggested capacity was 14,746 MW. The suggested capacity expansion for scenario 3 is illustrated in Figure 6.12 to Figure 6.16. The amount of flow of energy between grids is shown in Table 6.21.

Considering the changes in trend of suggested capacity expansion in the middle province of scenario 3 and scenario 1, the model recommended that cane trash, bagasse, corn stalk and rice husk should be used as raw material for the BIGCC power plant, rather than rice straw which was the main raw material suggested in scenario 1. This is because even though the heat value for rice straw is comparable to cane trash,

bagasse, corn stalk and rice husk (around 15 MJ/kg), the cost of rice straw is much more expensive. Rice straw is 3 times more expensive than bagasse, nearly 2 times more expensive than rice husk and more than 25 times more expensive than cane trash and corn stalk.

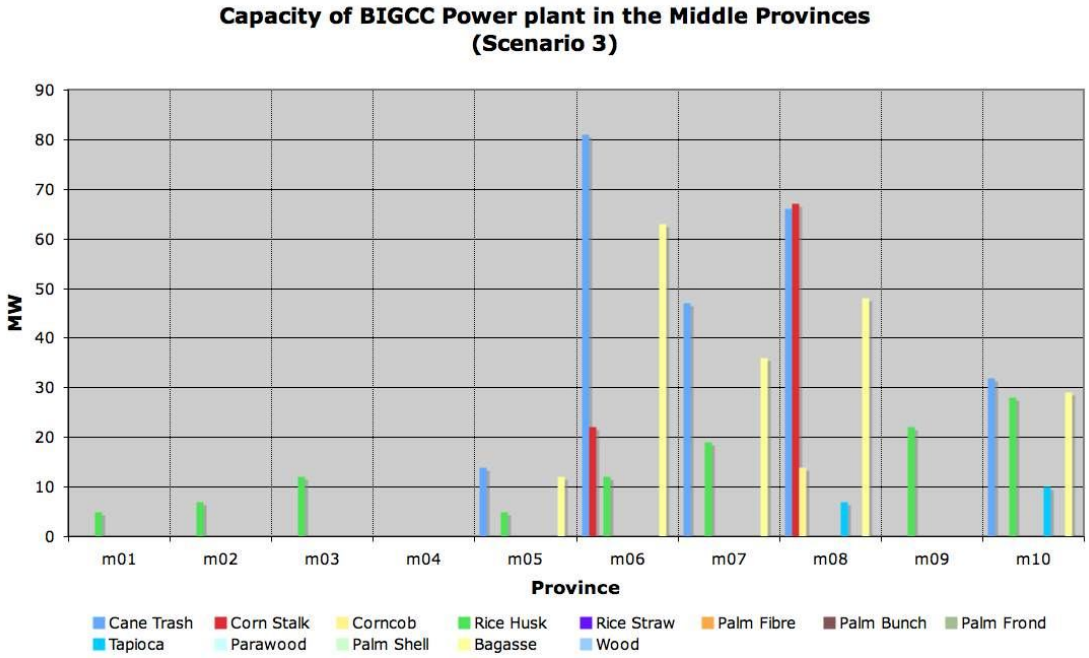


Figure 6.12: The middle provinces (Scenario 3: double generated biomass)

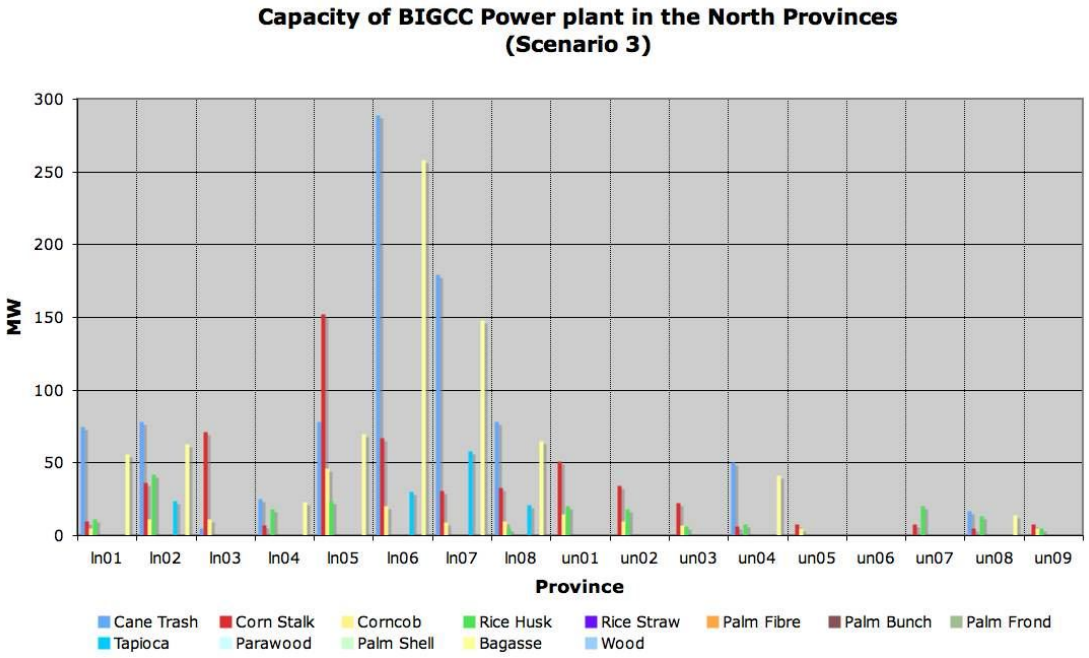


Figure 6.13: The north provinces (Scenario 3: double generated biomass)

Similar to suggested capacity expansion of the middle provinces, the BIGCC power plants, utilising similar biomass residues were suggested be built in the north, the north-east, the west and the east provinces to replace the rice straw as shown in Figure 6.13 to Figure 6.15.

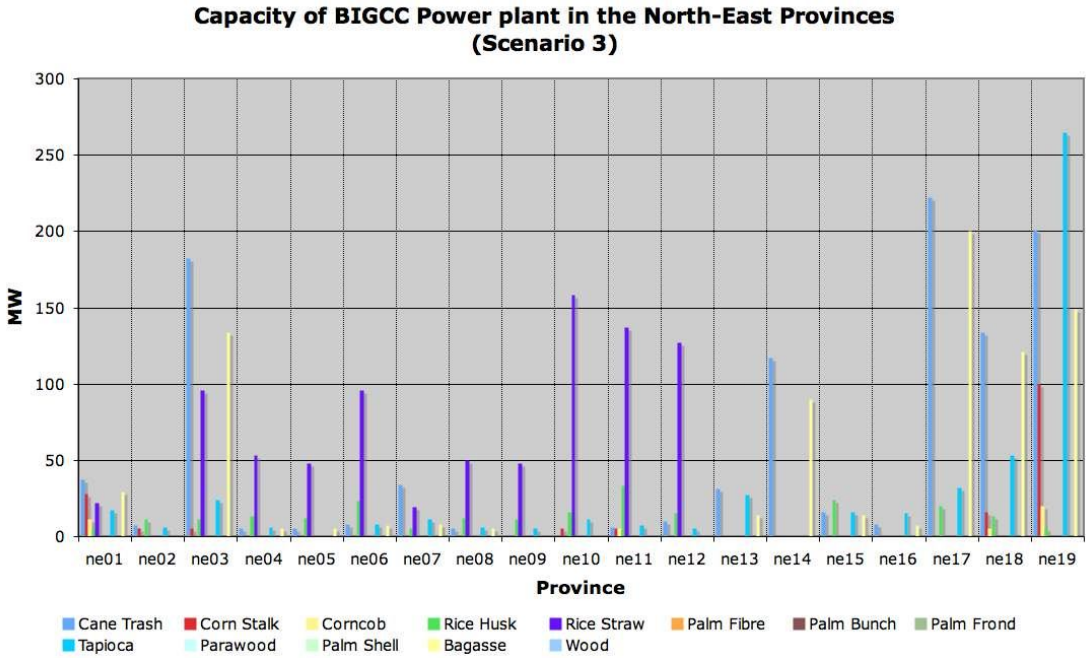


Figure 6.14: The north-east provinces (Scenario 3: double generated biomass)

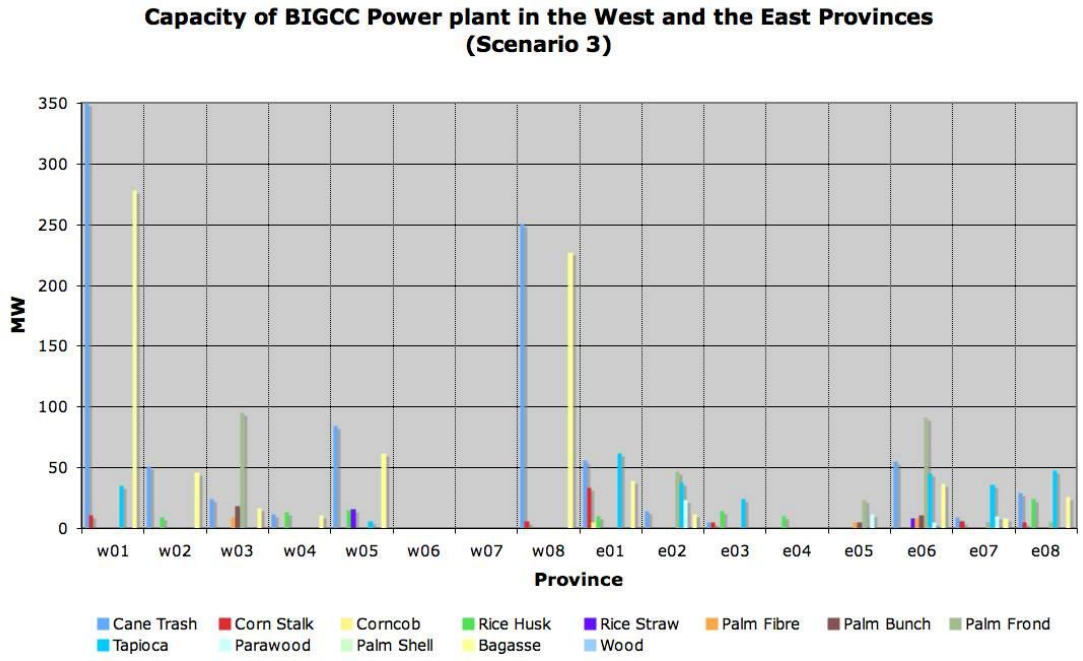


Figure 6.15: The west and the east provinces (Scenario 3: double generated biomass)

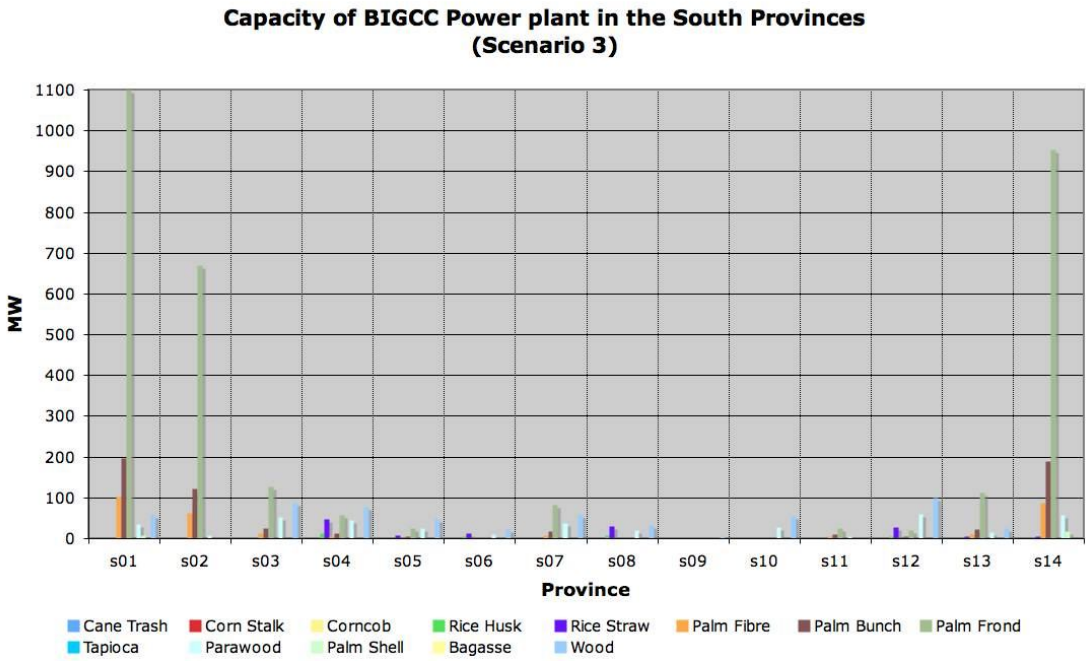


Figure 6.16: The south provinces (Scenario 3: double generated biomass)

From analysing the results of suggested capacity expansion of the south provinces for scenario 3, similar types of biomass as in scenario 1 were recommended. This is because other types were not available. However, a much higher capacity was recommended as illustrated in Figure 6.16. For example, the suggested capacity of the BIGCC power plants using palm frond as raw material in province s01, s02 and s14 were increased by more than 1,200 MW.

For this scenario, an estimated value of reductions of 8.58E+13 g of CO_2 per year are possible. The financial data for the capacity expansion strategy of Biomass-to-Energy power plants when the yield is double is shown in Table 6.21. The flow of electricity between grids is also shown in Table 6.22.

Table 6.21: Breakdown of financial details of the suggested network (Scenario 3)

Financial Detail ($)	**Scenario 3**
Revenue	1.0383E+11
Investment Cost	1.5961E+10
Fixed Cost	4.5994E+09
Variable Cost	2.4379E+09
Raw Material Cost	1.3717E+10
Raw Material Transportation Cost	4.0660E+09
Electricity Transmission Cost	1.0033E+08
Total Profit	6.2943E+10

Table 6.19: Flow of electricity between grids in ktoe (Scenario 3)

Flow of Electricity	m01	m02	m03	m04	m05	m07	m09
w01							111.2
w03	9.1						
w08		87.9	156.6				
s01	388.5			132.2		31.6	
s02	534.4						
s07					16.9		
s11					4.9		
s14	522.9	93.7			0.6		

Flow of Electricity	w02	w04	w06	w07
w01	62.0			
s01				80.1
s02			36.5	
s014		56.0		

Flow of Electricity	e03	e04	e05	e07	e08
w01	39.2	37.5		35.2	10.4
e02					1.2
s01				6.4	

Flow of Electricity	s04	s05	s06	s08	s09	s10	s12
s01	81.8					15.2	
s03		31.2		21.4			68.4
s07					46.0		
s13		12.8	75.7			5.2	

Flow of Electricity	un01	un02	un03	un04	un05	un06	un07	un08	un09
m10					19.8				
w03									37.1
ln01							5.5		16.2
ln02			41.4						
ln05			18.4						
ln06	71.7			2.2	50.5		212.5		
ln07						42.6	45.8	105.3	
ln08	68.2	43.1							

Flow of Electricity	ln04	ne02	ne04	ne05	ne06	ne08	ne09	ne10
m06				16.3		40.6	18.4	25.0
m08		45.7						
s14								149.0
ln05	36.2	9.7	5.1	43.7				
ne03			96.5					
ne07				9.1				
ne17					47.6			
ne19					40.8			

Flow of Electricity	ne11	ne12	ne13	ne15	ne16
w01		95.4			6.0
e01		69.8			
s01	115.2		178.8	51.0	
s07		45.5			
ne18				65.6	
ne19					87.4

A Pentium 4, 1.8 GHz Dell machine was also to solve the MILP model via the GAMS modelling tool and CPLEX v9.0. The corresponding computational statistics for solving the MILP models in this chapter are summarised in Table 6.22. The number of variables and equations are much higher than the previous model because of the increase in the number of grids.

The table clearly shows that the times required to solve the three scenarios are still minimal in comparison with the number of variables and equations involved in the scenarios. The optimality gaps are also very low which prove to be satisfactory. These results show that the MILP models are capable of identifying optimal energy planning strategies from biomass residues for Thailand in a very short time.

Table 6.22: Summary of computational results for the Biomass-to-Energy model

	Scenario 1	**Scenario 2**	**Scenario 3**
Number of single variables	739824	739824	739824
Number of discrete variables	346256	346256	346256
Number of equations	1770005	177005	177005
Optimality gap (%)	0.015	0.015	0.015
CPU time (sec)	35.820	34.198	34.077

6.4.3 Concluding Remarks

The spatial energy system optimisation model developed in the previous model was able to determine the optimal energy system supply chain network for Thailand based on the model assumptions. The model considered various energy production technologies from various resources. The model also divided the total mainland area of Thailand into 4 regions (grids). However, due to the facts that the Ministry of Energy of Thailand is promoting the development of new power plants from renewable energy and also large amounts of different types of biomass are available in Thailand, the power plants using biomass as raw material have been receiving higher attention. Therefore, the proposed model in this chapter focused on the Biomass-to-Energy system. The different types of biomass that are available in Thailand were taken into account in this model. Moreover, to fully represent the spatial nature of the energy system, the proposed model developed in this chapter divided the mainland

area of Thailand into 76 grids which represent the 76 provinces in different regions of Thailand.

The main difference in the mathematical formulation of this Biomass-to-Energy spatial model is the objective function. In this model, the objective is to maximise the total network profit rather than minimising the total cost. With the new objective, it is possible to determine the Biomass-to-Energy network which composes of power generation technologies that are both financially viable and also able to supply energy to different provinces of Thailand. However, from the results, the demand for all provinces cannot be met from only utilising the biomass resources available in Thailand. Three different scenarios were examined. The proposed model was able to determine the optimal Biomass-to-Energy supply chain networks according to the different conditions in each scenario. The optimal network for expansion strategy of power plant using unused biomass in each province was determined in the first scenario. The optimal Biomass-to-Energy structure utilising all estimated generated biomass in Thailand was suggested in the second scenario. Also, in the third scenario, the optimal supply chain network from unused biomass when the total yield of generated biomass was doubled was generated. For all scenarios, the proposed model suggested that the Biomass-to-Energy supply chain network suits a distributed power development plan where each of the biomass power plants are distributed across the country.

Due to the commercially proven in technology to convert biomass into energy, many power plants using biomass as raw material have already been developed in Thailand. Moreover, many biomass power plant projects have also been approved by the government to be established in Thailand. It is therefore difficult to apply the suggested Biomass-to-Energy supply chain networks to the real-world situation. However, biomass is not the only source of renewable energy; municipal solid waste (MSW) is also considered as a source of renewable energy. At present, the Ministry of Energy of Thailand is also promoting the development of new Waste-to-Energy projects. Only a few Waste-to-Energy power plants are in operations in Thailand. For these reasons, the work in the next chapter is the development of Waste-to-Energy spatial optimisation model with application to Thailand.

Chapter 7

Waste-To-Energy Spatial Energy System Modelling

7.1 Introduction

The previous chapter focused on developing a spatial multi-period optimisation model to determine an optimal spatial energy system from biomass for Thailand. At present, biomass power plants were built and in operation around the country, utilising almost all available biomass in Thailand. However, biomass is not the only source of renewable energy; energy from waste is also considered as renewable energy.

In view of current problems with waste management in Thailand and the policy created by the government of Thailand to promote all renewable energy together with the fact that there are only a few Waste-to-Energy power plants in operation in Thailand, this chapter is concentrated on developing a Waste-to-Energy spatial multi-period optimisation model for Thailand. The next section describes the background of solid waste management in Thailand.

7.1.1 Background of solid waste management in Thailand

The hierarchy of solid waste management begins with waste separation, collection, transportation, disposal and monitoring. At present, in Thailand, there is no definite regulation for the whole hierarchy.

For most of cities in Thailand, non-compaction trucks are still in use for daily solid waste collection. Only major cities use compaction trucks and container hauling trucks. Because of improper budget allowance for waste management to supply

adequate disposal equipment and labour, only 70-90% of generated waste is collected periodically.

With regard to disposal methods in Thailand, a majority of cities employ sanitary landfills as the disposal technique. However, the rest of the cities still use open dumping and burning on vacant land as their disposal method. Not all municipalities employ sanitary landfills. More sanitary landfill sites are expected to operate in the next few years.

Considering the current situation of Waste-to-Energy facility in Thailand, there are only five Waste-to-Energy projects using conventional technologies such as incinerator and anaerobic digesting in Thailand. The five WTE disposal sites are as follows [MOE, 2007] [MOE, 2008]:

1. Phuket disposal site can generate electricity 2.5 MW from waste 250 tons/day. Technology: Incinerator, stoker type
2. Rayong disposal site can generate electricity 0.625 MW from waste 60 tons/day. Technology: Anaerobic Digestion.
3. Rajathewa closing disposal site (waste from Bangkok) can generate electricity 0.95 MW from waste more than 1,000,000 tons. Technology: Landfill gas.
4. Kumpangsaen disposal site (waste from Bangkok) can generate electricity 1 MW from waste 5,000 tons/day. Technology: Landfill gas.
5. Chang Island disposal site can generate electricity 0.07 Mw from waste 20 tons/day. Technology: Anaerobic Digestion.

As a result of excessive expansion in industrial and socio-economic sectors, the problems of municipal solid waste (MSW) management in Thailand particularly in the capital city, named Bangkok and other regional cities in Thailand have continually grown bigger in recent years. It is reported by Taparugssanagorn, 2008, MOE, 2007 and MOE, 2008 that about 14.6 million tons of MSW were generated throughout the country, equal to 39,240 tons per day. The amount of waste generated increases

approximately 1.5% annually. However, only 60-80% of the residences in the municipal area are serviced for solid waste collection and disposal.

The major causes of the problems come from a combination of factors, including insufficient budget for MSW management, lack of waste disposal equipment, lack of disposal technology, incapability to identify suitable disposal sites by the responsible agencies, and unclear regulation for MSW management which consists of separation, collection, transportation, disposal and monitoring.

Without proper solid waste management, the number of unsanitary disposal sites would be increased and therefore pose threats to health and safety for humans and also create environmental contamination.

The increasing amounts of MSW create a great burden of solid waste management for the concerned local administrations. According to the current policy of promoting alternative energy in Thailand together with the problem of waste management mentioned above, the Ministry of Energy of Thailand aims to develop a total of 200 MW power plants using MSW as feedstock by the year 2020 [MOE, 2008].

One of the inducements to carry out research in the area of Waste-to-Energy in Thailand comes from the new government policy that supports and promotes alternative energy. The Board of Investment (BOI) offers an extensive package of tax and non-tax incentives, supporting the development of technologies such as mass transit systems, energy-conserving machinery and fuel cell technology. The Board of Investment is also promoting investments in energy efficient technology, which includes 8 years corporate income tax exemption, for electricity or steam power generation through the use of alternative energy sources such as MSW.

The government will support the purchase of power generated from renewable energy, in a suitable proportion and with appropriate purchasing prices by speeding up the announcement on the increase of purchasing capacity from Very Small Power Producers (VSPPs) and the establishment of purchasing price '**adders**' from the prices

specified in the Regulations. The subsidy adder will be paid for seven years, and depends on the renewable energy fuel. For MSW, the subsidy adder is 3.5 bath/kWh (i.e. approximately 150% of the current average wholesale electricity price).

7.1.2 Waste Treatment Technologies

The traditional MSW disposal method is to dump MSW in sanitary landfills. As the amount of MSW being generated increases everyday but on the other hand more lands are being occupied, it is crucial to divert MSW from landfills. Waste-to-Energy plants using incineration technology are a conventional way of diverting MSW from landfills and also generate benefit from the sale of electricity.

7.1.2.1 Incineration (Mass burn)

The incineration technology is a non-complex combustion process where waste is converted to energy by burning it directly in a special combustion chamber with an oxygen rich environment to make steam. Electricity can then be produced by driving the generated steam through a turbine generator. The process is also called mass burning. The designs of incineration plant have advanced over the past 20 to 30 years. However, the designs are still conventional.

Before feeding MSW into an incinerator or other advanced conversion technologies, a pre-treatment and processing of the MSW are usually performed. The MSW pre-treatment processes handle removing of non-conforming wastes such as construction and demolition debris, white goods, and car engines. Recyclables are also frequently removed in the pre-treatment stage. Moreover, the processes are used for moisture reduction and also for reducing the size of the MSW feed.

The main concern of the incineration process is the high level of pollutants that are formed during combustion due to the high availability of oxygen required by the process. The pollutants include sulphur dioxide, nitrogen oxide, hydrochloric acid,

dioxins, heavy metals and particulates. Extensive cleanup of the exhaust gases is necessary to make sure that emission standards are maintained.

While incineration plants are capable of reducing the amount of MSW in landfill, they raise other environmental impacts by producing hazardous ash and air emissions. The most serious environmental concern is the dioxins in the gases emitted from the incineration process, as the dioxins are expected to be the cause of cancer. For this reason, many of the older incinerator plants have to be closed down to meet tighter EU regulations in 1996. Moreover, new conventional incineration facilities are also very difficult to receive permits.

7.1.2.2 Gasification

Over the past few years, the development of advanced MSW thermal conversion technologies has provided a valuable alternative to incineration. The application of these technologies to MSW solves many of the issues and concerns that come with conventional incineration, including air emissions and production of hazardous ash. The advanced MSW thermal conversion technology that is receiving high attention is thermal “Gasification”. However, Waste-to-Energy facilities remain relatively rare.

While there are only a handful of these advanced MSW conversion facilities in operation globally, the basic technologies are well proven and dozens of companies worldwide are working to develop fully integrate power plants using the advanced conversion technology such as gasification. This is a rapidly evolving industry. With many facilities planned for construction and operation over the next few years, there will soon be significant operating experience to show the ability of these new technologies to provide an alternative to both landfills and incineration. The gasification technology is described in more detail below.

Thermal gasification is not a combustion process like the incineration process. It is a partial oxidation process that converts carbon-containing materials, such as coal, biomass, or wastes into a synthetic gas under very controlled conditions of heat and

availability of oxygen. The syngas consist primarily of hydrogen and carbon monoxide which can then be used to produce electricity and many products, including industrial chemicals and fuels.

The heart of the gasification system is the gasifier which is a pressurized vessel that carry out the partial oxidation process. There are several types of gasifier. The most popular category to identify the gasifier is the flow direction of the reactor such as up-draft, down-draft, and circulating. Other categories include the characteristic of the feed, the use of oxygen and the gas cooling process [Klein, 2002].

One of the limitations of the gasification process is the size of the feedstock. The size of the solid feedstock has to be ground into very small particles before feeding into the gasifier. The efficiency of the gasification process is also higher when using homogeneous feedstock in order to ensure constant operating conditions. However, the ideal feedstock varies by technology or design. Many gasification plants using homogenous matter such as coal, petroleum coke or biomass as feedstock have been in operation for decades throughout the world. However, gasification plants using MSW as feedstock are still very rare. This is due the heterogeneous nature of the MSW as it consists of wide range of different materials and sizes which is not ideal for the gasification process.

One way to convert the heterogeneous MSW into more homogeneous feedstock is to use a high level pre-treatment process called Mechanical Biological Treatment (MBT). The process converts MSW into refuse derived fuel (RDF) with a higher heat value. RDF can be processed more efficiently in the gasifier to produce syngas which can then be used to produce electricity. The RDF can also be used as a fuel elsewhere, such as blended with coal in electric utility boilers. The MBT pre-treatment process is described in more detail below.

7.1.2.3 Mechanical Biological Treatment (MBT)

MBT is defined as the processing or conversion of MSW with biologically degradable components via a combination of mechanical and biological processes. As stated, the MBT process involves two core stages: mechanical treatment and biological treatment. The mechanical and biological processes can be configured in different ways to produce a variety of products such as refuse derived fuel (RDF), solid recovered fuel (SRF), soil improver, compost, bio-stabilised material, biogas and also recycled products.

The mechanical part of the treatment involves separate MSW fractions into valuable products and/or streams suitable for biological processing. The mechanical process consists of sorting, separation, size reduction and sieving.

The biological part of the treatment includes aerobic rotting, anaerobic fermentation or combined processes. Aerobic systems include open windrow composting, in-hall composting, tunnel composting, in-vessel composting and, bio-drying. Anaerobic pre-treatment includes anaerobic digesting to produce bio gas. A detail review of MBT processes around the world is produced by Juniper consultants [Archer et al., 2005].

Refuse Derived Fuel (RDF) is refuse that passes through the MBT process and which will be used as a source of energy. This type of refuse is valuable and convenient for collection and transportation. Moreover, the remaining refuse is declined; therefore, it helps to reduce landfill areas and increase landfill durability.

For conversion of MSW to electricity, the pre-treatment processes must be properly integrated with the MSW conversion and power generation processes to ensure the reliable performance of the overall process. The amount of pre-treatment that is necessary depends on the conversion process. At present, the concept of integrating an MBT pre-treatment process to produce RDF from MSW with thermal gasification power plant to produce electricity is receiving an enormous amount of attention. One of the reference commercial plants is the Ecoenergia plant in Corteolona, Italy. The

plant produces approximately 9MW of electricity from RDF input of about 60,000 Tpa (equal to 120,000 Tpa of MSW). The Corteolona plant consists of a bio-drying section that produces RDF and bubbling fluidized bed combustion section that generates electricity. The plant has been in operation since 2004. However, Waste-to-Energy facilities of this type are still uncommon. Moreover, none of the facilities have been built in Thailand.

The model developed in this chapter applies the concept to the waste management of Thailand. The next section describes the model structure.

7.3 Proposed Waste-to-Energy technology with application to Thailand

The proposed Waste-to-Energy integrated technologies for the spatial Waste-to-Energy model given in this chapter comprises of three stages. The first stage is the pre-treatment of MSW. The technology of interest is the MBT technology which converts heterogeneous MSW to more homogeneous RDF. The second stage is the advance thermal conversion process. The gasification technology has been selected for this stage where production of syngas from RDF takes place. Finally, the third stage is the production of electricity using syngas to drive gas turbines to generate electricity. The stages are illustrated in Figure 7.1.

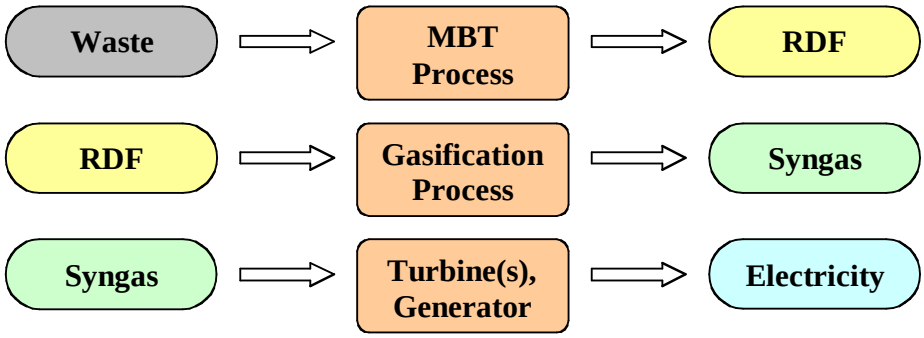


Figure 7.1 : Proposed Waste-to-Energy technologies for Thailand

Before describing the new model structure, the sites selection process for both the MBT pre-treatment plants and the thermal gasification power plant are described in the sub-section below.

7.3.1 Sites Selection

Selecting sites for the distributed thermal MSW gasification power plants is one of the key issues in implementing the model. There are many factors that should be considered in the decision making process; these factors include:

- Location of MSW sources
- Quantity of MSW
- Transportation between the sources and the plants
- Location of electricity grid
- Water Availability
- Protection from natural disasters such as flood
- Public acceptability

There are more than 100 landfills distributed throughout Thailand; however there are less than 10 operating incinerators and integrated systems. Figure 7.2 shows the location of landfills, incinerators and integrated systems in Thailand [MOE, 2008].

To reduce the transportation cost as much as possible, it is clear that the location of each of the sites should be in the same area or within a certain distance from a landfill. However, the public acceptability will be one of the most important determinants of the sites selection process. Citizens are rightfully concerned about the potential construction of a facility in their backyard, as many assume alternative technology poses a threat to the health and safety of residents and the environment.

In order to satisfy all the above factors, a proposed solution is to construct each of the thermal MSW gasification plants in ***industrial estates*** under the industrial estate authority of Thailand (I-EA-T). The Industrial Estate Authority of Thailand (I-EA-T)

is a state enterprise attached to the Ministry of Industry. It plays a significant role in the sustainable development of the Thai economy and Thailand's industrial sector while promoting environmental conservation. I-EA-T manages nearly to 40 industrial estates with international standards throughout the country Figure 7.3 shows the location of I-EA-T Industrial Estates [IEAT, 2010].

The industrial estates under I-EA-T are complete with comprehensive infrastructure, utilities and state-of-the-art environmental management systems. Each settlement is conveniently located within proximity to transportation networks, labour source, and supporting industries.

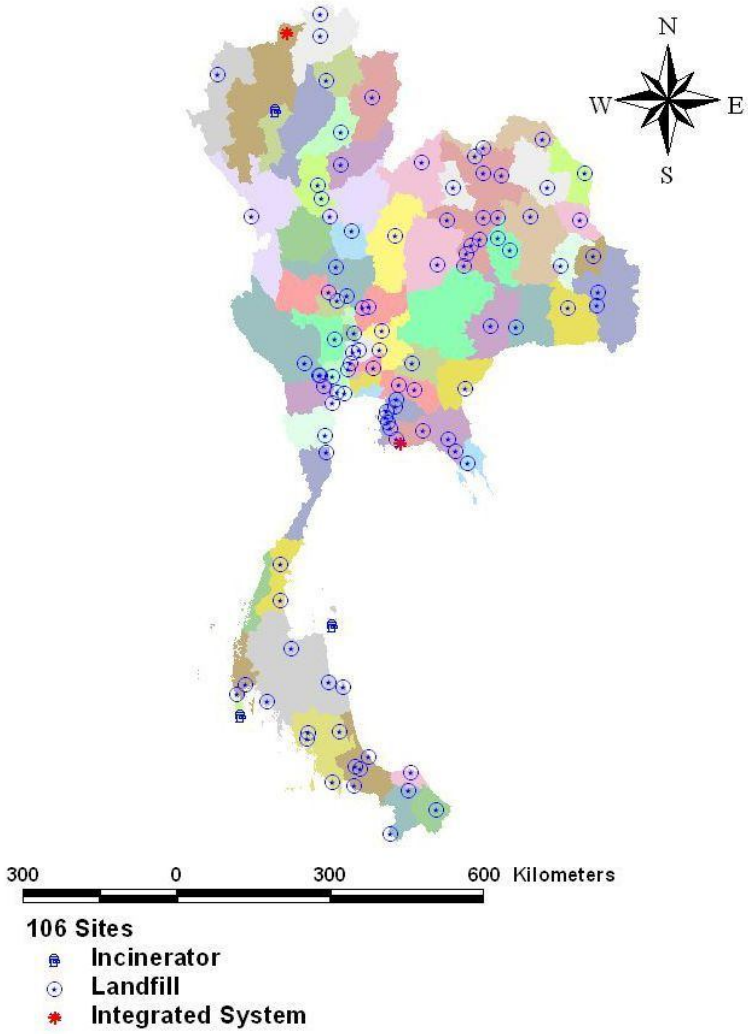


Figure 7.2: Location of Incinerators, Landfills and Integrated Systems in Thailand

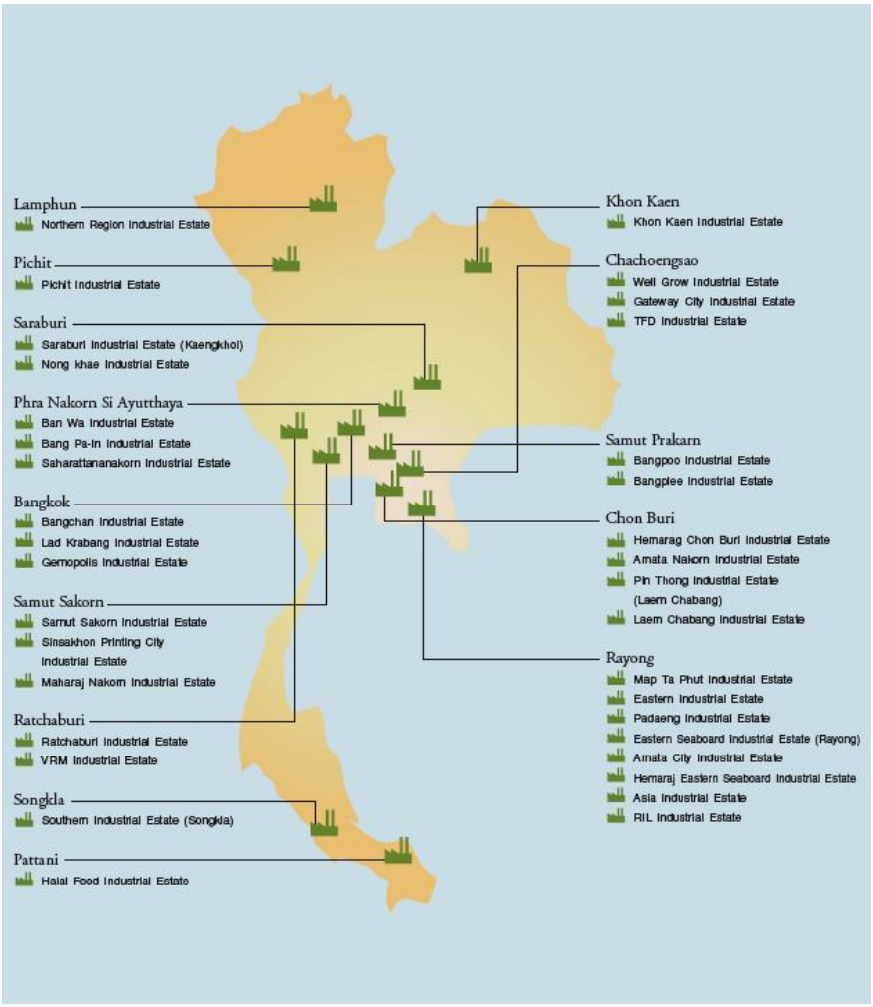


Figure 7.3: Location of I-EA-T Industrial Estates

The industrial estates provide many benefits with regard to transportation, location of high power electricity grid, water availability, drainage system and public acceptability. However they are not the location of MSW sources. MSW has to be transported from landfills or directly from transfer stations. Considering transportation problem of raw MSW, the most suitable locations for MBT plants are directly at the landfills or the transfer stations depending on the model structure.

One of the benefits of the MBT process is the volume reduction of MSW. Once the MSW has been processed by MBT process, the volume of the resultant RDF is about half of the original MSW. Moreover, the MBT process also removes any unpleasant smell of the MSW. Therefore, the transportation of RDF is much more convenient than MSW.

7.4 Model Structure

The model structure of this Waste-to-Energy model is different from the spatial energy models described in chapter 5 and chapter 6. The main difference is the grid component of the model structure. In the previous spatial energy models, energy production plants can be located in anywhere. However, the location of the proposed thermal gasification power plant is specified to be built in an industrial estate. On the other hand, the MBT plants are controlled to be built only at landfills or transfer stations depending on the model assumptions. The components of the model are described below in more detail.

7.4.1 Industrial Estate

Industrial Estate grids represent the location of each industrial estate throughout all regions of Thailand. In the model, thermal gasification power plants can only be built in industrial estates. The benefits of this assumption are explained in the previous section. The capacity of the thermal gasification power plant is bound by minimum and maximum limits of each industrial estate. The industrial estates in the spatial model are represented by the index e. The total number of industrial estates considered in this model is 35 which are listed in Table 7.1.

Table 7.1: List of industrial estates

Industrial Estate			
Lamphun	SamutSakorn1	Chachoengsao1	Rayong1
Pichit	SamutSakorn2	Chachoengsao2	Rayong2
KhonKaen	SamutSakorn3	Chachoengsao3	Rayong3
Saraburi1	Pattani	ChonBuri1	Rayong4
Saraburi2	Songkla	ChonBuri2	Rayong5
Ayutthaya1	Bangkok1	ChonBuri3	Rayong6
Ayutthaya2	Bangkok2	ChonBuri4	Rayong7
Ayutthaya3	Bangkok3		Rayong8
Ratchaburi1	Samutprakarn1		
Ratchaburi2	Samutprakarn2		

7.4.2 Landfill

Landfill grids represent the location of existing landfills in Thailand. As landfills are the source of MSW feedstock, MBT pre-treatment plants are allowed by the model to be built at all landfills to convert MSW into RDF. The capacity of each landfill is bound by maximum limits. The landfills given in the spatial model are coupled with the index l. The total number of landfills considered is 100 which are named as l01 to l100.

7.4.3 Province

Province grids represent the location of open-dump sites of each province in Thailand. This component is similar to the grid component in the previous model. MSW is generated and placed at open-dump sites of each province every day. The quantity of the MSW depends on the population in those provinces. The provinces are represented by the index p. There are 76 provinces considered in this model which are shown in Table 7.2.

Table 7.2: List of provinces

Middle Provinces	**West Province**	**East Provinces**	**North-East Provinces**	**South Provinces**	**Lower North Provinces**	**Upper North Provinces**
m01 to m10	w01 to w08	e01 to e08	ne01 to ne19	s01 to s14	ln01 to ln08	un01 to un09

7.4.4 Raw Material

Generally, the only raw material used in this model is the MSW. However, because large amounts of old MSW already exist in each landfill, the type of MSW feedstock can be categorised into 1) “Old MSW” which is the MSW has already been placed in a landfill, 2) “New MSW” which is the newly generated MSW. Moreover, as MSW can be converted by the MBT process to RDF which is a feedstock for the thermal gasification process, RDF is also another type of raw material for this model. The types of raw material are represented by index r.

7.4.5 Production Facilities

The production facilities component of this model are similar to the previous models given in this thesis. The main difference is the types of production technologies. In this model, the production technologies include MBT (Old MSW), MBT (New MSW), Incineration, Gasification and Combined Heat and Power Gasification (CHP) which are designated by the index i. While the MBT and Incineration facilities can only be built at landfills or provinces depending on model assumptions, the gasification facilities can only be developed at industrial estates. Also, each plant type has associated capital and operating & maintenance costs. Another major difference between this Waste-to-Energy spatial model and the previous spatial models is that the establishment of plants will be determined by the net profit from selling electricity instead of the demand of the grid.

7.4.6 Transportation Modes

In order to complete the hierarchy of Waste-to-Energy management, many transportation links between different nodes have to be established; for example, transportation of MSW between a province and a landfill, and transportation of MSW or RDF between a landfill and an industrial estate. In this model, transportation by truck is the only transportation mode. Similar to the previous model, the transportation mode has a delivery cost per distance travel, known delivery distance and flow rate limits. The delivery distance required by the model includes distances between provinces and landfills, provinces and industrial estates, and landfills and industrial estates.

7.4.7 Products

The proposed Waste-to-Energy spatial model has two products. The products are electricity and heat energy. The products are coupled with index v

7.5 Case Study: Waste-to-Energy management with application to Thailand

At present, Thailand has no regulations or guidelines on waste management. Wastes are collected from each province. Some of the wastes are transported to landfills. Some are disposed in open dumpsites. Moreover, there are only five operating Waste-to-Energy facilities, none of which uses advanced thermal gasification technology. The work described in this chapter investigates different strategies for developing Waste-to-Energy facilities in Thailand.

Four scenarios have been created to reflect different network structures. The first scenario represents a network, which utilises the daily waste being received at each landfill.

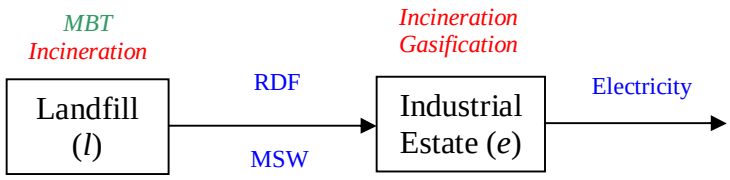
As mentioned earlier, some of the generated waste in each province is sent to dispose in landfill every day, however the rest of the waste is being placed in local open-dump sites. Therefore, in order to utilise all wastes that are being generated at each province of Thailand, the second scenario is created. The second scenario takes into account all the collected waste at each province.

Moreover, for every power plant such as thermal gasification power plant proposed for this model, not only can electricity be produced but also heat energy as well. As the previous scenarios only consider electricity as a main product, the third scenario adds heat energy as another final product.

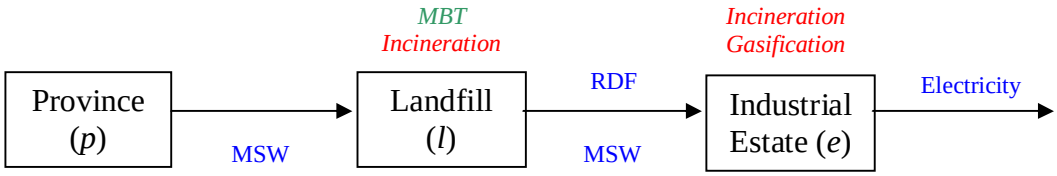
Furthermore, the previous three scenarios only take into account new wastes from each province. The final scenario also utilises the existing waste that has already been placed in each landfill of Thailand for many years.

The network configurations of the four cases are given below.

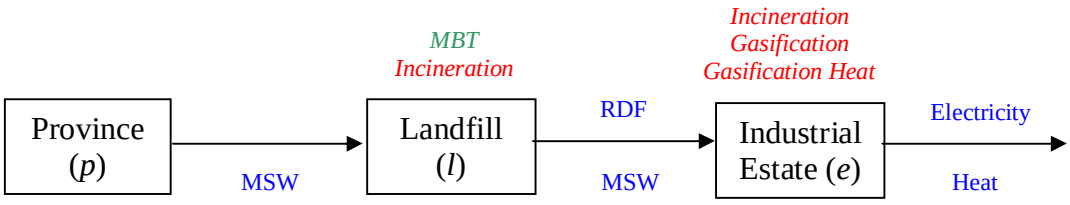
i. Wastes are utilised from landfills only



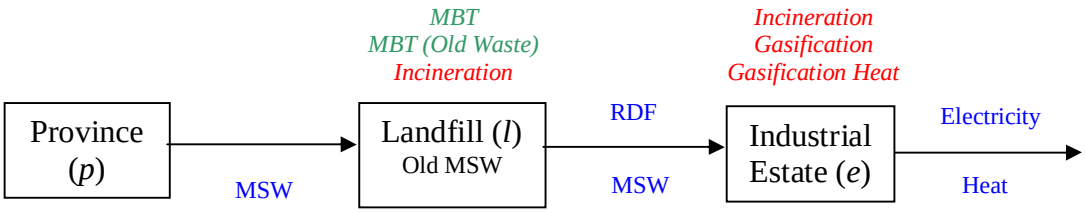
ii. Wastes are collected from each province and transported to landfills



iii. Include heat energy as output of thermal conversion technology



iv. Include utilisation of existing waste in landfill



7.5.1 Case I: Using existing landfill sites as source of raw material

7.5.1.1 Mathematical formulation

All four cases of the Spatial Waste-to-Energy model are formulated as MILP models which are described in the following sections.

7.5.1.1.1 Notation

Indices

i	=	Process of energy production
r	=	Resource for energy production (Raw material)
t	=	Time period
v	=	Energy vector
e	=	Industrial estate grid
l	=	Landfill grid

Parameters

$CostOM_{ir}$	=	Operating and Maintenance cost of process i per year per ton of raw material r used (Baht/ton/year)
$CostIV_i$	=	Investment cost for newly-built capacity i (Baht/MW)
$CostTR_r$	=	Cost to transport raw material r by truck (Baht/ton/km)
$ValueC_v$	=	Carbon credit value (Baht/MW)
$ValueR_r$	=	Tipping fee per ton of raw material used (Baht/ton)
$FR\min_r$	=	Minimum amount of raw material r that can be transported per

		trip (ton)
$FR\max_r$	=	Maximum amount of raw material r that can be transported per trip (ton)
$CostVE_e$	=	Cost variation between different industrial estates
$CostVL_l$	=	Cost variation between different landfill sites
rp_{rlt}	=	Amount of maximum potential domestic resource r in each landfill site per day at time period t (TPD)
rp_{rlt}^{unuse}	=	Amount of unuse domestic resource r in each landfill site per day at time period t (TPD)
RCT_{rl}	=	Add time index to the raw material cost parameters
RAT_{rl}	=	Add time index to the raw material availability parameters
FP	=	Fuel price (Baht/litre)
TFR	=	Truck fuel rate (litre/km)
TC	=	Truck capacity (ton)
$Days$	=	Number of days in operation per year (day)
gd_{el}	=	Average distance between industrial estate e and landfill l (km)
γE_{ri}^{input}	=	Proportion of resource r required for unit amount of process i at industrial estate e
αE_{vi}^{output}	=	Proportion of energy vector v produced per unit of process i at industrial estate e
γLR_{ri}^{input}	=	Proportion of resource r required for unit amount of pre-process i at landfill l
αLR_{ri}^{output}	=	Proportion of raw material r produced per unit of pre-process i at landfill l
γLV_{ri}^{input}	=	Proportion of resource r required for unit amount of process i at landfill l
αLV_{vi}^{output}	=	Proportion of raw material r produced per unit of process i at landfill l
DF_t	=	Discount factor at time period t

PP	=	Peak electricity value (Baht/kWh)
OPP	=	Off-peak electricity value (Baht/kWh)
FT	=	Ft rate (Baht/kWh)
$Adder$	=	Subsidy Adder (Baht/kWh)
$Plant^{maz}$	=	Maximum number of plant allow per one site
$Capacity^{total}$	=	Total maximum capacity of power plant (MW)
$bigM$	=	Large number
$smallm$	=	Small number

Binary Variable

$CE_{iet}^{establish}$	=	Active capacity expansion of process i at industrial estate e during time period t
$actR_{rlet}$	=	Active flow of resource r between landfill site l and industrial estate e at time period t

Variables

dp_{rlt}	=	Decision variable for using potential domestic resource r at landfill l per day in period t (TPD)
TEP_{vt}	=	Total production of energy vector v at time period t (MW)
EP_{vet}	=	Total production of energy vector v at each industrial estate e at time period t (MW)
$RawP_{rlt}$	=	Total production of resource r at each landfill site l at time period t (TPD)
IP_{vlt}	=	Total production of energy vector v at each landfill site l at time period t (MW)
EPE_{viet}	=	Production of energy vector v of process i at each industrial estate e at time period t (MW)
RPL_{rilt}	=	Production of resource r of process i at each landfill site l at

time period t (TPD)

EPL_{viet} = Production of energy vector v of process i at each landfill site l at time period t (MW)

UE_{riet} = Usage of resource r of process i at each industrial estate e at time period t (TPD)

UL_{rilt} = Usage of resource r of process i at each landfill site l at time period t (TPD)

$UL_{rilt}^{incineration}$ = Usage of resource r of incineration process i at each landfill site l at time period t

CE_{iet} = Capacity of process i at industrial estate e at time period t (MW)

CL_{ilt} = Capacity of pre-process i at landfill l at time period t (MW)

CLV_{ilt} = Capacity of incineration process i at landfill l at time period t (MW)

$CE_{iet}^{\exp and}$ = Expansion of process i at industrial estate e at time period t (MW)

$CL_{ilt}^{\exp and}$ = Expansion of pre-process i at landfill l at time period t (MW)

$CLV_{ilt}^{\exp and}$ = Expansion of incineration process i at landfill l at time period t (MW)

AUE_{ret} = Total usage of resource r at industrial estate e at time period t (TPD)

SUE_{ret} = Total supply of resource r at industrial estate e at time period t (TPD)

AUL_{rlt} = Total usage of resource r at landfill site l at time period t (TPD)

SUL_{rlt} = Total supply of resource r at landfill site l at time period t (TPD)

FR_{rlet} = Flow rate of resource r from landfill l to industrial estate e in at time period t (TPD)

$FR_{riet}^{\exp and}$ = Expansion of flow rate of resource r from landfill l to industrial

		estate e at time period t (TPD)
$Rdis_{rlet}$	=	Distance travel of resource r from landfill l to industrial estate e per trip at time period t (km)
$PeakE_{vet}$	=	Generated electricity during peak time (kWh)
$OffPeakE_{vet}$	=	Generated electricity during off-peak time (kWh)
$E\,\mathrm{Re}\,v_{vet}^{peak}$	=	Revenue from selling electricity during peak time at each industrial estate e at time period t (Baht)
$E\,\mathrm{Re}\,v_{vet}^{offpeak}$	=	Revenue from selling electricity during off-peak time at each industrial estate e at time period t (Baht)
$E\,\mathrm{Re}\,v_{vet}^{adder}$	=	Extra revenue from adder in selling electricity at each industrial estate e at time period t (Baht)
$E\,\mathrm{Re}\,v_{et}^{total}$	=	Total annual revenue from selling electricity at each industrial estate e at time period t (Baht)
$C\,\mathrm{Re}\,v_{et}^{total}$	=	Total annual revenue from selling carbon credits at each industrial estate e at time period t (Baht)
$T\,\mathrm{Re}\,v_{et}^{total}$	=	Total annual revenue from tipping fees at each industrial estate e at time period t (Baht)
$iPeakE_{vlt}$	=	Generated electricity from incineration process i at landfill l during peak hour (kWh)
$iOffPeakE_{vlt}$	=	Generated electricity from incineration process i at landfill l during off-peak hour (kWh)
$iE\,\mathrm{Re}\,v_{vlt}^{peak}$	=	Revenue from selling electricity during peak hour at each landfill site l at time period t (Baht)
$iE\,\mathrm{Re}\,v_{vlt}^{offpeak}$	=	Revenue from selling electricity during off-peak hour at each landfill site l at time period t (Baht)
$iE\,\mathrm{Re}\,v_{vlt}^{adder}$	=	Extra revenue from adder in selling electricity at each landfill site l at time period t (Baht)
$iE\,\mathrm{Re}\,v_{lt}^{total}$	=	Total annual revenue from selling electricity at each landfill site l at time period t (Baht)

$iT\,\mathrm{Re}\,v_{lt}^{total}$	=	Total annual revenue from tipping fees at each landfill site l at time period t (Baht)
$e\,\mathrm{Re}\,v_{et}^{total}$	=	Total annual revenue at each industrial estate e at time period t (Baht)
$l\,\mathrm{Re}\,v_{lt}^{total}$	=	Total annual revenue at each landfill site l at time period t (Baht)
$\mathrm{Re}\,v^{total}$	=	Total revenue (Baht)
$OMCost_{it}$	=	Operating and Maintenance cost of process i at time period t (Baht)
$OMCostE_{eit}$	=	Operating and Maintenance cost of process i at industrial estate e at time period t (Baht)
$OMCostL_{lit}$	=	Operating and Maintenance cost of process i at landfill site l at time period t (Baht)
$RtCost_{rt}^{total}$	=	Total cost for transporting resource r at time period t (Baht)
$RtCost_{rlet}$	=	Cost for transporting resource r from landfill site l to industrial estate e at time period t (Baht)
$CostPT_{el}$	=	Cost of transporting resource r per truck from landfill site l to industrial estate e (Baht)
$InvCost_{i}$	=	Investment cost for new process i (Baht)
$Cost^{total}$	=	Total cost (Baht)

The spatial optimisation model formulation consists of two types of entities: constraints and objective functions, which are described below. Due to the change in model structure, the mathematical formulation described in this chapter is independent from the mathematical formulations used in the previous chapters.

7.5.1.1.2 Constraints

Energy Production Constraints

In this waste to energy model, there are two types of location where two different conversion technologies operate.

The first location is a landfill site where municipal solid waste (MSW) will be transformed to refuse derived fuel (RDF) using a Mechanical Biological Treatment (MBT) pre-treatment process. The second location is an industrial estate where electricity will be produced from thermal conversion technologies such as gasification of RDF or direct incineration of MSW.

Production variables and production constraints are formulated to describe the processes and conversion technologies at both landfill sites and industrial estates.

For each industrial estate e, electrical power v for each process i, is represented by EPE_{viet} and can be described by parameter αE_{vi}^{output} and variable CE_{iet}, where αE_{vi}^{output} is the proportion of electrical power v produced by process i at industrial estate e.

EPE_{viet} is expressed as the sum of the proportion of electrical power v produced by process i (αE_{vi}^{output}) multiplied by the capacity of process i (CE_{iet}). The expression for EPE_{viet} is given in the form:

$$EPE_{viet} = \alpha E_{vi}^{output} \cdot CE_{iet} \qquad \forall v,i,g,t \qquad (7.1)$$

The total electrical power v of all processes at industrial estate e during time period t can be expressed as

$$EP_{vet} = \sum_{i} EPE_{viet} \qquad \forall v,e,t \qquad (7.2)$$

Similar constraints are also created for the MBT process at each landfill site. Daily production of RDF r for each process i, at landfill site l which is represented by RPL_{rilt} can be described by parameter αL_{ri}^{output} and variable CL_{ilt}, where αL_{ri}^{output} is the proportion of RDF r produced by process i at landfill site l.

$$RPL_{rilt} = \alpha RL_{ri}^{output} \cdot CL_{ilt} \qquad \forall r,i,l,t \qquad (7.3)$$

The total RDF r produced at landfill site l during time period t per day can be expressed as

$$RawP_{rlt} = \sum_{i} RPL_{rilt} \qquad \forall r,l,t \qquad (7.4)$$

Finally, constraints are also created for incineration processes at each landfill site. Electrical power v for incineration process i, at landfill site l which is represented by EPL_{vilt} can be described by parameter αLV_{vi}^{output} and variable CLV_{ilt}, where αLV_{vi}^{output} is the proportion of electrical power v produced by process incineration process i at landfill site l.

$$EPL_{vilt} = \alpha LV_{vi}^{output} \cdot CLV_{ilt} \qquad \forall v,i,/,t \qquad (7.5)$$

The total electrical power v of incineration process at landfill site l during time period t can be expressed as

$$IP_{vlt} = \sum_{i} EPL_{vilt} \qquad \forall v,l,t \qquad (7.6)$$

The total electrical power for the whole country during time period t can be expressed as follows:

$$TEP_{vt} = \sum_{e} EP_{vet} + \sum_{l} IP_{vlt} \qquad \forall v,t \qquad (7.7)$$

Resource Usage Constraints

The total resource usage r required by process i at industrial estate e (UE_{riet}) can be described in term of process capacity, as the proportion of resource r required for process i, which is represented by γE_{ri}^{input} multiplied by the capacity of process i, which is represented by CE_{iet}. The expression for UE_{riet} is given in the form:

$$UE_{riet} = \gamma E_{ri}^{input} \cdot CE_{iet} \qquad \forall r,i,e,t \qquad (7.8)$$

Additionally, the total resource usage r required by pre-treatment MBT process i at landfill site l (UL_{rilt}) is expressed as:

$$UL_{rilt} = \gamma LR_{ri}^{input} \cdot CL_{ilt} \qquad \forall r,i,l,t \qquad (7.9)$$

Finally, the total resource usage r required by incineration process i at landfill site l ($UL_{rilt}^{incineration}$) is expressed as:

$$UL_{rilt}^{incineration} = \gamma LV_{ri}^{input} \cdot CLV_{ilt} \qquad \forall r,i,l,t \qquad (7.10)$$

Resource Balance Constraints

The total resource balance on industrial estate grid e must be written to determine the production rate of electricity v and therefore capacity of process i in a particular industrial estate grid e.

The total resource usage at industrial estate e, which is represented by, AUE_{ret} can be expressed as sum of resource usage r for all processes i at industrial estate e. The variable is described in the form:

$$AUE_{ret} = \sum_{i} UE_{riet} \qquad \forall r,e,t \qquad (7.11)$$

The total supply of resource for industrial estate e (SUE_{ret}) is equal to the sum of total flow rate of resource r entering industrial estate grid e from all landfill sites l, which is given in the form:

$$SUE_{ret} = \sum_{l} FR_{rlet} \qquad \forall r,e,t \qquad (7.12)$$

On the other hand, the total resource balance on landfill site grid l must also be created to decide the production rate of RDF r ($RawP_{rlt}$), the required amount of MSW r (dp_{rlt}) and also the flow rate of resource r leaving landfill grid l to industrial estate e ($\sum_{e} FR_{rlet}$).

The supply of resource at each landfill site comes from local MSW and also production of RDF from the MBT process. The usage of resource at each landfill site includes the amount of MSW required by the MBT process and also the flow of MSW and RDF from the landfill site to other industrial estates.

The total resource usage at landfill site l (AUL_{rlt}) and the total supply of resource at landfill site l (SUL_{rlt}) are given in the form:

$$AUL_{rlt} = \sum_{i} UL_{rilt} + \sum_{i} UL_{rilt}^{incineration} + \sum_{e} FR_{rlet} \qquad \forall r,l,t \qquad (7.13)$$

$$SUL_{rlt} = dp_{rlt} + RawP_{rlt} \qquad \forall r,l,t \qquad (7.14)$$

The following constraints ensure that the balances of resource r at both industrial estate grid e and landfill site grid l are enforced.

$$AUE_{ret} = SUE_{ret} \qquad \forall r,e,t \qquad (7.15)$$

$$AUL_{rlt} = SUL_{rlt} \qquad \forall r,l,t \qquad (7.16)$$

The establishment of an MBT plant at a landfill site and power plant at an industrial estate are mainly determined by the availability of local resource. The following constraints are written to assure that the required amount of MSW r (dp_{rlt}) is less or equal than the amount available (rp_{rlt}) in each landfill site.

$$dp_{rlt} \leq rp_{rlt} \qquad \forall r,l,t \qquad (7.17)$$

$$rp_{rlt}^{unuse} = rp_{rlt} - dp_{rlt} \qquad \forall r,l,t \qquad (7.18)$$

Capacity Constraints

The capacity constraints control the maximum expansion of capacity of newly-built processes. The maximum expansion of capacity is limited by the maximum capacity of the transmission line of each grid. Bounds on technology capacity can be written as follows:

$$EP_{vet} \leq 9.9 \cdot Plant^{\max} \qquad \forall v,e,t \qquad (7.19)$$

$$TEP_{vt} \leq Capacity^{total} \qquad \forall v,t \qquad (7.20)$$

The value 9.9 is the maximum capacity of a power plant to be categorised as a very small power plant (VSPP) in Thailand.

As this model is a multi-period model, the capacity balances of process i at industrial estate e and landfill site l are given as follows:

$$CE_{iet} = CE_{iet-1} + CE_{iet}^{\exp and} \qquad \forall i,e,t \qquad (7.21)$$

$$CL_{ilt} = CL_{ilt-1} + CL_{ilt}^{\exp and} \qquad \forall i,l,t \qquad (7.22)$$

$$CLV_{ilt} = CLV_{ilt-1} + CLV_{ilt}^{\exp and} \qquad \forall i,l,t \qquad (7.23)$$

The above equations state that the current capacity of process i at industrial estate e or landfill site l during time period t is equal the capacity of the previous year plus the capacity of newly-built processes ($CE_{iet}^{\exp and}, CL_{ilt}^{\exp and}, CLV_{ilt}^{\exp and}$).

The minimum capacity expansion of process i at industrial estate e during time period t can be expressed as:

$$CE_{iet}^{\exp and} \le CE_{iet}^{establish} \cdot Capacity^{\min} \qquad \forall i,e,t \qquad (7.24)$$

The binary variable $CE_{iet}^{establish}$ is equal to 1 when a capacity expansion of process i at industrial estate e during time period t is suggested and 0 otherwise. The following equations justify the establishment of the capacity expansion of process i at industrial estate e during time period t. The minimum capacity is assumed to be 5MW of all cases

$$CE_{iet}^{\exp and} - bigM \cdot CE_{iet}^{establish} \le 0 \qquad \forall i,e,t \qquad (7.25)$$

$$CE_{iet}^{\exp and} - smallm \cdot CE_{iet}^{establish} \ge 0 \qquad \forall i,e,t \qquad (7.26)$$

Transportation Constraints

The distance of travel of raw material from landfill site l to industrial estate e ($Rdis_{rlet}$) is controlled by the following set of equations where $actR_{rlet}$ is a binary variable which has the value 1 when resource r is transferred from landfill site l to

industrial estate e or 0 otherwise. Parameter gd_{el} is the average distance between landfill site l and industrial estate e.

$$Rdis_{rlet} = actR_{rlet} \cdot gd_{el} \qquad \forall r,l,e,t \qquad (7.27)$$

$$Rdis_{rlet} \leq dis^{\max} \qquad \forall r,l,e,t \qquad (7.28)$$

The flow of resource r from landfill site grid l to industrial estate grid e will only exist if transportation of resource is required by process i at industrial estate e. The following equations justify the establishment of the flow between the two grids in the network.

$$FR_{rlet} - bigM \cdot actR_{rlet} \leq 0 \qquad \forall r,l,e,t \qquad (7.29)$$

$$FR_{rlet} - smallm \cdot actR_{rlet} \geq 0 \qquad \forall r,l,e,t \qquad (7.30)$$

To ensure that each year no less than the same amount of resource r is transferred from landfill site l to industrial estate e, the following expression is formulated.

$$FR_{rlet} = FR_{rlet-1} + FR_{rlet}^{\exp and} \qquad \forall r,l,e,t \qquad (7.31)$$

7.5.1.1.3 Objective functions

In this model, one of the objectives is to maximise the total profit of the system over the planning horizon. Each year, the total profit is calculated by subtracting the total annual cost from the total annual revenue. The revenue and cost elements are shown below.

Cost Equations

- ***Investment costs***

Investment costs include all capital investments required to make the incremental capacity operational for all technologies plus any transmission and/or distribution investment costs of conversion technologies.

The total investment cost of process i during time period t ($InvCost_{it}$) can be expressed in terms of capacity of newly-built processes i at all industrial estate e and landfill sites l ($\sum_{e} CE_{iet}^{\exp and}$, $\sum_{l} CL_{ilt}^{\exp and}$, $\sum_{l} CLV_{ilt}^{\exp and}$) and the investment cost of each newly-built capacity i as follows:

$$InvCost_{it} = DF_t \cdot \left(\sum_{e} CE_{iet}^{\exp and} + \sum_{l} CL_{ilt}^{\exp and} + \sum_{l} CLV_{ilt}^{\exp and} \right) \cdot CostIV_i \quad \forall i,t \tag{7.32}$$

where

DF_t is the discount factor during time period t

- **Operation and Maintenance (O&M) costs**

The O&M costs of process i during time period t ($OMCost_{it}$) can be expressed as the sum of O&M costs of each process i during time period t at industrial estate e ($OMCostE_{eit}$) and landfill site l ($OMCostL_{lit}$). The variable $OMCost_{it}$ is given in the form:

$$OMCost_{it} = \sum_{e} OMCostE_{eit} + \sum_{e} OMCostL_{lit} \qquad \forall i,t \tag{7.33}$$

$$OMCostE_{eit} = DF_t \cdot \sum_{e} \left(UE_{riet} \cdot CostOM_{ir} \cdot CostVE_e \right) \qquad \forall e,i,t \tag{7.34}$$

$$OMCostL_{lit} = DF_t \cdot \sum_l \left(\left(UL_{rilt} + UL_{rilt}^{incineration} \right) \cdot CostOM_{ir} \cdot CostVL_l \right) \quad \forall l, i, t \tag{7.35}$$

where

$CostOM_{ir}$	is the operation and maintenance cost of process i
$CostVE_e$	is the cost variation between industrial estates e
$CostVL_l$	is the cost variation between landfill sites l

- **Transportation costs**

It is assumed that the transportation of resource r from landfill site l to industrial estate e is carried out by trucks which are the only one transportation mode in this model. The following equations define the total transportation cost of resource r during time period t ($RtCost_{rt}^{total}$):

$$RtCost_{rt}^{total} = DF_t \cdot \sum_e \sum_l RtCost_{rlet} \quad \forall r, t \tag{7.36}$$

$$RtCost_{rlet} = \frac{FR_{rlet} \cdot Days \cdot CostPT_{el}}{TC} \quad \forall r, l, e, t \tag{7.37}$$

$$CostPT_{el} = FP \cdot TFR \cdot 2gd_{el} \quad \forall e, l \tag{7.38}$$

where

$CostPT_{el}$	is the cost of transporting resource r per truck from landfill site l to industrial estate e
gd_{el}	is the distance between industrial estate and landfill site
FP	is the fuel price
TFR	is the truck fuel rate
TC	is the truck capacity
$Days$	is the number of days in operation

The total cost can be expressed as the following equation.

$$Cost^{total} = \sum_{t}\left(\sum_{i} InvCost_{it} + \sum_{i} OMCost_{it} + \sum_{r} RtCost_{rt}^{total}\right) \quad (7.39)$$

Revenue equations

The revenues for this waste to energy model consist of three main sources which are electricity produced by the system, carbon credit and tipping fees.

- ***Electricity***

It is important to realise that the revenue from selling electricity will vary between different countries. The following equations are based on the data currently used in Thailand.

The amount of electricity generated during peak times and off-peak times at industrial estate e during time period t in kWh are given in the form:

$$PeakE_{vet} = EP_{vet} \cdot PeakHour \cdot 1000 \qquad \forall v,e,t \qquad (7.40)$$

$$OffPeakE_{vet} = EP_{vet} \cdot OffPeakHour \cdot 1000 \qquad \forall v,e,t \qquad (7.41)$$

The revenues from selling electricity during peak ($E\,\mathrm{Re}\,v_{vet}^{peak}$) and off-peak ($E\,\mathrm{Re}\,v_{vet}^{offpeak}$) hours are calculated using the following equations.

$$E\,\mathrm{Re}\,v_{vet}^{peak} = 0.98 \cdot PeakE_{vet} \cdot (PP + FT) \qquad \forall v,e,t \qquad (7.42)$$

$$E\,\mathrm{Re}\,v_{vet}^{offpeak} = 0.98 \cdot OffPeakE_{vet} \cdot (OPP + FT) \qquad \forall v,e,t \qquad (7.43)$$

The adder is also formulated in this model by the following expression:

$$E\,\mathrm{Re}v_{vet}^{adder} = Adder \cdot \left(PeakE_{vet} + OffPeakE_{vet}\right) \qquad \forall v,e,t \qquad (7.44)$$

Therefore, the total revenue from selling electricity at industrial estate e during time period t can be expressed as:

$$E\,\mathrm{Re}v_{et}^{total} = DF_t \cdot \sum_{v}\left(E\,\mathrm{Re}v_{vet}^{peak} + E\,\mathrm{Re}v_{vet}^{offpeak} + E\,\mathrm{Re}v_{vet}^{adder}\right) \quad \forall e,t \qquad (7.45)$$

Similar equations to calculate sales of electricity from incineration plant at each landfill are as follows:

$$iPeakE_{vlt} = IP_{vlt} \cdot PeakHour \cdot 1000 \qquad \forall v,l,t \qquad (7.46)$$

$$iOffPeakE_{vlt} = IP_{vlt} \cdot OffPeakHour \cdot 1000 \qquad \forall v,l,t \qquad (7.47)$$

$$iE\,\mathrm{Re}v_{vlt}^{peak} = 0.98 \cdot iPeakE_{vlt} \cdot \left(PP + FT\right) \qquad \forall v,l,t \qquad (7.48)$$

$$iE\,\mathrm{Re}v_{vlt}^{offpeak} = 0.98 \cdot iOffPeakE_{vlt} \cdot \left(OPP + FT\right) \qquad \forall v,l,t \qquad (7.49)$$

$$iE\,\mathrm{Re}v_{vlt}^{adder} = Adder \cdot \left(iPeakE_{vlt} + iOffPeakE_{vlt}\right) \qquad \forall v,l,t \qquad (7.50)$$

$$iE\,\mathrm{Re}v_{lt}^{total} = DF_t \cdot \sum_{v}\left(iE\,\mathrm{Re}v_{vlt}^{peak} + iE\,\mathrm{Re}v_{vlt}^{offpeak} + iE\,\mathrm{Re}v_{vlt}^{adder}\right) \qquad \forall l,t \qquad (7.51)$$

- ***Carbon credit***

The second revenue stream for this model is the revenue from selling carbon credits ($C\,\mathrm{Re}v_{et}^{total}$). The variable can be described as the discounted value of the sum of electricity production v at industrial estate e during time period t (EP_{vet}) multiplied by the value of carbon credit ($ValueC_v$).

$$C\,\mathrm{Re}v_{et}^{total} = DF_t \cdot \sum_v \left(EP_{vet} \cdot ValueC_v \right) \qquad \forall e,t \qquad (7.52)$$

- ***Tipping fees***

The final revenue stream is the tipping fee or gate fee for removing resource r from each landfill site l. The total tipping fees at industrial estate e during time period t ($T\,\mathrm{Re}v_{et}^{total}$) is given in the form:

$$T\,\mathrm{Re}v_{et}^{total} = DF_t \cdot \sum_i \left(\sum_r \left(UE_{riet} \right) \cdot 330 \cdot ValueR_r \right) \qquad \forall e,t \qquad (7.53)$$

The total tipping fees at landfill l from incineration plant during time period t ($iT\,\mathrm{Re}v_{it}^{total}$) is given in the form:

$$iT\,\mathrm{Re}v_{lt}^{total} = DF_t \cdot \sum_i \left(\sum_r \left(ULE_{rilt} \right) \cdot 330 \cdot ValueR_r \right) \qquad \forall l,t \qquad (7.54)$$

The total revenue for all time period t can then be expressed in the form:

$$\mathrm{Re}v^{total} = \sum_t \left(\sum_e \left(\mathrm{Re}v_{et}^{total} \right) + \sum_l \left(l\,\mathrm{Re}v_{lt}^{total} \right) \right) \qquad (7.55)$$

$$\mathrm{Re}v_{et}^{total} = E\,\mathrm{Re}v_{et}^{total} + C\,\mathrm{Re}v_{et}^{total} + T\,\mathrm{Re}v_{et}^{total} \qquad \forall e,t \qquad (7.56)$$

$$l\,\mathrm{Re}v_{lt}^{total} = iE\,\mathrm{Re}v_{lt}^{total} + iT\,\mathrm{Re}v_{lt}^{total} \qquad \forall l,t \qquad (7.57)$$

The objective function is to maximise profit from the revenue from the sum of electricity, carbon credit and tipping fees subtracted by the sum of investment costs, transportation costs and operation and maintenance costs that are discounted back to

the beginning of the planning horizon. Thus the objective function is given in the form:

$$\begin{aligned} \textit{Maximise} \quad & \sum_t \left(\sum_e \left(\mathrm{Re}v_{et}^{total} \right) + \sum_l \left(l\,\mathrm{Re}v_{lt}^{total} \right) \right) \\ & - \sum_t \left(\sum_i InvCost_{it} + \sum_i OMCost_{it} + \sum_r RtCost_{rt}^{total} \right) \end{aligned} \tag{7.58}$$

Or

$$\textit{Maximise} \quad \mathrm{Re}v^{total} - Cost^{total} \tag{7.59}$$

7.5.1.2 Input Data: Case I

One of the most crucial parts in developing a realistic Waste-to-Energy spatial model for Thailand is the data collection. It is necessary to understand and obtain the data required for the application of Waste-to-Energy supply chain design. Similar to previous spatial models, the data required can be grouped into technology data, financial data, raw material data and grid data. The following subsections describe the input data required to develop the Waste-to-Energy spatial model.

The data presented in this section is based on both actual data obtained from agencies in Thailand and also on theoretical assumptions. However, the data is considered to characterise the real-world problem well. Furthermore, the costs and revenues are expressed in Baht rather than US$.

Technology Data

As this model only considers technology related to converting waste into energy, the three technologies considered in this model are Incineration, Mechanical Biological Treatment (MBT) and Gasification. Although the MBT and gasification processes are the proposed Waste-to-Energy processes for waste management in Thailand, the incineration process is also considered for comparison.

Moreover, there are many types of MBT and gasification processes as the two technologies have been developed by many companies worldwide. Some MBT technologies involve more advanced machinery than others and hence the difference in prices. The selected MBT technology for this model is a more simple process.

As mentioned in the previous chapters, in order to calculate the amount of input raw material and output product of a process, the input and output factors are required. The factors are given in Table 7.3 and Table 7.4.

Table 7.3: Input factor of each technology

Technology Types	**MSW (TPD)**	**RDF (TPD)**	**Electrical Power (MW)**
Incineration	100	-	-
Mechanical Biological Treatment (MBT)	4	-	-
Gasification	-	13.09	-

[Taparugssanagorn, 2008] [MOE, 2007] [Breeze, 2005] [Archer et al., 2005] [Klein, 2002]

Table 7.4: Output factor of each technology

Technology Types	**MSW (TPD)**	**RDF (TPD)**	**Electrical Power (MW)**
Incineration	-	-	1
Mechanical Biological Treatment (MBT)	-	1	-
Gasification	-	-	1

[Taparugssanagorn, 2008] [MOE, 2007] [Breeze, 2005] [Archer et al., 2005] [Klein, 2002]

Financial Data

The financial data required for the first case can be divided into revenue streams data and costs data which are presented below.

Revenue streams Data

The potential revenue streams form an important aspect of the overall plant economics. The revenues arise from electricity sales, tipping fees from the management of solid waste residue that would otherwise be disposed to landfill, and carbon credits. The following subsection describes the data required to calculate the revenue streams.

Electricity sales

The main factor that contributes to the economic viability of a MSW thermal gasification power plant in Thailand is the price of electricity. The subsidy adder for using MSW as fuel is 3.5 baht/kWh. As mentioned earlier, the Ministry of Energy of Thailand has a policy to develop a total of 200 MW power plants using MSW as feedstock by the year 2020, therefore both EGAT and PEA have high incentives to accept new power purchase agreements from a new Waste-to-Energy facility. The electricity prices are shown in Table 7.5.

Table 7.5: Electricity prices

Electricity Revenue Streams	Prices (Baht/kWh)
Peak Electricity	2.93
Off-peak Electricity	1.12
Ft rate	0.68
Subsidy Adder	3.5

[EGAT, 2010] [PEA, 2010]

Tipping fees

As this proposed model deals with converting wastes into energy, instead of paying for a raw material such as coal or natural gas, the appropriate agency has to pay a "tipping fee" for the amount of MSW that has been removed. In Thailand, the tipping fee is not fixed; therefore it is difficult to estimate the fee, prior to any negotiations with any solid waste feedstock supplier. However, the value of tipping fees can be

estimated to lie in the range of 200 to 400 baht/ton of MSW. The tipping fees for each kind of raw material used in this model are given in Table 7.6.

Table 7.6: Tipping fees for each raw material.

Raw Material Types	Tipping Fees (Baht)
MSW	200

Carbon credit (Certified Emissions Reductions)

The financial value of gaining certification of carbon credits depends on the value of the carbon credits generated by the project, minus the costs associated with gaining certification. For a MSW thermal gasification power project in Thailand, GHG savings are achieved in two ways:

- Avoiding landfilling of MSW, which directly generates methane (CH4). Methane's GHG potential is 23 times that of CO2 which means that one ton of CH4 is approximately equal to 23 carbon credits.
- Induction of new gasification technology, which significantly reduce GHG emissions relative to coal-fired power plant.

Assuming one metric ton of CO2 is worth US $15, then for a 10 MW gasification power plant, the benefit gained from earning carbon credits could be worth approximately US $1,450,000 or 50,000,000 Baht annually. The revenue from selling carbon credits for a 1 MW Waste-to-Energy facility is given in Table 7.7.

Table 7.7: Carbon credit for 1 MW gasification power plant .

Capacity of Gasification Power Plant	Revenue from Carbon credit (Baht)
1 MW	5,000,000

Cost Data

The costs data include technology costs and transportation costs which are presented below.

Technology costs

The capital costs for gasification technologies are similar world-wide. However most gasification power plants operating around the world do not use MSW or RDF as raw material. Moreover, the capacities of those plants are much higher than normal Waste-to-Energy facilities. The costs of gasification technology used in this model are based on the costs of integrated coal gasification technology [Breeze, 2005]. Furthermore, the O&M cost for a power plant in Thailand is assumed to be less than the cost in developed countries due to much lower cost of labour in Thailand. The costs of those technologies are presented in Table 7.8 and 7.9.

Table 7.8: Capital costs of selected Waste-to-Energy technologies

Technology Types	**Capital Costs**	**Unit**
Incineration	200,000,000	Baht/MW
Mechanical Biological Treatment (MBT)	944,000	Baht/TPD
Gasification	65,450,000	Baht/MW

[Taparugssanagorn, 2008] [MOE, 2007] [Breeze, 2005] [Archer et al., 2005] [Klein, 2002]

Table 7.9: O&M costs of selected Waste-to-Energy technologies

Technology Types	**Capital Costs**	**Unit**
Incineration	330,000	Baht/Ton per year
Mechanical Biological Treatment (MBT)	163,885	Baht/Ton per year
Gasification	330,000	Baht/Ton per year

[Taparugssanagorn, 2008] [MOE, 2007] [Breeze, 2005] [Archer et al., 2005] [Klein, 2002]

Discount Factor

In order to calculate the NPV of the project over the planning horizon, a discount factor is required. Assuming the interest rate to be 4%, the discount factor for the planning horizon of 10 years is given in Table 7.10.

Table 7.10: Discount Factor (Interest rate = 4%)

Year	Discount Factor
1	1
2	0.961538
3	0.924556
4	0.888996
5	0.854804
6	0.821927
7	0.790314
8	0.759917
9	0.730690
10	0.702586

Raw Material Data

The main raw material used in this model is the MSW. Even though the refuse derived fuel (RDF) is a product of the MBT process, it is also considered as one of the raw materials. At present, wastes are collected and transported to local landfills. However, each province in Thailand does not have its own landfill to dispose waste. Some of the provinces have to transport their waste to the closest available landfills. The quantities of MSW being transported to each landfill in Thailand are given in Table 7.11.

Table 7.11: Quantity of MSW being received at each landfill

Landfill 1 to 50	Quantity of MSW (TPD)	Landfil 26 to 50	Quantity of MSW (TPD)	Landfil 51 to 75	Quantity of MSW (TPD)	Landfil 76 to 100	Quantity of MSW (TPD)
l01	15	**l26**	45	**l51**	75	**l76**	15
l02	75	**l27**	45	**l52**	15	**l77**	15
l03	15	**l28**	45	**l53**	15	**l78**	45
l04	15	**l29**	45	**l54**	236	**l79**	45
l05	15	**l30**	15	**l55**	260	**l80**	134
l06	15	**l31**	15	**l56**	75	**l81**	75
l07	45	**l32**	45	**l57**	75	**l82**	15
l08	15	**l33**	15	**l58**	631	**l83**	272
l09	15	**l34**	45	**l59**	75	**l84**	267
l10	45	**l35**	322	**l60**	15	**l85**	45
l11	75	**l36**	15	**l61**	75	**l86**	15
l12	45	**l37**	15	**l62**	15	**l87**	15
l13	45	**l38**	15	**l63**	400	**l88**	45
l14	45	**l39**	45	**l64**	15	**l89**	45
l15	15	**l40**	45	**l65**	15	**l90**	15
l16	15	**l41**	45	**l66**	45	**l91**	45
l17	45	**l42**	196	**l67**	45	**l92**	75
l18	328	**l43**	45	**l68**	15	**l93**	150
l19	15	**l44**	15	**l69**	45	**l94**	286
l20	15	**l45**	45	**l70**	911	**l95**	15
l21	45	**l46**	15	**l71**	75	**l96**	15
l22	45	**l47**	15	**l72**	75	**l97**	45
l23	45	**l48**	45	**l73**	240	**l98**	75
l24	15	**l49**	45	**l74**	45	**l99**	45
l25	75	**l50**	240	**l75**	150	**l100**	45

[MOE, 2007]

Table 7.12: O&M cost variation factor between industrial estates

Industrial Estate	Cost_variation_factor
Lamphun	1
Pichit	1
KhonKaen	1
Saraburi1	1.2
Saraburi2	1.2
Ayutthaya1	1
Ayutthaya2	1.1
Ayutthaya3	1.2
Ratchaburi1	1
Ratchaburi2	1.1
SamutSakorn1	1
SamutSakorn2	1.1
SamutSakorn3	1.2
Pattani	1
Songkla	1
Bangkok1	1.4
Bangkok2	1.6
Bangkok3	1.8
Samutprakarn1	1.7
Samutprakarn2	1.75
Chachoengsao1	1
Chachoengsao2	1.1
Chachoengsao3	1.2
ChonBuri1	1
ChonBuri2	1.1
ChonBuri3	1.2
ChonBuri4	1.3
Rayong1	1
Rayong2	1.05
Rayong3	1.1
Rayong4	1.15
Rayong5	1.2
Rayong6	1.25
Rayong7	1.3
Rayong8	1.35

Grid Data

The grid data required by the model is the estimated distances between landfills and industrial estates as shown in Table A2. A distance between a landfill and an industrial estate was calculated by locating and measuring the two locations on a representative map of Thailand and scaled up the distance according to the scale used by the map.

Because the costs of labour and maintenance in each industrial estate are different, the proposed model captures the feature by using a cost variation factor which is given in Table 7.12. The industrial estates which are closer to the capital city (Bangkok) were assumed to have higher cost variation factor due to the higher cost of labour and land.

7.5.1.3 Results and Discussion: Case I

The optimal network structure for waste management in Thailand generated by optimising the first version of the proposed model is shown in Figure 7.4. It can be seen from the figure that the thermal gasification technology to produce electricity from RDF has been chosen for all power plants. The MBT process has also been chosen as a pre-treatment process to produce RDF from MSW at landfills. The RDF produced at the selected landfills is transported to the chosen industrial estates by truck.

Comparing the number of sites for potential power plants (industrial estate) with the number of sites of available energy sources (province and landfill), the number of sites of energy sources are much higher. One of the aims of this model is to select primary energy source sites which provide enough wastes to supply to power plants to produce electricity. The locations of landfill which provide RDF to the gasification power plants at industrial estates are mainly determined by the distance between the two grid types. The shorter the distance the lower the transportation cost and therefore higher NPV for the project.

The results also show that, with the current amount of wastes being received at each landfill, the total potential capacity of Waste-to-Energy facilities is limited to only 154 MW. Due to the fact that both industrial estates and MSW are located mostly in the middle region of Thailand, approximately 85 MW of gasification power plants from RDF were suggested to be built at industrial estates in that region as shown in Figure 7.4. The north-east region has only one main industrial estate. The model suggested that 27.3 MW of gasification power plants should be established at the location. Similar capacity of the gasification power plants were recommend to be constructed

in the south region. The north region was suggested with the smallest capacity due to the least amount of collected waste being received at the landfills in the north region. It can also be seen in the figure that only a few landfills have enough capacity to produce RDF more than 100 ton per day. The majority of landfills can only produce less than 20 ton of RDF per day.

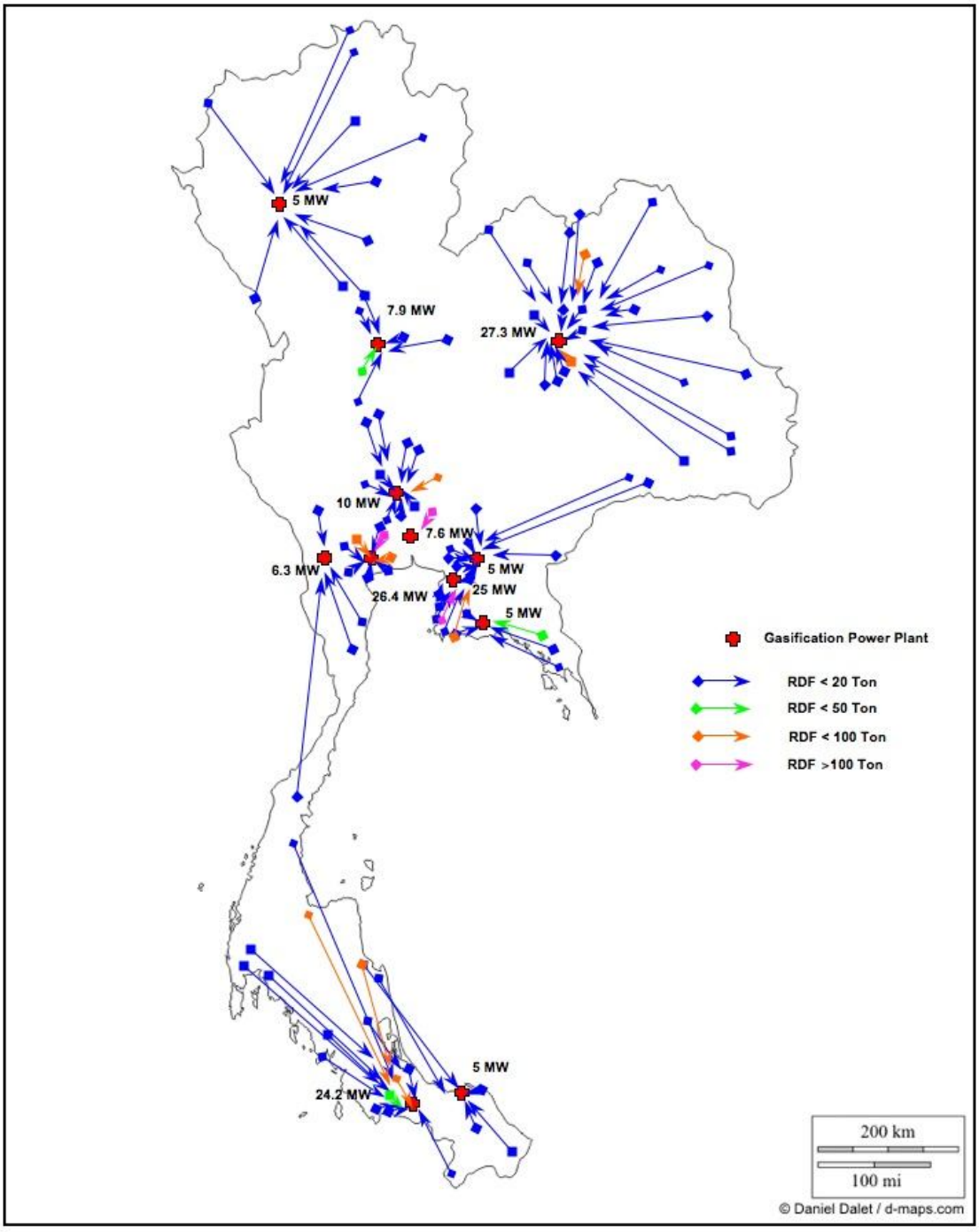


Figure 7.4: Case I optimal network structure

Considering the financial side of the suggested network structure, the NPV for converting waste into energy over the planning horizon comes to 35,950 million bahts. Take into account the discount factor, the revenue and cost related results are shown in Table 7.13 and Table 7.14.

Table 7.13: Total network revenue, cost and profit over the planning horizon of Case I

Year	Revenue (Baht)	Cost (Baht)	Profit (Baht)
1	8,500,000,000	14,900,000,000	-6,400,000,000
2	8,180,000,000	2,700,000,000	5,480,000,000
3	7,860,000,000	2,600,000,000	5,260,000,000
4	7,560,000,000	2,500,000,000	5,060,000,000
5	7,270,000,000	2,400,000,000	4,870,000,000
6	6,990,000,000	2,310,000,000	4,680,000,000
7	6,720,000,000	2,220,000,000	4,500,000,000
8	6,460,000,000	2,130,000,000	4,330,000,000
9	6,210,000,000	2,050,000,000	4,160,000,000
10	5,980,000,000	1,970,000,000	4,010,000,000
Total	**71,730,000,000**	**35,780,000,000**	**35,950,000,000**

Table 7.14: Total network capital cost for new process plants of Case I

Plant type	Capital Cost (Baht)
MBT	1,910,000,000
Gasification	10,140,000,000

The proposed concept of converting MSW into RDF at landfills using the MBT pre-treatment process and generating electricity from the RDF using gasification technology at the industrial estates seems to be both a financially and environmentally attractive strategy for converting waste into energy in Thailand.

7.5.2 Case II: The waste at existing open dump sites at each province can only be transferred to the landfill sites which can then be used as sources of raw material

7.5.2.1 Mathematical formulation

The mathematical notation and formulation of this model are also consistent with the one presented in Case I. This section summaries only the notation and formulation that are newly formulated.

7.5.2.1.1 Notation

Indices

p	=	Open-dump at each province grid

Parameters

$rP_{rpt}^{\max}$	=	Amount of maximum potential domestic resource r in each province p per day at time period t (TPD)
$rL_{rlt}^{\max}$	=	Amount of maximum potential domestic resource r in each landfill l per day at time period t (TPD)
rP_{rlt}^{unuse}	=	Amount of unused domestic resource r in each province p per day at time period t (TPD)
pld_{lp}	=	Average distance between landfill site l and province p (km)

Variables

dp_{rpt}	=	Decision variable for amount of raw material r used at province p in period t (TPD)
AUP_{rpt}	=	Total usage of resource r at province p at time period t (TPD)
SUP_{rpt}	=	Total supply of resource r at province p at time period t (TPD)
FM_{rplt}	=	Flow rate of resource r from province p to landfill site l at time period t (TPD)
$FM^{\exp and}_{rplt}$	=	Expansion of flow rate of resource r from province p landfill site l at time period t (TPD)
$MtCost_{rplt}$	=	Cost for transporting resource r from province p to landfill site l at time period t (Baht)
$Mdis_{rplt}$	=	Distance travel of resource r from province p to landfill site l per trip at time period t (km)
$CostPTM_{lp}$	=	Cost of transporting resource r per truck from province p to landfill site l (Baht)

Binary Variable

$actM_{rlet}$	=	Active flow of resource r between province p landfill site l at time period t

7.5.2.1.2 Constraints

The mathematical constraints given in Case I are updated to account for additional flows of resources between landfill site grid l and newly formulated grid p. The new grid p represents open-dump sites at each province of Thailand.

Resource Balance Constraints

The structure of the network in this model is slightly different from the previous model where an additional type of grid (p) is generated to reflect the new flow of MSW from an open-dump site of a province to a landfill site. The flow of MSW or RDF from a landfill site to an industrial estate is the same as previous model. The repeated resource balance constraints include:

$$AUE_{ret} = \sum_{l} UE_{riet} \qquad \forall r, e, t \qquad (7.60)$$

$$AUL_{rlt} = \sum_{i} UL_{rilt} + \sum_{i} UL_{rilt}^{incineration} + \sum_{e} FR_{rlet} \qquad \forall r, l, t \qquad (7.61)$$

$$SUE_{ret} = \sum_{l} FR_{rlet} \qquad \forall r, e, t \qquad (7.62)$$

The modified resource balance constraints are given in the form:

$$AUP_{rpt} = \sum_{l} FM_{rplt} \qquad \forall r, p, t \qquad (7.63)$$

$$SUP_{rpt} = dp_{rpt} \qquad \forall r, p, t \qquad (7.64)$$

The modification affects the network structure and the decision variables of the model. In this model, the available resources r (MSW) are located at open-dump sites of each province p and not at each landfill site l as in case I. Therefore, the decision variable for determining the amount of available resource r (MSW) being used at province p (dp_{rpt}) is equal to the flow of resource r from open-dump sites at province p to landfill site l ($\sum_{p} FM_{rplt}$).

The supply of resource r for process i at landfill site l (SUL_{rlt}) has also been updated which can be expressed as:

$$SUL_{rlt} = \sum_{p} FM_{rplt} + RawP_{rlt} \qquad \forall r, l, t \qquad (7.65)$$

The maximum amount of resource r at open-dump sites at province p that can be processed is limited by the availability of the resource ($rP_{rpt}^{\max}$). There is also an upper bound on the amount of resource r being transferred to landfill site l as each landfill site can only maintain a certain amount of waste ($rL_{rlt}^{\max}$). The bounds are given in the form:

$$dp_{rpt} \leq rP_{rpt}^{\max} \qquad \forall r, p, t \qquad (7.66)$$

$$\sum_{p} FM_{rplt} \leq rL_{rlt}^{\max} \qquad \forall r, l, t \qquad (7.67)$$

The amount of unused resource r at each open-dump site of each province p (rP_{rpt}^{unuse}) can be described as:

$$rP_{rpt}^{unuse} = rP_{rpt}^{\max} - dp_{rpt} \qquad \forall r, p, t \qquad (7.68)$$

Transportation Constraints

In this model, a similar set of transportation constraints as described in case I is created to model the extra flow of resource r between province grid p and landfill site gird l during time period t ($Mdis_{rplt}$). The same set of transportation constraints in case I is also used in this model to account for the flow of resource r between landfill site grid l and industrial estate grid e ($Rdis_{rlet}$).

$$Mdis_{rplt} = actM_{rplt} \cdot pld_{lp} \qquad \forall r, p, l, t \qquad (7.69)$$

$$Mdis_{rplt} \leq dis^{\max} \qquad \forall r, p, l, t \qquad (7.70)$$

$$FM_{rplt} - bigM \cdot actM_{rplt} \leq 0 \qquad \forall r, p, l, t \qquad (7.71)$$

$$FM_{rplt} - smallm \cdot actM_{rplt} \geq 0 \qquad \forall r, p, l, t \qquad (7.72)$$

The updated constraints are given above where pld_{lp} is the average distance between landfill site l and province p and the binary variable $actM_{rplt}$ has the value 1 when resource r is being transferred from province p to landfill site l or 0 otherwise.

The time evolution constraints for the flow of resource r between province grid p and landfill site grid l during time period t is given in the form:

$$FM_{rplt} = FM_{rplt-1} + FM_{rplt}^{\exp and} \qquad \forall r, p, l, t \qquad (7.73)$$

7.5.2.1.3 Objective function

The objective function for this model is to maximise the total profit from distribution of waste-to-energy facilities over a planning horizon. Most of the revenue and cost terms are generally similar to the ones presented in the previous models. The only exception is the transportation costs which will be addressed below.

Cost Equations

- **Transportation costs**

The transportation cost for this model is similar to the case I model. The main difference is that the transportation costs are divided into two parts. The first part is the cost for transporting resource r (MSW) from province grid p to landfill site grid l ($MtCost_{rplt}$). The second part is the cost for transporting resource r (MSW or RDF) from landfill site grid l to industrial estate grid e ($RtCost_{rlet}$). The total transportation costs during time period t ($RtCost_{rt}^{total}$) is given in the form:

$$RtCost_{rt}^{total} = DF_t \cdot \left(\sum_e \sum_l RtCost_{rlet} + \sum_l \sum_p MtCost_{rplt} \right) \forall r,t \qquad (7.74)$$

$$MtCost_{rlet} = \frac{FM_{rplt} \cdot Days \cdot CostPTM_{lp}}{TC} \qquad \forall r,l,e,t \qquad (7.75)$$

$$RtCost_{rlet} = \frac{FR_{rlet} \cdot Days \cdot CostPT_{el}}{TC} \qquad \forall r,l,e,t \qquad (7.76)$$

$$CostPT_{el} = FP \cdot TFR \cdot 2gd_{el} \qquad \forall l,e \qquad (7.77)$$

$$CostPTM_{lp} = FP \cdot TFR \cdot 2pld_{lp} \qquad \forall l,p \qquad (7.78)$$

where

$CostPTM_{lp}$ is the cost of transporting resource r per truck from province p to landfill site l

pld_{lp} is the distance between landfill site l and province p

The following objective function is repeated below for ease of reference:

$$\begin{aligned} Maximise \quad & \sum_t \left(\sum_e \left(\mathrm{Re}v_{et}^{total} \right) + \sum_l \left(l\,\mathrm{Re}v_{lt}^{total} \right) \right) \\ & - \sum_t \left(\sum_i InvCost_{it} + \sum_i OMCost_{it} + \sum_r RtCost_{rt}^{total} \right) \end{aligned} \qquad (7.79)$$

Or

$$Maximise \quad \mathrm{Re}v^{total} - Cost^{total} \qquad (7.80)$$

7.5.2.2 Input Data: Case II

In this model, the mainland area of Thailand has been divided into grids which represent each province in Thailand. Different provinces generate different amounts of waste. As described in scenario I, some of the generated waste in each province is sent to disposal in landfill every day; however the rest of the waste is placed in local open-dump sites. In general, the higher the population density the higher amount of waste. The extra raw material data entailed for this case is the amount of wastes collected and placed at open-dump site of each province which are given in Table 7.15 [MOE,2007].

The additional grid data required for this second case is the distances between open-dump site of each province and landfills. The estimated distances between the two grid types are shown in Table A3. The distances were calculated using the same scaling method for calculating distances between landfills and industrial estates in case I. However, only the distances which were shorter than 500 km were accurately measured and highlighted in Table A3, the rest of the distances were assumed to be a high number.

The rest of the data input is similar to the previous case.

Table 7.15: Quantity of MSW being received at open-dump sites of each province

Middle and West Provinces	Quantity of MSW (TPD)
m01	9340
m02	631.39
m03	399.97
m04	801.84
m05	65.27
m06	239.4
m07	69.12
m08	141.47
m09	195.93
m10	38.5
w01	75
w02	45
w03	45
w04	45
w05	15
w06	15
w07	45
w08	328

South and East Provinces	Quantity of MSW (TPD)
s01	77.55
s02	90.58
s03	99.95
s04	267.33
s05	132.55
s06	81.77
s07	33.92
s08	43.23
s09	202.36
s10	118.67
s11	31.68
s12	286.21
s13	42.94
s14	272.93
e01	15
e02	15
e03	72.88
e04	26.43
e05	62.88
e06	911.2
e07	152.46
e08	120.78

North-East Provinces	Quantity of MSW (TPD)
ne01	95.5
ne02	61.5
ne03	328
ne04	106
ne05	72
ne06	96.2
ne07	40.9
ne08	52.7
ne09	39.2
ne10	232.3
ne11	103.8
ne12	83.7
ne13	161.7
ne14	147.4
ne15	84.8
ne16	134.7
ne17	322
ne18	122.7
ne19	416.2

Lower and Upper North Provinces	Quantity of MSW (TPD)
ln01	111.3
ln02	157.2
ln03	149.3
ln04	109.9
ln05	164.3
ln06	196.3
ln07	89.4
ln08	53.9
un01	192.9
un02	105.2
un03	65
un04	74.7
un05	96
un06	27.3
un07	447.9
un08	216.3
un09	71.9

[MOE,2007]

7.5.2.3 Results and Discussion: Case II

The resultant optimal network structure for the second version of the proposed model is illustrated in Figure 7.5. The blue circle represents the selected province. The black square represents the selected landfill. The blue line represents the flow of MSW from province to landfill. The black line represents the flow of RDF from landfill to industrial estate.

From the figure it can be summarised that the network structure has a similar pattern as the previous scenario in term of the chosen technologies and the locations of MBT plants and gasification power plants. Similar to the strategy for choosing the locations of MBT plants and gasification power plants, the locations of primary energy source (MSW) were also influenced by the distance between open-dump sites in each province and landfills.

One of the differences between the results of this case and the previous case is the total power production capacity. As in this second version, the wastes being generated in all provinces were considered, the model was able to suggest an optimal network structure that can reach a power production capacity of 200 MW.

Similar to the previous case, the majority of suggested power plants were clustered in the middle region as the quantity of MSW being produced by provinces in the middle region is the highest in Thailand. The suggested capacity in the middle region was 171 MW. The rest of the suggested capacities were spread between the north, the north-east and the south regions as shown in Figure 7.5.

Moreover, by relaxing the total power production capacity to be a very high number to utilise all waste produced by each province, the total capacity of Waste-to-Energy facilities can be as high as 400 MW.

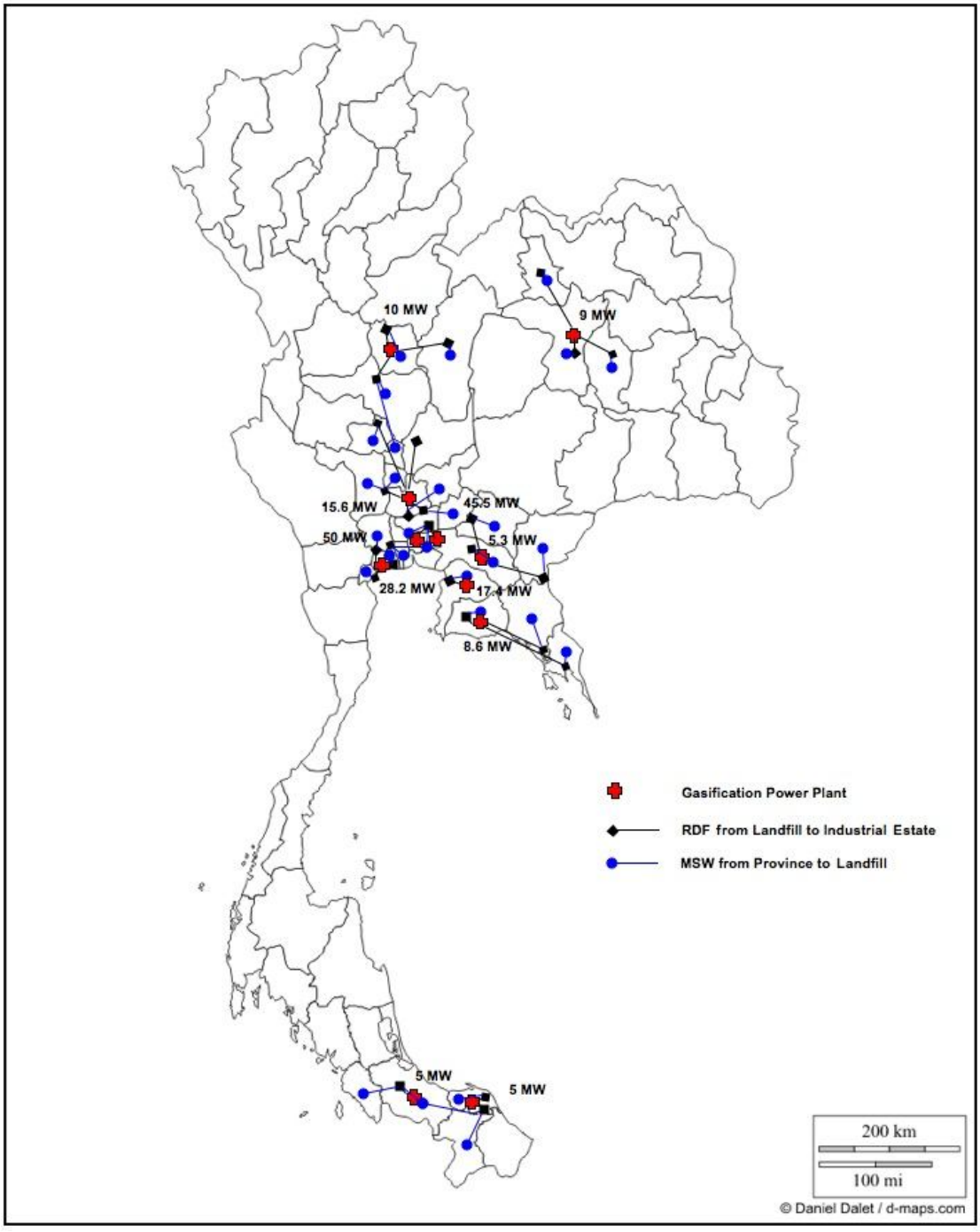


Figure 7.5: Case II optimal network structure

Figure 7.5 shows the location and the capacity of the suggested power plants around the country. The location of the selected provinces and landfills were also presented. However, the quantity of each flow is not shown. Table 7.16 summarises the

established flows between province and landfill of the suggested network. Table 7.17 summarises the established flows between landfill and industrial estate.

Table 7.16: Flow of MSW from province to landfill (TPD)

Province/Landfill	lf42	lf44	lf47	lf49	lf58	lf61	lf62	lf63
m01					304			4600
m02					631			
m03								400
m05				65				
m06							239	
m07	69							
m08			141					
m09						196		
m10		39						

Province/Landfill	lf49	lf54	lf56	lf57
w02		237		
w06				46
w07			260	
w08	113			

Province/Landfill	lf62	lf64	lf66	lf68	lf74	lf75	lf77	lf78
e01								82
e02					239			
e03		73						
e04	26							
e05							63	
e06				911				
e07						152		
e08			121					

Province/Landfill	lf93	lf97	lf98
s06		82	
s10			119
s12			61
s13	37		

Province/Landfill	lf12	lf13	lf42
ln04	110		
ln05		164	
ln06			196

Province/Landfill	lf15	lf34	lf35
ne02	62		
ne15		85	
ne17			322

It is worth noticing that the province m01 which represents Bangkok, the capital city of Thailand, does not contain any landfill within the city. The model suggested that the MSW generated from Bangkok should be sent to landfill lf63 and lf58. The longest distance per trip to transport MSW between province and landfill is 33 km.

Table 7.17: Flow of RDF from landfill to industrial estate (TPD)

Industrial Estate / Landfill	lf12	lf13	lf15	lf34	lf35	lf42	lf44	lf47	lf49
Pichit	27	41				66			
KhonKaen			15	21	80				
Ayutthaya1							10	35	45
SamutSakorn1									
Bangkok1									
Bangkok2									
Chachoengsao1									
ChonBuri1									
Rayong1									
Songkla									
Pattani									

Industrial Estate / Landfill	lf54	lf56	lf57	lf58	lf61	lf62	lf63	lf64	lf66	lf68
Pichit										
KhonKaen										
Ayutthaya1					49	66				
SamutSakorn1	59	65	12	234						
Bangkok1							654			
Bangkok2							596			
Chachoengsao1								18	30	
ChonBuri1										228
Rayong1										
Songkla										
Pattani										

Industrial Estate / Landfill	lf74	lf75	lf77	lf78	lf93	lf97	lf98
Pichit							
KhonKaen							
Ayutthaya1							
SamutSakorn1							
Bangkok1							
Bangkok2							
Chachoengsao1				20			
ChonBuri1							
Rayong1	60	38	16				
Songkla					65		
Pattani						20	45

The financial details of the optimal network structure are given in Table 7.18 and Table 7.19. As expected, the NPV of this case is higher than the previous case, as the amount of available MSW to be utilised is higher.

Table 7.18: Total network revenue, cost and profit over the planning horizon of Case II

Year	Revenue (Baht)	Cost (Baht)	Profit (Baht)
1	11,000,000,000	19,700,000,000	-8,700,000,000
2	10,600,000,000	4,010,000,000	6,590,000,000
3	10,100,000,000	3,860,000,000	6,240,000,000
4	9,760,000,000	3,710,000,000	6,050,000,000
5	9,380,000,000	3,570,000,000	5,810,000,000
6	9,020,000,000	3,430,000,000	5,590,000,000
7	8,680,000,000	3,300,000,000	5,380,000,000
8	8,340,000,000	3,170,000,000	5,170,000,000
9	8,020,000,000	3,050,000,000	4,970,000,000
10	7,710,000,000	2,930,000,000	4,780,000,000
Total	**92,610,000,000**	**50,730,000,000**	**41,880,000,000**

Table 7.19: Total network capital cost for new process plants of Case II

Plant type	Capital Cost (Baht)
MBT	2,470,000,000
Gasification	13,090,000,000

7.5.3 Case III: In addition to the structure of model presented in Case II, production of heat energy from gasification process.

7.5.3.1 Mathematical formulation

Electricity is not the only energy form that can be produced through a gasification process; heat energy is also a by-product of the process. The mathematical notation and formulation to model the production and sale of heat energy are presented in this section. In this case, heat power is also included in the energy vector v as well as electrical power.

7.5.3.1.1 Notation

Parameters

$DemandH_e$ = Heat power demand at each industrial estate e (MW)

Variables

$EH\,\mathrm{Re}v_{et}^{total}$ = Revenue from heat in industrial estate e at time period t (Baht)

7.5.3.1.2 Constraints

Demand Constraint

The maximum amount of heat production at industrial estate e during time period t is bounded by the heat demand of the industrial estate. The constraint is expressed below.

$$EP_{vet} \leq DemandH_{e} \qquad \forall v,e,t : v = heat \qquad (7.81)$$

7.6.3.1.3 Objective function

Again, the objective function for this model is to maximise the total profit from distribution of waste-to-energy facilities over a planning horizon. The cost terms are exactly the same as the ones formulated for the previous models. As mentioned earlier, the heat energy is also modelled in this model, therefore the revenue equations have been modified to account for the revenue generated from selling heat energy as well as electricity and other revenues. The updated revenue equations are addressed below.

- **Revenue equations**

The revenues come from the exogenous energy produced by the system, selling carbon credits, tipping fees and also from selling heat. The heat energy used in this model was expressed as thermal power in MW. By considering heat energy as thermal power which can be measured in MW, the revenue from selling thermal power can be calculated using similar equations as for electric power. However, as the subsidy adder supported by the government is only active for selling electricity, the adder was excluded from the revenue equations for thermal power or heat energy. The new revenue equations are described below:

$$E\,\mathrm{Re}v_{vet}^{peak} = 0.98 \cdot PeakE_{vet} \cdot (PP + FT) \qquad \forall v,e,t \qquad (7.82)$$

$$E\,\mathrm{Re}v_{vet}^{offpeak} = 0.98 \cdot OffPeakE_{vet} \cdot (OPP + FT) \qquad \forall v,e,t \qquad (7.83)$$

$$E\,\mathrm{Re}v_{vet}^{adder} = Adder \cdot (PeakE_{vet} + OffPeakE_{vet}) \qquad \forall v,e,t : v = electricity \qquad (7.84)$$

$$E\,\mathrm{Re}v_{vet}^{adder} = 0 \qquad \forall v,e,t : v = heat \tag{7.85}$$

Therefore, the total revenue from selling electricity and heat energy at industrial estate e during time period t can be expressed as:

$$EH\,\mathrm{Re}v_{et}^{total} = DF_t \cdot \sum_{v}\left(E\,\mathrm{Re}v_{vet}^{peak} + E\,\mathrm{Re}v_{vet}^{offpeak} + E\,\mathrm{Re}v_{vet}^{adder}\right) \quad \forall e,t \tag{7.86}$$

The total revenue can be expressed in the form:

$$\mathrm{Re}v^{total} = \sum_{t}\sum_{e}\left(EH\,\mathrm{Re}v_{et}^{total} + C\,\mathrm{Re}v_{et}^{total} + T\,\mathrm{Re}v_{et}^{total}\right) \tag{7.87}$$

7.5.3.2 Input Data: Case III

The input data of this case is the same as in case II apart from additional data related to the new CHP gasification technology introduced to this case and the heat demand in each industrial estate. The input and output factors of CHP gasification technology are given in Table 7.20 and Table 7.21.

Table 7.20: Input factor of each technology

Technology Types	RDF (TPD)
CHP Gasification	13.09

[Enerkem, 2003] [EIA, 2007] [Klein, 2002]

Table 7.21: Output factor of each technology

Technology Types	Electrical Power (MW)	Heat Thermal Power (MW)
CHP Gasification	1	1.56

[Enerkem, 2003] [EIA, 2007] [Klein, 2002]

The costs of CHP gasification power plant were assumed to be 20% higher than the original gasification costs used in case I. The costs of the new conversion technology used in this model are shown in Table 7.22.

Table 7.22: Capital and O&M costs for a CHP gasification power plant

Cost	**CHP gasification power plant**	**Unit**
Capital cost	78,540,000	Baht/MW
O&M cost	396,000	Baht/Ton per year

As it is difficult to obtain actual heat demands in each industrial estate, only estimated values have been used in the model. The estimated heat demands for each industrial estate are given in Table 7.23.

Table 7.23: Heat Power Demand at each industrial estate

Industrial Estate	**Heat Power Demand (MW)**	**Industrial Estate**	**Heat Power Demand (MW)**
Lamphun	0	**Samutprakarn1**	0
Pichit	0	**Samutprakarn2**	0
KhonKaen	20	**Chachoengsao1**	0
Saraburi1	0	**Chachoengsao2**	0
Saraburi2	0	**Chachoengsao3**	0
Ayutthaya1	0	**ChonBuri1**	20
Ayutthaya2	0	**ChonBuri2**	0
Ayutthaya3	0	**ChonBuri3**	0
Ratchaburi1	25	**ChonBuri4**	0
Ratchaburi2	0	**Rayong1**	30
SamutSakorn1	0	**Rayong2**	0
SamutSakorn2	0	**Rayong3**	0
SamutSakorn3	0	**Rayong4**	0
Pattani	0	**Rayong5**	0
Songkla	0	**Rayong6**	0
Bangkok1	50	**Rayong7**	0
Bangkok2	0	**Rayong8**	0
Bangkok3	0		

7.5.3.3 Results and Discussion: Case III

The resultant optimal network structure for the second version of the proposed model is illustrated in Figure 7.5.

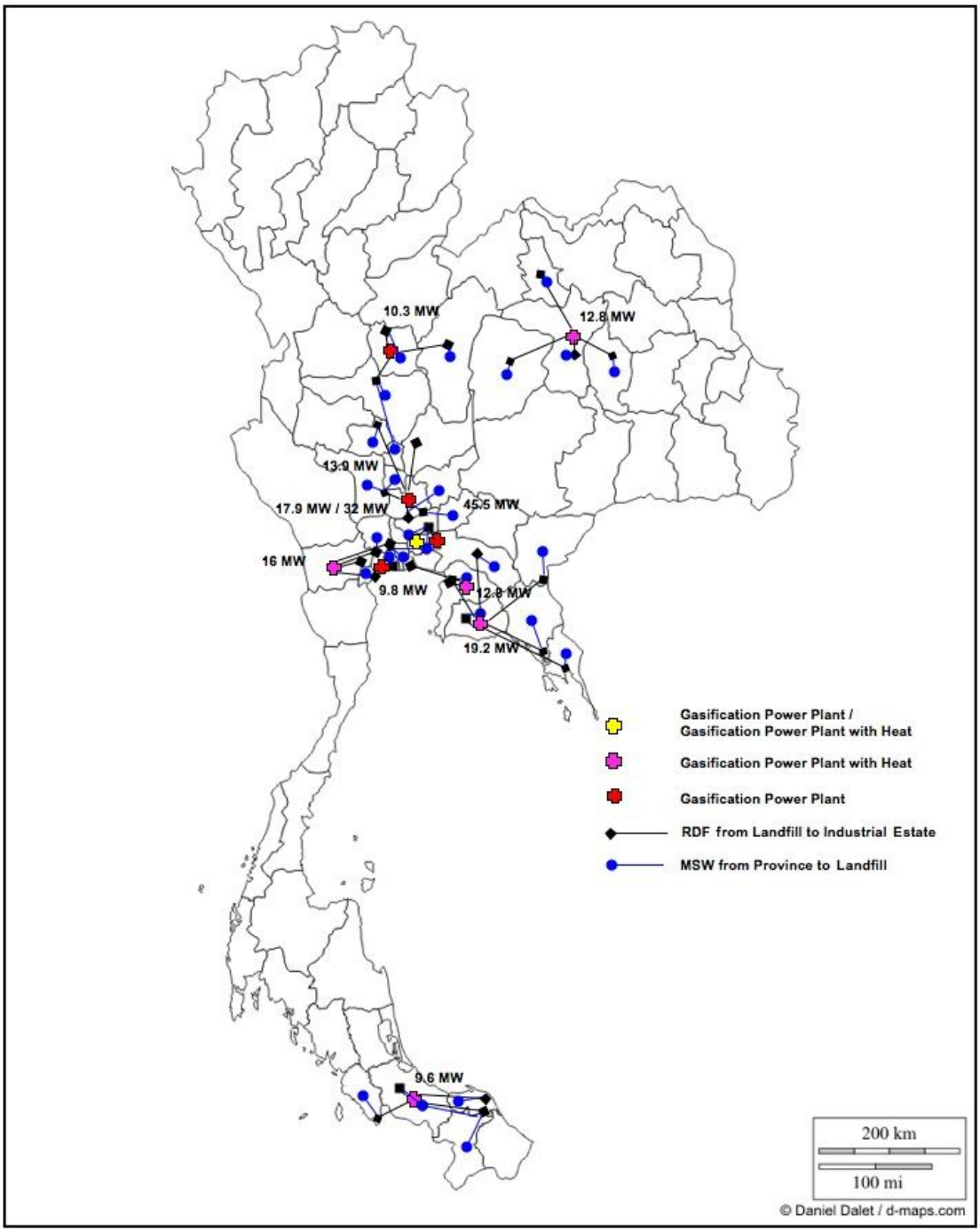


Figure 7.6: Case III optimal network structure

The third version of the proposed model includes heat energy as one of the energy outputs. The addition is done by introducing combined heat and power gasification power plant (CHP) to the list of technology options. Table 7.24 and Table 7.25 show the flows between province, landfill and industrial estate of the suggested network.

Table 7.24: Flow of MSW from province to landfill (TPD)

Province/Landfill	lf42	lf44	lf47	lf49	lf58	lf61	lf62	lf63
m01								4600
m02					631			
m03								400
m05				65				
m06							171	
m07	69							
m08			141					
m09						196		
m10		39						

Province/Landfill	lf49	lf53	lf54	lf56	lf57
w02			237		
w05		216			
w06					46
w07				260	
w08	113				

Province/Landfill	lf66	lf68	lf74	lf75	lf77	lf78
e01						82
e02			239			
e03	73					
e05					63	
e06		911				
e07				152		
e08	121					

Province/Landfill	lf93	lf95	lf98
s10			93
s12	286		
s13		43	

Province/Landfill	lf12	lf13	lf42
ln04	110		
ln05		164	
ln06			196

Province/Landfill	lf15	lf34	lf35	lf39
ne02	62			
ne15		85		
ne16		80		
ne17			322	
ne18				123

Table 7.25: Flow of RDF from landfill to Industrial Estate (TPD)

Industrial Estate / Landfill	lf12	lf13	lf15	lf34	lf35	lf39	lf42	lf44	lf47	lf49
Pichit	27	41					66			
KhonKaen			15	41	80	31				
Ayutthaya1								10	35	45
SamutSakorn1										
Ratchaburi1										
Bangkok1										
Bangkok2										
ChonBuri1										
Rayong3										
Songkla										

Industrial Estate / Landfill	lf53	lf54	lf56	lf57	lf58	lf61	lf62	lf63	lf66	lf68
Pichit										
KhonKaen										
Ayutthaya1						49	43			
SamutSakorn1			56		72					
Ratchaburi1	54	59		11	85					
Bangkok1								654		
Bangkok2								596		
ChonBuri1										159
Rayong3									48	69
Songkla										

Industrial Estate / Landfill	lf74	lf75	lf77	lf78	lf93	lf95	lf97	lf98
Pichit								
KhonKaen								
Ayutthaya1								
SamutSakorn1								
Ratchaburi1								
Bangkok1								
Bangkok2								
ChonBuri1								
Rayong3	60	38	16	20				
Songkla					72	11	20	23

The results recommended that the CHP gasification power plant is more financially attractive than the normal gasification power plant. However, the capacity of such technology is limited by the amount of heat demand in each industrial estate. Therefore, it can be seen in Figure 7.6 that both CHP gasification power plants and normal gasification power plant were suggested by the model so that the total power production capacity reach the target of 200 MW.

The financial details of the optimal network structure of this third version are shown in Table 7.26 and Table 7.27.

Table 7.26: Total network revenue, cost and profit over the planning horizon of Case III

Year	Revenue (Baht)	Cost (Baht)	Profit (Baht)
1	14,000,000,000	21,300,000,000	-7,300,000,000
2	13,400,000,000	4,230,000,000	9,170,000,000
3	12,900,000,000	4,070,000,000	8,830,000,000
4	12,400,000,000	3,910,000,000	8,490,000,000
5	11,900,000,000	3,760,000,000	8,140,000,000
6	11,500,000,000	3,610,000,000	7,890,000,000
7	11,000,000,000	3,480,000,000	7,520,000,000
8	10,600,000,000	3,340,000,000	7,260,000,000
9	10,200,000,000	3,210,000,000	6,990,000,000
10	9,820,000,000	3,090,000,000	6,730,000,000
Total	**117,720,000,000**	**54,000,000,000**	**63,720,000,000**

Table 7.27: Total network capital cost for new process plants of Case III

Plant type	Capital Cost (Baht)
MBT	2,470,000,000
Gasification	6,380,000,000
CHP Gasification	8,060,000,000

The NPV of this third case came to 63,720 million baht which is much higher than the previous two cases. The main reason behind this is due to additional revenue gained from selling heat in the industrial estates.

7.5.4 Case IV: Extended version of case III: Existing wastes in each of the landfill sites are also considered as source of raw material. A Budget constraint is also modelled in this case.

7.5.4.1 Mathematical formulation

Following on from case III, one of the main assumptions is that the only raw material in the model is MSW from open-dump sites at each province around Thailand. The previous models do not include existing waste at each landfill site as one of the resources. This extended model incorporates the existing waste at each landfill as another source of MSW.

The additional mathematical notation and formulation to model the extended case is presented in this section.

7.5.4.1.1 Notation

Parameters

$InLF_{rl}^{now}$	=	Existing resource r in landfill site l (ton)
$Budget_t$	=	Budget per year for investing in power plant (Baht)

Variables

$Cost_t^{year}$	=	Total annual cost at time period t (Baht)
$InLF_{rlt}^{esisting}$	=	Existing resource r in landfill site l at time period t (ton)
dlf_{rlt}^{day}	=	Decision variable for using potential existing resource r at landfill l in period t (TPD)
$dlfy_{rlt}^{year}$	=	Decision variable for using potential existing resource r at

landfill l per year in period t (ton/year)

7.5.4.1.2 Constraints

All of the constraints apart from the resource balance constraints are formulated in the same way as for the previous model. The resource balance constraints are given in the following section. The budget constraint is also described in this section.

Resource Balance Constraints

The only modification to the previous resource balance constraints is at the equation for supply of resource r at landfill site l during time period t (SUL_{rlt}). Another decision variable to determine the amount of existing waste r at landfill site l being used during time period t per day(dlf_{rlt}^{day}) is added to the SUL_{rlt} equation which is given in the form:

$$SUL_{rlt} = \sum_{p} FM_{rplt} + RawP_{rlt} + dlf_{rlt}^{day} \qquad \forall r,l,t \qquad (7.88)$$

The amount of existing waste r at landfill site l being used during time period t per year ($dlfy_{rlt}^{year}$) must not exceed the total amount of existing waste available at landfill site l during time period t ($InLF_{rlt}^{existing}$).

$$dlfy_{rlt}^{year} = dlf_{rlt}^{day} \cdot 330 \qquad \forall r,l,t \qquad (7.89)$$

$$dlfy_{rlt}^{year} \leq InLF_{rlt}^{existing} \qquad \forall r,l,t \qquad (7.90)$$

The time evolution constraints for the amount of existing waste r in landfill site l during time period t are expressed as:

$$InLF_{rlt}^{existing} = InLF_{rl}^{now} - dlfy_{rlt}^{year} \qquad \forall r,l,t : t = 0 \qquad (7.91)$$

$$InLF_{rlt}^{existing} = InLF_{rl't-1'}^{existing} - dlfy_{rlt}^{year} \qquad \forall r,l,t : t \geq 1 \qquad (7.92)$$

Budget Constraint

So far, there is no limit on how much money can be spent on investing in and operating the waste-to-energy facility. In order to develop the existing model to reflect the real world as much as possible, a budget constraint is added to this case to control the amount of money that investors are allowed to use each year.

The budget constraint can be expressed in the form:

$$Cost_t^{year} \leq Budget_t \qquad \forall t \qquad (7.93)$$

$$Cost_t^{year} = \sum_i InvCost_i + \sum_i OMCost_{it} + \sum_r RtCost_{rt}^{total} \qquad \forall t \qquad (7.94)$$

7.5.4.2 Input Data: Case IV

The input data for this case is the same as the previous case. However, the main difference is an extra type of raw material that has been added to this scenario. As mentioned in the previous section, the MSW can be differentiated into new MSW which is generated every day, and existing MSW which has already been placed at landfills for decades. The existing MSW at each landfill has been included as another source of raw material for this Waste-to-Energy spatial model.

Identifying the cost for a MBT process that can convert old waste in landfill into RDF is difficult. For this case, the cost was assumed to be 10% higher than the original MBT process. The costs of the MBT process of existing waste in landfill are presented in Table 7.28 and Table 7.29.

Table 7.28: Capital cost for MBT process of old waste

Scenario	Capital Costs	Unit
Scenario I: 10% increased	1,038,400	Baht/TPD

Table 7.29: O&M cost for MBT process of old waste

Scenario	Capital Costs	Unit
Scenario I: 10% increased	363,000	Baht/Ton per year

It is also very difficult to collect the actual amount of waste that has already been placed in each landfill. Therefore, the amount of existing waste in each landfill has also been estimated in this model. The estimation was done by multiplying the amount of new waste being received at each landfill per year by 50 years. The amounts of existing MSW at each landfill are presented in Table 7.30.

Table 7.30: Quantity of existing MSW at each landfill

Landfill 1 to 50	Quantity of MSW (Ton)	Landfil 26 to 50	Quantity of MSW (Ton)	Landfil 51 to 75	Quantity of MSW (Ton)	Landfil76 to 100	Quantity of MSW (Ton)
l01	273,750	**l26**	821,250	**l51**	1,368,750	**l76**	273,750
l02	1,368,750	**l27**	821,250	**l52**	273,750	**l77**	273,750
l03	273,750	**l28**	821,250	**l53**	273,750	**l78**	821,250
l04	273,750	**l29**	821,250	**l54**	4,307,000	**l79**	821,250
l05	273,750	**l30**	273,750	**l55**	4,745,000	**l80**	2,445,500
l06	273,750	**l31**	273,750	**l56**	1,368,750	**l81**	1,368,750
l07	821,250	**l32**	821,250	**l57**	1,368,750	**l82**	273,750
l08	273,750	**l33**	273,750	**l58**	11,515,750	**l83**	4,964,000
l09	273,750	**l34**	821,250	**l59**	1,368,750	**l84**	4,872,750
l10	821,250	**l35**	5,876,500	**l60**	273,750	**l85**	821,250
l11	1,368,750	**l36**	273,750	**l61**	1,368,750	**l86**	273,750
l12	821,250	**l37**	273,750	**l62**	273,750	**l87**	273,750
l13	821,250	**l38**	273,750	**l63**	7,300,000	**l88**	821,250
l14	821,250	**l39**	821,250	**l64**	273,750	**l89**	821,250
l15	273,750	**l40**	821,250	**l65**	273,750	**l90**	273,750
l16	273,750	**l41**	821,250	**l66**	821,250	**l91**	821,250
l17	821,250	**l42**	3,577,000	**l67**	821,250	**l92**	1,368,750
l18	5,986,000	**l43**	821,250	**l68**	273,750	**l93**	2,737,500
l19	273,750	**l44**	273,750	**l69**	821,250	**l94**	5,219,500
l20	273,750	**l45**	821,250	**l70**	16,625,750	**l95**	273,750
l21	821,250	**l46**	273,750	**l71**	1,368,750	**l96**	273,750
l22	821,250	**l47**	273,750	**l72**	1,368,750	**l97**	821,250
l23	821,250	**l48**	821,250	**l73**	4,380,000	**l98**	1,368,750
l24	273,750	**l49**	821,250	**l74**	821,250	**l99**	821,250

Another set of data required for is this case is the budget available to investors to spend each year. The budget throughout the planning horizon is given in Table 7.31.

Table 7.31: Budget throughout the planning horizon

Year	Budget (Baht)
1	5,000,000,000
2	5,000,000,000
3	5,000,000,000
4	5,000,000,000
5	5,000,000,000
6	5,000,000,000
7	5,000,000,000
8	5,000,000,000
9	5,000,000,000
10	5,000,000,000

7.5.4.3 Results and Discussion: Case IV

The final version of the proposed model took into account the existing waste in each landfill as a possible source of raw material. The MBT process for converting existing waste in landfill was introduced. In the previous cases, the network structures of each time period were the same. However, the optimal network structures for each time period were not all the same in this case. This was due to the additional budget constraint which has been incorporated into the proposed model. The constraint only allows a certain amount of money to be spent in each time period. The capacities of the chosen technologies in each time period are presented in Table 7.32 to 7.35. The optimal network structure of the last time period is shown in Figure 7.7.

Table 7.32: Capacity of gasification power plant for Case IV

Year	Gasification Power Plant (MW)			
	SamutSakorn1	ChonBuri1	Choburi2	Rayong2
1	0	0	0	0
2	0	0	0	0
3	0	23.7	0	0
4	24.9	37.1	0	0
5	47.0	37.1	8.3	0
6	47.0	37.1	8.3	0
7	47.0	37.1	8.3	0
8	47.0	37.1	8.3	5
9	47.0	37.1	8.3	5
10	47.0	37.1	8.3	5

Table 7.33: Capacity of CHP gasification power plant for Case IV

Year	CHP Gasification Power Plant (MW)					
	KhonKaen	Ratchaburi1	Songkla	Bangkok1	ChonBuri1	Rayong1
1	12.8	0	9.6	5.9	12.8	5
2	12.8	0	9.6	32.1	12.8	19.2
3	12.8	16	9.6	32.1	12.8	19.2
4	12.8	16	9.6	32.1	12.8	19.2
5	12.8	16	9.6	32.1	12.8	19.2
6	12.8	16	9.6	32.1	12.8	19.2
7	12.8	16	9.6	32.1	12.8	19.2
8	12.8	16	9.6	32.1	12.8	19.2
9	12.8	16	9.6	32.1	12.8	19.2
10	12.8	16	9.6	32.1	12.8	19.2

Table 7.34: Capacity of MBT pre-treatment plant of old waste for Case IV

Year	MBT Old waste (TPD of RDF)														
	lf35	lf36	lf51	lf52	lf53	lf55	lf56	lf57	lf63	Lf70	lf74	Lf75	Lf76	Lf94	Lf96
1	149	18.9	0	0	0	0	0	0	77.9	167.8	56.6	0	0	107	18.9
2	149	18.9	0	0	0	0	0	0	419.6	167.8	56.6	8.9	0	107	18.9
3	149	18.9	36.9	23	23	0	0	115.2	419.6	498.4	56.6	195.2	0	107	18.9
4	149	18.9	36.9	23	23	326.7	0	115.2	419.6	653.8	56.6	195.2	0	107	18.9
5	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	0	107	18.9
6	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	0	107	18.9
7	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	0	107	18.9
8	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	37.1	107	18.9
9	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	37.1	107	18.9
10	149	18.9	36.9	23	23	466.9	148.1	115.2	419.6	831.7	56.6	195.2	37.1	107	18.9

Table 7.35: Capacity of MBT pre-treatment plant of new waste for Case IV

Year	MBT (TPD of RDF)
	lf57
1	11.6
2	11.6
3	11.6
4	11.6
5	11.6
6	11.6
7	11.6
8	11.6
9	11.6
10	11.6

From analysing both figures, it can be concluded that in most situations, MBT of existing waste in landfill is the preferred option as by choosing the technology, there is no need to import waste from another province and therefore the reduction in

transportation cost. However, if the cost of importing MSW from a province is lower than the increased in cost of the MBT process, then the original MBT process would be chosen instead. The previous statement is illustrated by a flow of MSW between landfill 57 and province w06 in Figure 7.7. Furthermore, the summary of the financial details of the network are presented in Table 7.36 and Table 7.37.

The financial details shown in Table 7.36 reflect the effect of budget constraints where the total cost of the suggested networks of each year were limited to below or equal to 5,000 million bahts. It can also be seen in Table 7.37 that the investments of new process plants was not all made in the first year in order to follow the budget constraint. The NPV is also less than case III because of the effect of the budget constraint.

Table 7.36: Total network revenue, cost and profit over the planning horizon of Case IV

Year	Revenue (Baht)	Cost (Baht)	Profit (Baht)
1	3,890,000,000	5,000,000,000	-1,110,000,000
2	7,000,000,000	5,000,000,000	2,000,000,000
3	9,170,000,000	5,000,000,000	4,170,000,000
4	10,690,000,000	5,000,000,000	5,690,000,000
5	11,700,000,000	4,630,000,000	7,070,000,000
6	11,250,000,000	2,480,000,000	8,770,000,000
7	10,820,000,000	2,390,000,000	8,430,000,000
8	10,620,000,000	2,660,000,000	7,960,000,000
9	10,210,000,000	2,270,000,000	7,940,000,000
10	9,820,000,000	2,180,000,000	7,640,000,000
Total	**95,170,000,000**	**36,610,000,000**	**58,560,000,000**

Table 7.37: Total network capital cost for new process plants throughout the planning horizon of Case IV

Year	MBT	MBT (Old waste)	Gasification	CHP Gasification
1		628,100,000		3,629,000,000
2		527,100,000		3,046,000,000
3	10,140,000	488,400,000	1,436,000,000	1,164,000,000
4		463,600,000	2,232,000,000	
5		352,3600,000	1,698,000,000	
Total	**10,140,000**	**5,630,800,000**	**5,366,000,000**	**7,839,000,000**

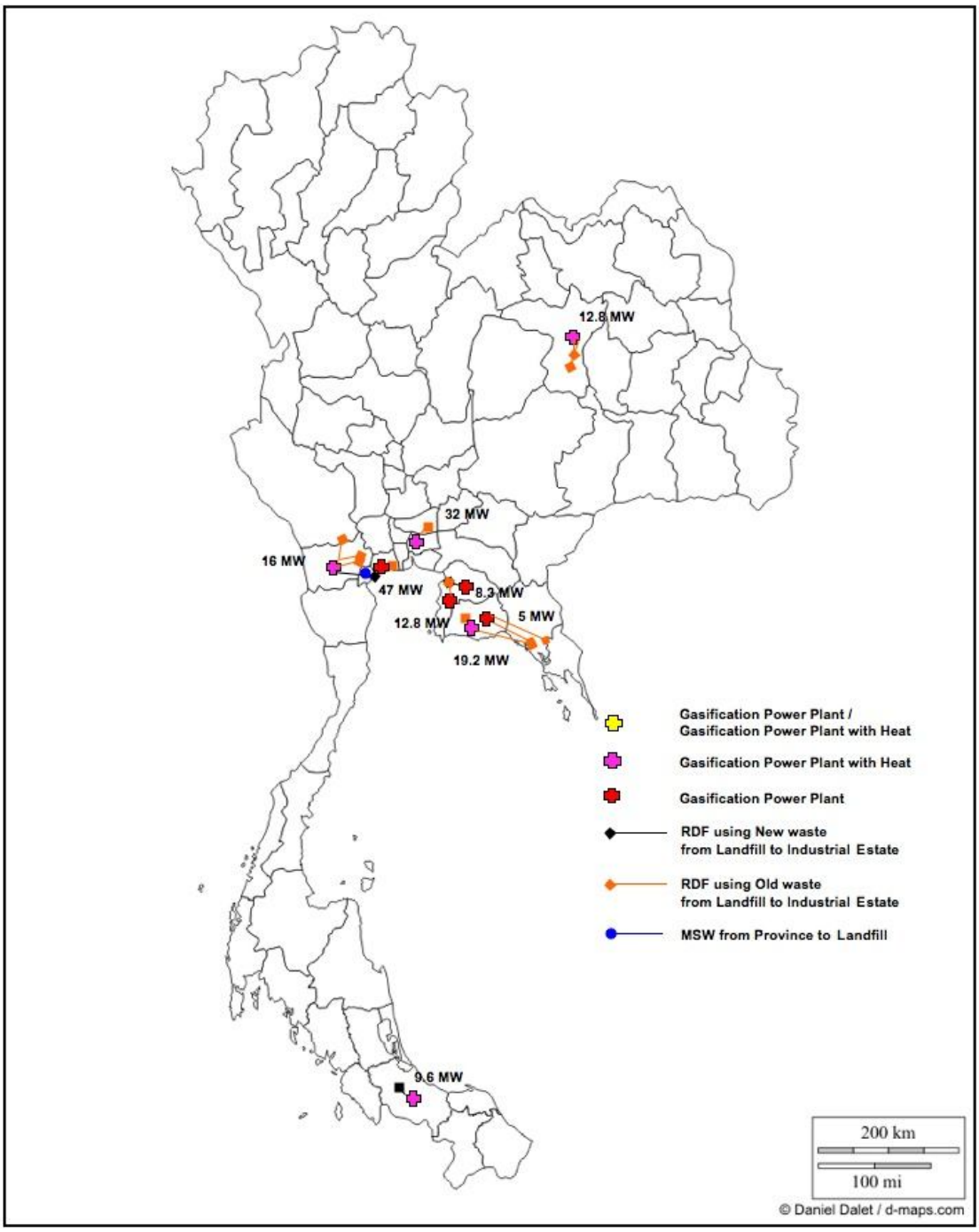


Figure 7.7: Case IV optimal network structure

A Pentium 4, 1.8 GHz Dell machine was used to solve the MILP models for the Waste-to-Energy problem of Thailand via the GAMS modelling tool and CPLEX v9.0. The corresponding computational statistics for solving the MILP models in this chapter are summarised in Table 7.38.

The table shows that the time required to solve the four different configurations are all less than a min. The first case only considers the 100 landfills and the 35 industrial estates. The second case considers the 76 provinces as well as the landfills and the industrial estates. Additional to the second case, the third case takes into account the heat demand as well as the electricity demand. The fourth case includes existing waste in landfill as well as new waste from each province.

The first case used the least time to solve which is as expected as the number of variables and equations were the smallest between the four cases. The forth case has the highest CPU time due to the higher complexity in the configuration. The optimality gaps are the same as the previous chapters.

Table 7.38: Summary of computational results for the Waste-to-Energy model

	Case 1	**Case 2**	**Case 3**	**Case 4**
Number of single variables	417364	1179444	1207424	1813025
Number of discrete variables	71050	223050	223400	334750
Number of equations	486174	1403774	1433284	2152055
Optimality gap (%)	0.015	0.015	0.015	0.015
CPU time (sec)	8.798	24.770	28.433	54.386

7.6 Concluding Remarks

The new policy stated by the Ministry of Energy of Thailand to promote the development of new Waste-to-Energy facilities, together with the government subsidy adders for the price of electricity, and the lack of guidelines for waste management in Thailand had led to the work described in this chapter. The aim of this chapter was to develop a spatial optimisation model that can assist in making strategic decisions for new long-term planning of Waste-to-Energy supply chains for Thailand.

Similar to the previous chapters, the work carried out in this chapter can be divided into two main parts. The first part involved understanding and collecting data required to develop such a model. The second part was the actual development of the optimisation model to determine optimal configurations of the future Waste-to-Energy supply chain in Thailand.

The developed model is capable of determining the capacities and locations of pre-treatment processes (MBT) and thermal conversion processes (Incineration, Gasification and CHP Gasification), locations of raw material (MSW and RDF), and the flow rates of the raw materials throughout the network. Moreover, the budget constraint incorporated in case III and IV allows the models to suggest Waste-to-Energy network structures that reflect the real world situation where not all the budget is available in the first year. The objective function of the model was to maximise the net present value of the project over the planning horizon.

In this work, four different versions of the network configurations were studied. The first configuration utilised only the wastes being received at each landfill site in Thailand. The second configuration utilised all wastes being collected at open-dump sites in each province of Thailand. The third configuration considered heat energy as well as electricity energy as a source of revenue. The final configuration also considered existing waste in landfills as well as newly generated waste. One of the features of the four configurations that differentiate them from common waste management methods is the selected location to built gasification power plants. The industrial estates in Thailand were chosen as the locations.

The optimal network structures for all four cases as a result of optimising the different network configurations of the proposed mode have many features in common. These similar features include the type of chosen technologies, the geographical location of the production plants and the chosen location of source of raw material (both province and landfill).

The first similarity is the type of chosen technologies. The conversion of MSW to RDF by an MBT process follow by thermal gasification technology of the RDF to generate electricity is preferred, rather than incineration of MSW. Even though the incineration plant is allowed to be built at both landfills and industrial estates, none of the network structures suggested the technology. The combined heat and power gasification technology is more financially desirable than the two technologies assuming the estimated costs used by the model. However, the capacity of such power plants is limited by the heat demands in each industrial estate in Thailand. The second similarity is the geographical location and the capacity of the power plants. As for all

cases, thermal gasification power plants are only allowed to be located at industrial estates. Therefore it is not surprising that all suggested network structures follow the constraint. Moreover, the capacity of power plant at each industrial estate is limited by the maximum capacity of each industrial estate. The third similarity is the location of primary energy source. In this model the primary energy source is MSW and RDF. It is evident that the chosen locations of landfill and province that provide wastes for thermal conversion processes are located close to the industrial estates to minimise the cost of importing MSW or RDF from nearby grids.

As the objective function of the proposed model is to maximise the net present value of Waste-to-Energy network over the planning horizon, the results shows that for all network configurations, thermal gasification power plant using RDF as raw material is a viable waste management method that can reduce waste and also generate income for investors throughout the planning horizon. However, these results are specific to Thailand as other countries might not have similar government support as in Thailand.

Chapter 8

Conclusions and Future work

This chapter provides a summary of the work described in this report. It also provides a future research plan in the area of energy system modelling at the national level.

8.1 Contribution of this Thesis

Thailand is currently depending heavily on fossil fuels to generate energy to meet the country's demand by different sectors. In order to reduce dependency on oil imports and to ensure the national energy supply security and sustainable energy development, Thailand's energy policy has placed a greater emphasis on diversification of energy supplies. Thailand is generously endowed with abundant renewable energy resources such as biomass, solar, and hydro energy, which are widely distributed across the country and can be harnessed via commercially viable technologies to generate energy or electricity. Thailand, however, has so far exploited relatively a small portion of its full potential. The above statement was the driving force for the work carried out in this thesis. In order to identify optimal future energy policy planning for the energy system of Thailand.

The main contribution of the work described in this thesis is the development of quantitative modelling tools which are capable of determining optimal energy supply chain networks towards sustainability as well as incorporating the spatially disaggregated nature of an energy system under uncertainty in demand over long-term horizon at the national level. In order to develop the modelling tools described above,

successions of models have been developed in stages. All the models developed in this thesis have been applied to the case study of energy system of Thailand.

The first model considered the multi-period deterministic formulation of the energy supply chain network. In this case, the model assumed a perfect foresight of the future energy demand. In the attempt to reduce the GHG emissions of the future energy supply chain network, the emission constraints were formed as part of the mathematical formulation to control the amount of GHG emissions. The second model reformulated the first model to a scenario-based stochastic energy system optimisation model which was able to capture the uncertainty in demand. The third model extended the first deterministic model to take into account the spatial nature of an energy system. The aspect was incorporated into the previously developed model by introducing grid and transportation mode indices. The mainland area of Thailand has been divided into four grids representing different regions of Thailand. The decisions to be determined by the models were: (1) the type, scale and location of the energy production technologies, (2) the type and scale of domestic resource usage, (3) the scale of imported resources, (4) the transportation (flow rate) of resources and energy between grids. The decisions were to be made for multiple time periods to satisfy future energy demand throughout the network. Apart from using cost as a performance measure, the environmental concerns were also considered. The model was also able to identify optimal alternative energy supply chain networks which take into account the maximum amount of GHG emissions permitted throughout the planning horizon. The fourth model investigated the spatial model further by focusing on the Biomass-to-Energy supply chain network. The mainland area of Thailand has been divided into seventy grids in this model. Different types of biomass and thermal conversion technologies for biomass were applied to the model. The final model explored further into another type of renewable energy. The multi-period spatial Waste-to-Energy optimisation model was developed to determine the optimal Waste-to-Energy supply chain network where different network structures were explored.

As mentioned before, the energy system of Thailand has been used as the case study for all the models developed in this Thesis, the data specific to energy system planning for Thailand was obtained and applied to each of the developed models. Based on the assumptions inherent in the models, it has been found that the advanced

gas combined cycle was the most economical non-renewable power production technologies while biomass and lignite were the most economical for producing heat energy. Most of the renewable power generation technologies were also suggested, including, geothermal, hydro, wind and solar thermal technologies. In order to reduce the total GHG emissions of the network, various technologies have been recommended including biomass integrated gasification combined cycle and advanced gas combined cycle with carbon sequestration.

In consideration of the geographical locations of different renewable resources and energy demand, the hydro and geothermal power plants supply the demand in the north region of Thailand. The solar thermal power plants supply the demand in the north-east region of Thailand. The wind power supply the demand in the south region of Thailand. The biomass resources supply the heat demand throughout the country. For the non-renewable power plants, the advanced gas combined cycle power plant was the most popular option from all the proposed models. The power plant was suggested to be located in the south region of Thailand to supply energy to the local demand and also transmits the electricity energy through transmission lines to other parts of the country. These conclusions were derived from the results of the first three models developed.

For the last two models, it has been found that the Biomass-to-Energy supply chain is more suited as a distributed energy plan rather than the centralised one. This was due to the fact that the biomass resources are available throughout the country and it is more economical to utilise the local resources for the local demand rather than transporting the large amounts of biomass to neighbouring grids. However, if the amount of the specific type of biomass in a local grid is not enough to produce sufficient amount of electricity, then importing the biomass from others grids is required. Moreover, the total suggested biomass power plant capacity from all biomass available in Thailand was suggested to be 10,033 MW. The estimated electricity demand used in this proposed model for the whole country is 14,746 MW. Therefore, based on the model assumptions, nearly 70% of the total electricity demand could be fulfilled by energy from the total generated biomass in Thailand.

Furthermore, the results from the final proposed model which considered the planning of Waste-to-Energy supply chain for Thailand, has indicated that the conversion of MSW to RDF by MBT process followed by thermal gasification technology of the RDF to generate electricity is the preferred network structure for converting waste into energy. The suggested network structure where the industrial estates in Thailand have been chosen as the site for the thermal gasification power plants and the landfill being the site for the MBT process was proven by the proposed model to be financially attractive and also environmentally conscious.

Considering the computational statistics for all models described in this thesis, the CPU times to solve each model are considered to be minimal compared to the number of variables and constraints of each model. The CPU times for all models are less than a minute. However, as mentioned in section 6.4.2, when the number of grids for the Biomass-to-Energy model in Chapter 6 becomes 76 grids rather than the 4 grids which were used in Chapter 5, the size of the file containing the results from solving the model became too large for the CPLEX solver memory. Therefore, only one time period with the duration of 10 years has been considered in Chapter 6 to make the problem solvable. However, with a higher memory of the CPLEX solver, the proposed multi-period Biomass-to-Energy spatial model is expected to be functional and is able to generate an optimal solution.

In conclusion, the work presented in this thesis has resulted in optimisation modelling tools which can help decision makers in determining the optimal energy planning strategy at the national level by means of energy supply chain networks. However, in reality, the energy system planning over long-term period is a large scale complex problem which can be influenced by many factors which were not considered in this thesis. The next section identifies future research direction which could improve the developed models further.

8.2 Future Research Direction

The work described in this thesis includes the design and development of optimisation models for determining optimal supply chain networks for long-term energy planning

at the national level. However, there are still a variety of research areas which could improve the feasibility of the models. The future research areas are addressed in greater detail below.

Trend of changes in energy production technologies

The proposed multi-period spatial model only took into account the existing costs of the energy production technologies that are currently available. However, the costs of the advanced technologies will most likely be decreased through time which make them more financially attractive. By incorporating rates of change of the cost of each technology to the developed model, a more realistic energy supply chain network could be achieved.

Trend of changes in cost and availability of resources

As mentioned above the costs of energy production technologies are most likely to vary through time, it is also true for the costs and availability of resources. For example, the costs of importing crude oil and petroleum products are certain to increase through time as more and more crude oil reserves being used up. The costs of most resources are likely to be increased through time. However, the renewable resources such as solar energy, wind energy and thermal energy are still going to remain free. However, the costs of biomass and MSW are likely to increase even though they are renewable sources which used to be free or even getting paid for. These are due to their increases in demands for energy production. The higher the demand also means the higher costs of the resource. Therefore, a future research in changes in both cost and availability of resources are also necessary for determining the future energy supply chain network.

Pipeline and Transmission line structures

In the proposed spatial model, the pipelines and transmission lines were assumed to be established throughout the country which means that the transportation of

resources and energy by the two transportation modes are possible to all grids. In reality, the transmission line and pipeline can not cover the whole country. As the proposed model only divided the mainland area into four grids, it is safe to assume that the structures for both pipeline and transmission line were created. However, if the number of grids were to increase, then a further research into the two transportation modes is required. Furthermore, as the model only used an estimated transportation costs, obtaining the more accurate costs could improve the accuracy of the model.

Increase number of grids

The proposed spatial model only divides the mainland area of Thailand into four grids. However, in order to investigate the energy supply chain in higher details, a higher number of grids is required (similar to the work in chapter 6 and 7). The proposed mathematical formulation does not need to be modified but it is necessary to obtain more data which could be a possible area of future work.

Technology Options

The thermal conversion technologies considered in the model were incineration and gasification. Considering the fact that there are many types of gasification process developed by many companies around the world and each process has different thermal conversion efficiency, by incorporating these technology options for the model to choose is a possible future research direction. Furthermore, there are also many types of MBT process and power generation process (steam turbine, gas turbine), these technology options could also be investigated in the future work. This concept can also be applied to the spatial energy system optimisation model where many production technologies have been considered.

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Appendix A

Table A1: Distance between grids

EngName	Grid	M1	M9	M5	M7	M10	LN8	LN6	LN7	LN3	UN8	UN9	UN7	UN6	UN2	UN1	UN3	UN5	UN4	LN1	LN4	LN2
Bangkok	M1	0	76	105	142	194	219	240	358	426	599	670	696	924	691	785	668	551	491	427	344	377
Phra Nakhon Si Ayutthaya	M9	76	0	31	71	121	156	172	289	357	531	602	623	856	620	714	579	479	419	358	285	301
Ang Thong	M5	105	31	0	40	92	119	141	258	326	500	571	592	825	589	683	566	448	388	327	254	270
Singburi	M7	142	71	40	0	53	83	101	218	286	460	531	552	785	549	643	526	408	348	287	214	230
Chainat	M10	194	121	92	53	0	42	64	181	249	423	494	515	748	516	606	489	371	311	250	177	193
Uthai Thani	LN8	219	156	119	83	42	0	50	167	234	408	479	500	733	497	591	474	357	297	238	163	179
Nakhon Sawan	LN6	240	172	141	101	64	50	0	117	185	359	428	449	683	448	542	425	307	247	188	113	129
Kamphaeng Phet	LN7	358	289	258	218	181	167	117	0	68	241	316	337	569	382	477	359	241	177	77	90	103
Tak	LN3	426	357	326	286	249	234	185	68	0	174	244	265	499	304	398	362	244	179	79	157	138
Lampang	UN8	599	531	500	460	423	408	359	241	174	0	71	92	412	131	225	227	109	140	207	332	244
Lamphun	UN9	670	602	571	531	494	479	428	316	244	71	0	21	342	201	295	297	180	210	277	385	312
Chiang Mai	UN7	696	623	592	552	515	500	449	337	265	92	21	0	349	222	182	318	201	231	298	406	333
Mae Hong Son	UN6	924	856	825	785	748	733	683	569	499	412	342	349	0	543	634	639	521	552	578	656	637
Phayao	UN2	691	620	589	549	516	497	448	382	304	131	201	222	543	0	94	176	141	214	337	379	319
Chiang Rai	UN1	785	714	683	643	606	591	542	477	398	225	295	182	634	94	0	270	235	308	400	474	413
Nan	UN3	668	579	566	526	489	474	425	359	362	227	297	318	639	176	270	0	118	191	282	359	295
Phrae	UN5	551	479	448	408	371	357	307	241	244	109	180	201	521	141	235	118	0	74	165	239	178
Uttaradit	UN4	491	419	388	348	311	297	247	177	179	140	210	231	552	214	308	191	74	0	100	189	118
Sukhothai	LN1	427	358	327	287	250	238	188	77	79	207	277	298	578	337	400	282	165	100	0	125	59
Phichit	LN4	344	285	254	214	177	163	113	90	157	332	385	406	656	379	474	359	239	189	125	0	73
Phitsanulok	LN2	377	301	270	230	193	179	129	103	138	244	312	333	637	319	413	295	178	118	59	73	0
Lopburi	M8	153	98	67	33	85	111	130	247	315	489	558	579	814	578	672	554	437	377	316	243	259
Saraburi	M6	107	63	58	79	128	157	175	293	361	535	604	625	860	624	718	600	483	423	362	289	305
Chaiyaphum	NE18	342	298	293	276	298	340	342	460	466	572	643	664	965	655	741	623	506	446	387	360	336
Phetchabun	LN5	346	302	297	232	217	233	192	273	308	414	485	506	807	489	583	465	348	288	229	129	170
Loei	NE1	520	476	471	466	462	448	398	372	407	513	581	602	906	588	682	564	447	387	328	301	269
Nakhon Ratchasima	NE19	259	215	210	231	280	309	324	445	513	687	756	777	1012	776	870	752	635	575	514	441	457
Khon Kaen	NE17	449	405	400	421	448	498	493	422	457	563	631	652	956	638	732	614	497	437	378	352	319
Udon Thani	NE3	564	520	515	536	585	613	563	537	572	678	746	767	4071	753	847	729	612	552	493	467	434
Nong Khai	NE4	615	571	566	587	636	664	614	588	623	729	797	818	1122	804	898	780	663	603	544	518	485
Sakhon Nakhon	NE6	647	603	598	619	668	697	653	627	662	768	836	857	1161	843	937	819	702	642	583	557	524
Nakhon Phanom	NE5	740	696	691	712	761	790	746	720	755	861	929	950	1254	936	1030	912	795	735	676	650	617
Maha Sarakham	NE15	475	431	426	447	496	525	521	495	530	636	704	725	1029	711	805	687	570	510	451	423	392
Roi Et	NE16	512	450	445	466	515	544	562	535	570	676	744	765	1069	751	845	727	610	550	491	463	432
Buriram	NE13	410	366	361	382	431	460	478	596	664	838	907	928	1163	927	1021	903	786	726	665	592	608
Surin	NE12	457	413	408	429	478	507	525	643	711	885	954	975	1210	974	1068	950	833	773	712	639	655
Sisaket	NE11	571	527	522	543	592	621	639	757	804	910	978	999	1303	985	1079	961	844	784	726	699	666
Kalasin	NE14	519	475	470	491	540	569	525	499	533	640	708	729	1033	715	809	691	574	514	455	429	396
Yasothon	NE8	531	484	482	503	552	581	599	606	641	747	818	839	1140	822	916	799	681	621	562	536	503
Ubon Ratchathani	NE10	629	582	580	601	650	679	697	704	739	845	916	937	1238	920	1014	897	779	719	660	634	601
Mukdahan	NE7	642	598	593	614	663	692	710	849	700	806	877	898	1199	881	975	858	740	680	621	595	562
Amnat Charoen	NE9	585	538	536	557	606	635	653	660	695	801	872	893	1194	876	970	853	735	675	616	590	557
Nongbua Lamphu	NE2	577	533	528	463	448	464	415	425	460	566	634	549	933	635	729	611	494	434	361	377	322
Samut Sakhon	W7	36	112	141	178	230	255	276	394	462	635	706	732	960	727	821	704	587	527	463	380	413
Samut Songkhram	W6	72	148	177	214	266	291	312	430	498	671	742	768	996	763	857	740	623	563	499	416	449
Nakhon Pathom	W2	56	132	161	198	250	275	296	414	482	655	726	752	980	747	841	724	607	547	483	400	433
Suphanburi	W8	100	176	205	242	294	319	340	458	526	699	770	796	1024	791	885	768	651	591	527	444	477
Kanchanaburi	W1	128	204	233	270	322	347	368	486	554	727	798	824	1052	819	913	796	679	619	555	472	505
Ratchaburi	W5	100	176	205	242	294	319	340	458	526	699	770	796	1024	791	885	768	651	591	527	444	477
Phetchaburi	W4	123	199	228	265	317	342	363	481	549	722	793	819	1047	814	908	791	674	614	550	467	500
Prachuap Khiri Khan	W3	281	357	386	423	475	500	521	639	707	880	951	977	1205	972	1066	949	832	772	708	625	658
Chumphon	S2	463	539	568	605	657	682	703	821	889	1062	1133	1159	1387	1154	1248	1131	1014	954	890	807	840
Ranong	S11	568	644	673	710	762	787	808	926	994	1167	1238	1264	1492	1259	1353	1236	1119	1059	995	912	945
Surat Thani	S14	644	720	749	786	838	863	884	1002	1070	1243	1314	1340	1568	1335	1429	1312	1195	1135	1071	988	1021
Phang Nga	S7	788	864	893	930	982	1007	1028	1146	1214	1387	1458	1484	1712	1479	1573	1456	1339	1279	1215	1132	1165
Phuket	S9	862	938	967	1004	1056	1081	1102	1220	1288	1461	1532	1558	1786	1553	1647	1530	1413	1353	1289	1206	1239
Krabi	S1	814	890	919	956	1008	1033	1054	1172	1240	1413	1484	1510	1738	1505	1599	1482	1365	1305	1241	1158	1191
Nakhon Si Thammarat	S4	780	856	885	922	974	999	1020	1138	1206	1379	1450	1476	1704	1471	1565	1448	1331	1271	1207	1124	1157
Trang	S3	828	904	933	970	1022	1047	1068	1186	1254	1427	1498	1524	1752	1519	1613	1496	1379	1319	1255	1172	1205
Phattalung	S8	840	916	945	982	1034	1059	1080	1198	1266	1439	1510	1536	1764	1531	1625	1508	1391	1331	1267	1184	1217
Songkhla	S12	950	1026	1055	1092	1144	1169	1190	1308	1376	1549	1620	1646	1874	1641	1735	1618	1501	1441	1377	1294	1327
Satun	S13	973	1049	1078	1115	1167	1192	1213	1331	1399	1572	1643	1669	1897	1664	1758	1641	1524	1464	1400	1317	1350
Pattani	S6	1055	1131	1160	1197	1249	1274	1295	1413	1481	1654	1725	1751	1979	1746	1840	1723	1606	1546	1482	1399	1432
Yala	S10	1084	1160	1189	1226	1278	1303	1324	1442	1510	1683	1754	1780	2008	1775	1869	1752	1635	1575	1511	1428	1461
Narathiwat	S5	1149	1225	1254	1291	1343	1368	1389	1507	1575	1748	1819	1845	2073	1840	1934	1817	1700	1640	1576	1493	1526
Nonthaburi	M2	20	70	99	122	173	199	220	338	406	579	650	676	904	671	765	648	531	471	407	324	357
Pathumthani	M3	46	40	88	113	177	173	194	312	380	553	624	650	878	645	739	622	505	445	381	298	331
Samut Prakan	M4	29	105	133	171	223	248	269	387	455	628	699	725	953	720	814	697	580	520	456	373	406
Chachoengsao	E8	82	158	148	224	276	301	322	440	508	681	752	778	1006	773	867	750	633	573	509	426	459
Chonburi	E6	81	157	169	223	275	300	321	439	507	680	751	777	1005	772	866	749	632	572	508	425	458
Rayong	E2	179	255	266	321	373	398	419	537	605	778	849	875	1103	870	964	847	730	670	606	523	556
Chanthaburi	E7	245	321	332	387	439	464	485	603	671	844	915	941	1169	936	1030	913	796	736	672	589	622
Trat	E5	315	391	402	457	509	534	555	673	741	914	985	1011	1239	1006	1100	983	866	806	742	659	692
Prachinburi	E3	135	150	144	214	263	209	230	348	416	589	660	686	914	681	775	658	541	481	417	334	367
Nakhon Nayok	E4	107	75	116	156	194	164	185	303	371	544	615	641	869	636	730	613	496	436	372	289	322
Sakaeo	E1	237	230	242	289	345	349	370	488	556	729	800	826	1054	821	915	798	681	621	557	474	507

Table A1: Distance between grids (continue)

	M8	M6	NE18	LN5	NE1	NE19	NE17	NE3	NE4	NE6	NE5	NE15	NE16	NE13	NE12	NE11	NE14	NE8	NE10	NE7	NE9	NE2	W7	W6	W2	W8	W1	W5
M1	153	107	342	346	520	259	449	564	615	647	740	475	512	410	457	571	519	531	629	642	585	577	36	72	56	100	128	100
M9	98	63	298	302	476	215	405	520	571	603	696	431	450	366	413	527	475	484	582	598	538	533	112	148	132	176	204	176
M5	67	58	293	297	471	210	400	515	566	598	691	426	445	361	408	522	470	482	580	593	536	528	141	177	161	205	233	205
M7	33	79	276	232	466	231	421	536	587	619	712	447	466	382	429	543	491	503	601	614	557	463	178	214	198	242	270	242
M10	85	128	298	217	462	280	448	585	636	668	761	496	515	431	478	592	540	552	650	663	606	448	230	266	250	294	322	294
LN8	111	157	340	233	448	309	498	613	664	697	790	525	544	460	507	621	569	581	679	692	635	464	255	291	275	319	347	319
LN6	130	175	342	192	398	324	493	563	614	653	746	521	562	478	525	639	525	599	697	710	653	415	276	312	296	340	368	340
LN7	247	293	460	273	372	445	422	537	588	627	720	495	535	596	643	757	499	606	704	849	660	425	394	430	414	458	486	458
LN3	315	361	466	308	407	513	457	572	623	662	755	530	570	664	711	804	533	641	739	700	695	460	462	498	482	526	554	526
UN8	489	535	572	414	513	687	563	678	729	768	861	636	676	838	885	910	640	747	845	806	801	566	635	671	655	699	727	699
UN9	558	604	643	485	581	756	631	746	797	836	929	704	744	907	954	978	708	818	916	877	872	634	706	742	726	770	798	770
UN7	579	625	664	506	602	777	652	767	818	857	950	725	765	928	975	999	729	839	937	898	893	549	732	768	752	796	824	796
UN6	814	860	965	807	906	1012	956	4071	1122	1161	1254	1029	1069	1163	1210	1303	1033	1140	1238	1199	1194	933	960	996	980	1024	1052	1024
UN2	578	624	655	489	588	776	638	753	804	843	936	711	751	927	974	985	715	822	920	881	876	635	727	763	747	791	819	791
UN1	672	718	741	583	682	870	732	847	898	937	1030	805	845	1021	1068	1079	809	916	1014	975	970	729	821	857	841	885	913	885
UN3	554	600	623	465	564	752	614	729	780	819	912	687	727	903	950	961	691	799	897	858	853	611	704	740	724	768	796	768
UN5	437	483	506	348	447	635	497	612	663	702	795	570	610	786	833	844	574	681	779	740	735	494	587	623	607	651	679	651
UN4	377	423	446	288	387	575	437	552	603	642	735	510	550	726	773	784	514	621	719	680	675	434	527	563	547	591	619	591
LN1	316	362	387	229	328	514	378	493	544	583	676	451	491	665	712	726	455	562	660	621	616	361	463	499	483	527	555	527
LN4	243	289	360	129	301	441	352	467	518	557	650	423	463	592	639	699	429	536	634	595	590	377	380	416	400	444	472	444
LN2	259	305	336	170	269	457	319	434	485	524	617	392	432	608	655	666	396	503	601	562	557	322	413	449	433	477	505	477
M8	0	46	243	251	441	198	388	503	554	586	679	414	433	349	396	510	458	470	568	679	524	319	189	225	209	253	281	253
M6	46	0	235	239	413	152	342	457	508	540	633	368	387	303	350	464	412	424	522	535	478	409	143	179	163	207	235	207
NE18	243	235	0	259	225	119	150	266	317	349	442	176	216	192	304	417	220	261	359	372	315	174	378	414	398	442	470	442
LN5	251	239	259	0	190	310	240	342	393	444	537	313	353	461	508	519	316	428	531	481	482	231	382	418	402	446	474	446
NE1	441	413	225	190	0	344	206	152	202	311	404	278	318	417	462	552	283	391	489	437	445	106	556	592	576	620	648	620
NE19	198	152	119	310	344	0	190	305	356	388	481	216	235	151	198	312	260	272	370	383	326	351	295	331	315	359	387	359
NE17	388	342	150	240	206	190	0	115	166	205	298	73	113	200	256	347	77	184	282	243	238	161	485	521	505	549	577	549
NE3	503	457	266	342	152	305	115	0	51	159	252	188	228	315	373	462	192	303	401	278	357	46	600	636	620	664	692	664
NE4	554	508	317	393	202	356	166	51	0	210	303	239	279	366	422	513	243	350	448	329	404	97	651	687	671	715	743	715
NE6	586	540	349	444	311	388	205	159	210	0	93	172	175	321	312	347	128	230	286	119	207	205	683	719	703	747	775	747
NE5	679	633	442	537	404	481	298	252	303	93	0	265	268	414	350	332	221	215	271	104	192	298	776	812	796	840	868	840
NE15	414	368	176	313	278	216	73	188	239	172	265	0	40	145	177	274	44	115	213	210	165	234	511	547	531	575	603	575
NE16	433	387	216	353	318	235	113	228	279	175	268	40	0	146	137	230	47	71	169	162	125	274	548	584	568	612	640	612
NE13	349	303	192	461	417	151	200	315	366	321	414	145	146	0	51	225	184	191	269	302	245	361	446	482	466	510	538	510
NE12	396	350	304	508	462	198	256	373	422	312	350	177	137	51	0	143	184	135	227	246	189	419	493	529	513	557	585	557
NE11	510	464	417	519	552	312	347	462	513	347	332	274	230	225	143	0	279	159	61	228	136	508	607	643	627	671	699	671
NE14	458	412	220	316	283	260	77	192	243	128	221	44	47	184	184	279	0	118	216	156	172	238	555	591	575	619	647	619
NE8	470	424	261	428	391	272	184	303	350	230	215	115	71	191	135	159	118	0	98	111	54	349	567	603	587	631	659	631
NE10	568	522	359	531	489	370	282	401	448	286	271	213	169	269	227	61	216	98	0	167	75	447	665	701	685	729	757	729
NE7	679	535	372	481	437	383	243	278	329	119	104	210	162	302	246	228	156	111	167	0	88	320	678	714	698	742	770	742
NE9	524	478	315	482	445	326	238	357	404	207	192	165	125	245	189	136	172	54	75	88	0	324	621	657	641	685	713	685
NE2	319	409	174	231	106	351	161	46	97	205	298	234	274	361	419	508	238	349	447	320	324	0	613	649	633	677	705	677
W7	189	143	378	382	556	295	485	600	651	683	776	511	548	446	493	607	555	567	665	678	621	613	0	37	48	123	119	78
W6	225	179	414	418	592	331	521	636	687	719	812	547	584	482	529	643	591	603	701	714	657	649	37	0	63	160	112	43
W2	209	163	398	402	576	315	505	620	671	703	796	531	568	466	513	627	575	587	685	698	641	633	48	63	0	105	65	41
W8	253	207	442	446	620	359	549	664	715	747	840	575	612	510	557	671	619	631	729	742	685	677	123	160	105	0	91	147
W1	281	235	470	474	648	387	577	692	743	775	868	603	640	538	585	699	647	659	757	770	713	705	119	112	65	91	0	87
W5	253	207	442	446	620	359	549	664	715	747	840	575	612	510	557	671	619	631	729	742	685	677	78	43	41	147	87	0
W4	276	230	465	469	643	382	572	687	738	770	863	598	635	533	580	694	642	654	752	765	708	700	88	53	98	204	144	54
W3	434	388	623	627	801	540	730	845	896	928	1021	756	793	691	738	852	800	812	910	923	866	858	245	211	255	361	295	211
S2	616	570	805	809	983	722	912	1027	1078	1110	1203	938	975	873	920	1034	982	994	1092	1105	1048	1040	428	393	438	544	478	393
S11	721	675	910	914	1088	827	1017	1132	1183	1215	1308	1043	1080	978	1025	1139	1087	1099	1197	1210	1153	1145	532	498	542	648	582	498
S14	797	751	986	990	1164	903	1093	1208	1259	1291	1384	1119	1156	1054	1101	1215	1163	1175	1273	1286	1229	1221	609	574	618	724	658	574
S7	941	895	1130	1134	1308	1047	1237	1352	1403	1435	1528	1263	1300	1198	1245	1359	1307	1319	1417	1430	1373	1365	753	718	763	869	803	719
S9	1015	969	1204	1208	1382	1121	1311	1426	1477	1509	1602	1337	1374	1272	1319	1433	1381	1393	1491	1504	1447	1439	827	792	837	943	877	793
S1	967	921	1156	1160	1334	1073	1263	1378	1429	1461	1554	1289	1326	1224	1271	1385	1333	1345	1443	1456	1399	1391	778	744	788	894	828	744
S4	933	887	1122	1126	1300	1039	1229	1344	1395	1427	1520	1255	1292	1190	1237	1351	1299	1311	1409	1422	1365	1357	746	711	755	861	795	711
S3	981	935	1170	1174	1348	1087	1277	1392	1443	1475	1568	1303	1340	1238	1285	1399	1347	1359	1457	1470	1413	1405	793	758	802	908	842	758
S8	993	947	1182	1186	1360	1099	1289	1404	1455	1487	1580	1315	1352	1250	1297	1411	1359	1371	1469	1482	1425	1417	805	770	814	920	854	770
S12	1103	1057	1292	1296	1470	1209	1399	1514	1565	1597	1690	1425	1462	1360	1407	1521	1469	1481	1579	1592	1535	1527	915	880	925	1030	964	880
S13	1126	1080	1315	1319	1493	1232	1422	1537	1588	1620	1713	1448	1485	1383	1430	1544	1492	1504	1602	1615	1558	1550	939	904	948	1054	988	904
S6	1208	1162	1397	1401	1575	1314	1504	1619	1670	1702	1795	1530	1567	1465	1512	1626	1574	1586	1684	1697	1640	1632	1020	985	1029	1135	1069	985
S10	1237	1191	1426	1430	1604	1343	1533	1648	1699	1731	1824	1559	1596	1494	1541	1655	1603	1615	1713	1726	1669	1661	1049	1014	1058	1164	1098	1014
S5	1302	1256	1491	1495	1669	1408	1598	1713	1764	1796	1889	1624	1661	1559	1606	1720	1668	1680	1778	1791	1734	1726	1114	1079	1124	1230	1164	1080
M2	165	101	352	326	530	256	459	574	625	657	750	485	522	420	467	581	529	541	639	652	595	587	49	101	37	89	181	121
M3	134	101	312	300	490	256	419	534	585	617	710	445	482	380	427	541	489	501	599	612	555	547	106	144	81	80	221	174
M4	182	137	354	375	532	293	461	576	627	659	752	487	524	422	469	583	531	543	641	654	597	589	72	112	93	127	239	154
E8	235	150	347	428	525	237	454	569	620	652	745	480	517	415	462	576	524	536	634	647	590	582	118	154	138	167	210	182
E6	234	201	392	427	570	280	499	614	665	697	790	525	562	460	507	621	569	581	679	692	635	627	117	153	137	180	209	181
E2	332	272	422	525	600	345	529	644	695	727	820	555	592	490	537	651	599	611	709	722	665	657	215	251	235	277	307	279
E7	398	313	462	591	640	332	569	684	735	767	860	595	632	530	577	691	639	651	749	762	705	697	281	317	301	343	373	345
E5	468	380	502	661	680	399	609	724	775	807	900	635	672	570	617	731	679	691	789	802	745	737	351	387	371	413	443	415
E3	172	86	222	336	400	194	329	444	495	527	620	355	392	290	337	451	399	411	509	522	465	457	171	207	191	188	263	235
E4	118	58	252	291	430	231	359	474	525	557	650	385	422	320	367	481	429	441	539	552	495	487	143	179	163	160	235	207
E1	240	184	222	476	400	174	329	444	495	527	620	355	392	290	337	451	399	411	509	522	465	457	273	309	293	286	365	337

Table A1: Distance between grids (continue)

	W4	W3	S2	S11	S14	S7	S9	S1	S4	S3	S8	S12	S13	S6	S10	S5	M2	M3	M4	E8	E6	E2	E7	E5	E3	E4	E1
M1	123	281	463	568	644	788	862	814	780	828	840	950	973	1055	1084	1149	20	46	29	82	81	179	245	315	135	107	237
M9	199	357	539	644	720	864	938	890	856	904	916	1026	1049	1131	1160	1225	70	40	105	158	157	255	321	391	150	75	230
M5	228	386	568	673	749	893	967	919	885	933	945	1055	1078	1160	1189	1254	99	88	133	148	169	266	332	402	144	116	242
M7	265	423	605	710	786	930	1004	956	922	970	982	1092	1115	1197	1226	1291	122	113	171	224	223	321	387	457	214	156	289
M10	317	475	657	762	838	982	1056	1008	974	1022	1034	1144	1167	1249	1278	1343	173	177	223	276	275	373	439	509	263	194	345
LN8	342	500	682	787	863	1007	1081	1033	999	1047	1059	1169	1192	1274	1303	1368	199	173	248	301	300	398	464	534	209	164	349
LN6	363	521	703	808	884	1028	1102	1054	1020	1068	1080	1190	1213	1295	1324	1389	220	194	269	322	321	419	485	555	230	185	370
LN7	481	639	821	926	1002	1146	1220	1172	1138	1186	1198	1308	1331	1413	1442	1507	338	312	387	440	439	537	603	673	348	303	488
LN3	549	707	889	994	1070	1214	1288	1240	1206	1254	1266	1376	1399	1481	1510	1575	406	380	455	508	507	605	671	741	416	371	556
UN8	722	880	1062	1167	1243	1387	1461	1413	1379	1427	1439	1549	1572	1654	1683	1748	579	553	628	681	680	778	844	914	589	544	729
UN9	793	951	1133	1238	1314	1458	1532	1484	1450	1498	1510	1620	1643	1725	1754	1819	650	624	699	752	751	849	915	985	660	615	800
UN7	819	977	1159	1264	1340	1484	1558	1510	1476	1524	1536	1646	1669	1751	1780	1845	676	650	725	778	777	875	941	1011	686	641	826
UN6	1047	1205	1387	1492	1568	1712	1786	1738	1704	1752	1764	1874	1897	1979	2008	2073	904	878	953	1006	1005	1103	1169	1239	914	869	1054
UN2	814	972	1154	1259	1335	1479	1553	1505	1471	1519	1531	1641	1664	1746	1775	1840	671	645	720	773	772	870	936	1006	681	636	821
UN1	908	1066	1248	1353	1429	1573	1647	1599	1565	1613	1625	1735	1758	1840	1869	1934	765	739	814	867	866	964	1030	1100	775	730	915
UN3	791	949	1131	1236	1312	1456	1530	1482	1448	1496	1508	1618	1641	1723	1752	1817	648	622	697	750	749	847	913	983	658	613	798
UN5	674	832	1014	1119	1195	1339	1413	1365	1331	1379	1391	1501	1524	1606	1635	1700	531	505	580	633	632	730	796	866	541	496	681
UN4	614	772	954	1059	1135	1279	1353	1305	1271	1319	1331	1441	1464	1546	1575	1640	471	445	520	573	572	670	736	806	481	436	621
LN1	550	708	890	995	1071	1215	1289	1241	1207	1255	1267	1377	1400	1482	1511	1576	407	381	456	509	508	606	672	742	417	372	557
LN4	467	625	807	912	988	1132	1206	1158	1124	1172	1184	1294	1317	1399	1428	1493	324	298	373	426	425	523	589	659	334	289	474
LN2	500	658	840	945	1021	1165	1239	1191	1157	1205	1217	1327	1350	1432	1461	1526	357	331	406	459	458	556	622	692	367	322	507
M8	276	434	616	721	797	941	1015	967	933	981	993	1103	1126	1208	1237	1302	165	134	182	235	234	332	398	468	172	118	240
M6	230	388	570	675	751	895	969	921	887	935	947	1057	1080	1162	1191	1256	101	101	137	150	201	272	313	380	86	58	184
NE18	465	623	805	910	986	1130	1204	1156	1122	1170	1182	1292	1315	1397	1426	1491	352	312	354	347	392	422	462	502	222	252	222
LN5	469	627	809	914	990	1134	1208	1160	1126	1174	1186	1296	1319	1401	1430	1495	326	300	375	428	427	525	591	661	336	291	476
NE1	643	801	983	1088	1164	1308	1382	1334	1300	1348	1360	1470	1493	1575	1604	1669	530	490	532	525	570	600	640	680	400	430	400
NE19	382	540	722	827	903	1047	1121	1073	1039	1087	1099	1209	1232	1314	1343	1408	256	256	293	237	280	345	332	399	194	231	174
NE17	572	730	912	1017	1093	1237	1311	1263	1229	1277	1289	1399	1422	1504	1533	1598	459	419	461	454	499	529	569	609	329	359	329
NE3	687	845	1027	1132	1208	1352	1426	1378	1344	1392	1404	1514	1537	1619	1648	1713	574	534	576	569	614	644	684	724	444	474	444
NE4	738	896	1078	1183	1259	1403	1477	1429	1395	1443	1455	1565	1588	1670	1699	1764	625	585	627	620	665	695	735	775	495	525	495
NE6	770	928	1110	1215	1291	1435	1509	1461	1427	1475	1487	1597	1620	1702	1731	1796	657	617	659	652	697	727	767	807	527	557	527
NE5	863	1021	1203	1308	1384	1528	1602	1554	1520	1568	1580	1690	1713	1795	1824	1889	750	710	752	745	790	820	860	900	620	650	620
NE15	598	756	938	1043	1119	1263	1337	1289	1255	1303	1315	1425	1448	1530	1559	1624	485	445	487	480	525	555	595	635	355	385	355
NE16	635	793	975	1080	1156	1300	1374	1326	1292	1340	1352	1462	1485	1567	1596	1661	522	482	524	517	562	592	632	672	392	422	392
NE13	533	691	873	978	1054	1198	1272	1224	1190	1238	1250	1360	1383	1465	1494	1559	420	380	422	415	460	490	530	570	290	320	290
NE12	580	738	920	1025	1101	1245	1319	1271	1237	1285	1297	1407	1430	1512	1541	1606	467	427	469	462	507	537	577	617	337	367	337
NE11	694	852	1034	1139	1215	1359	1433	1385	1351	1399	1411	1521	1544	1626	1655	1720	581	541	583	576	621	651	691	731	451	481	451
NE14	642	800	982	1087	1163	1307	1381	1333	1299	1347	1359	1469	1492	1574	1603	1668	529	489	531	524	569	599	639	679	399	429	399
NE8	654	812	994	1099	1175	1319	1393	1345	1311	1359	1371	1481	1504	1586	1615	1680	541	501	543	536	581	611	651	691	411	441	411
NE10	752	910	1092	1197	1273	1417	1491	1443	1409	1457	1469	1579	1602	1684	1713	1778	639	599	641	634	679	709	749	789	509	539	509
NE7	765	923	1105	1210	1286	1430	1504	1456	1422	1470	1482	1592	1615	1697	1726	1791	652	612	654	647	692	722	762	802	522	552	522
NE9	708	866	1048	1153	1229	1373	1447	1399	1365	1413	1425	1535	1558	1640	1669	1734	595	555	597	590	635	665	705	745	465	495	465
NE2	700	858	1040	1145	1221	1365	1439	1391	1357	1405	1417	1527	1550	1632	1661	1726	587	547	589	582	627	657	697	737	457	487	457
W7	88	245	428	532	609	753	827	778	746	793	805	915	939	1020	1049	1114	49	106	72	118	117	215	281	351	171	143	273
W6	53	211	393	498	574	718	792	744	711	758	770	880	904	985	1014	1079	101	144	112	154	153	251	317	387	207	179	309
W2	98	255	438	542	618	763	837	788	755	802	814	925	948	1029	1058	1124	37	81	93	138	137	235	301	371	191	163	293
W8	204	361	544	648	724	869	943	894	861	908	920	1030	1054	1135	1164	1230	89	80	127	167	180	277	343	413	188	160	286
W1	144	295	478	582	658	803	877	828	795	842	854	964	988	1069	1098	1164	181	221	239	210	209	307	373	443	263	235	365
W5	54	211	393	498	574	719	793	744	711	758	770	880	904	985	1014	1080	121	174	154	182	181	279	345	415	235	207	337
W4	0	158	340	445	521	666	740	691	658	705	716	827	851	932	961	1026	175	228	208	236	235	333	399	469	289	261	391
W3	158	0	183	288	364	508	582	534	500	548	560	670	693	775	804	869	332	385	365	393	392	490	556	626	446	418	548
S2	340	183	0	117	193	338	412	363	330	378	389	500	523	604	633	699	514	567	547	575	574	672	738	808	628	600	730
S11	445	288	117	0	219	226	300	296	356	406	415	525	549	630	659	725	619	672	652	680	679	777	843	913	733	705	835
S14	521	364	193	219	0	196	287	211	134	226	238	304	372	408	437	503	695	748	728	756	755	853	919	989	809	781	911
S7	666	508	338	226	196	0	87	86	245	221	283	403	366	486	515	581	840	893	873	901	900	998	1064	1134	954	926	1056
S9	740	582	412	300	287	87	0	176	336	312	370	494	453	577	606	671	914	967	947	975	974	1072	1138	1208	1028	1000	1130
S1	691	534	363	296	211	86	176	0	233	131	193	313	276	396	425	491	865	918	898	926	925	1023	1089	1159	979	951	1081
S4	658	500	330	356	134	245	336	233	0	123	99	161	233	266	295	360	832	885	865	893	892	990	1056	1126	946	918	1048
S3	705	548	378	406	226	221	312	131	123	0	56	176	140	260	288	355	879	932	912	940	939	1037	1103	1173	993	965	1095
S8	716	560	389	415	238	283	370	193	99	56	0	121	134	205	234	299	891	944	924	952	951	1049	1115	1185	1005	977	1107
S12	827	670	500	525	304	403	494	313	161	176	121	0	125	99	128	194	1001	1054	1034	1062	1061	1159	1225	1295	1115	1087	1217
S13	851	693	523	549	372	366	453	276	233	140	134	125	0	208	237	303	1025	1078	1058	1086	1085	1183	1249	1319	1139	1111	1241
S6	932	775	604	630	408	486	577	396	266	260	205	99	208	0	35	92	1106	1159	1139	1167	1166	1264	1330	1400	1220	1192	1322
S10	961	804	633	659	437	515	606	425	295	288	234	128	237	35	0	128	1135	1188	1168	1196	1195	1293	1359	1429	1249	1221	1351
S5	1026	869	699	725	503	581	671	491	360	355	299	194	303	92	128	0	1201	1254	1234	1262	1261	1359	1425	1495	1315	1287	1417
M2	175	332	514	619	695	840	914	865	832	879	891	1001	1025	1106	1135	1201	0	26	42	76	95	192	259	328	151	100	249
M3	228	385	567	672	748	893	967	918	885	932	944	1054	1078	1159	1188	1254	26	0	66	89	109	207	272	342	127	101	225
M4	208	365	547	652	728	873	947	898	865	912	924	1034	1058	1139	1168	1234	42	66	0	71	64	162	228	295	147	137	245
E8	236	393	575	680	756	901	975	926	893	940	952	1062	1086	1167	1196	1262	76	89	71	0	43	140	249	319	76	100	174
E6	235	392	574	679	755	900	974	925	892	939	951	1061	1085	1166	1195	1261	95	109	64	43	0	98	164	234	119	143	217
E2	333	490	672	777	853	998	1072	1023	990	1037	1049	1159	1183	1264	1293	1359	192	207	162	140	98	0	110	179	186	214	258
E7	399	556	738	843	919	1064	1138	1089	1056	1103	1115	1225	1249	1330	1359	1425	259	272	228	249	164	110	0	70	245	255	148
E5	469	626	808	913	989	1134	1208	1159	1126	1173	1185	1295	1319	1400	1429	1495	328	342	295	319	234	179	70	0	309	322	218
E3	289	446	628	733	809	954	1028	979	946	993	1005	1115	1139	1220	1249	1315	151	127	147	76	119	186	245	309	0	29	98
E4	261	418	600	705	781	926	1000	951	918	965	977	1087	1111	1192	1221	1287	100	101	137	100	143	214	255	322	29	0	127
E1	391	548	730	835	911	1056	1130	1081	1048	1095	1107	1217	1241	1322	1351	1417	249	225	245	174	217	258	148	218	98	127	0

Table A2: Distances between landfills and industrial estates in Thailand (km)

Industrial Estate	Landfill									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Lamphun	250	225	167	150	208	133	142	125	150	167
Pichit	467	425	417	325	283	225	158	133	100	200
KhonKaen	525	483	592	417	333	325	283	317	308	433
Saraburi1	642	600	608	508	458	400	333	317	292	358
Saraburi2	642	600	608	508	458	400	333	317	292	358
Ayutthaya1	642	600	583	508	467	400	342	308	275	325
Ayutthaya2	642	600	583	508	467	400	342	308	275	325
Ayutthaya3	642	600	583	508	467	400	342	308	275	325
Ratchaburi1	758	717	658	625	608	533	467	425	400	375
Ratchaburi2	758	717	658	625	608	533	467	425	400	375
SamutSakorn1	750	708	667	617	592	517	450	408	383	375
SamutSakorn2	750	708	667	617	592	517	450	408	383	375
SamutSakorn3	750	708	667	617	592	517	450	408	383	375
Pattani	1,517	1,475	1,433	1,383	1,350	1,275	1,217	1,183	1,150	1,150
Songkla	1,517	1,475	1,433	1,392	1,358	1,292	1,225	1,192	1,158	1,158
Bangkok1	725	683	667	592	550	492	425	392	358	392
Bangkok2	725	683	667	592	550	492	425	392	358	392
Bangkok3	725	683	667	592	550	492	425	392	358	392
Samutprakarn1	750	708	700	608	583	517	450	425	392	425
Samutprakarn2	750	708	700	608	583	517	450	425	392	425
Chachoengsao1	783	742	758	650	592	542	492	467	442	492
Chachoengsao2	783	742	758	650	592	542	492	467	442	492
Chachoengsao3	783	742	758	650	592	542	492	467	442	492
ChonBuri1	817	775	758	683	642	583	517	492	458	492
ChonBuri2	817	775	758	683	642	583	517	492	458	492
ChonBuri3	817	775	758	683	642	583	517	492	458	492
ChonBuri4	817	775	758	683	642	583	517	492	458	492
Rayong1	858	808	817	717	658	625	558	533	508	508
Rayong2	858	808	817	717	658	625	558	533	508	508
Rayong3	858	808	817	717	658	625	558	533	508	508
Rayong4	858	808	817	717	658	625	558	533	508	508
Rayong5	858	808	817	717	658	625	558	533	508	508
Rayong6	858	808	817	717	658	625	558	533	508	508
Rayong7	858	808	817	717	658	625	558	533	508	508
Rayong8	858	808	817	717	658	625	558	533	508	508

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Lamphun	192	242	308	292	367	400	417	417	450	533
Pichit	67	17	83	208	233	300	325	300	333	433
KhonKaen	283	233	150	167	92	150	167	117	125	242
Saraburi1	250	208	175	333	292	367	392	350	367	467
Saraburi2	250	208	175	333	292	367	392	350	367	467
Ayutthaya1	242	200	192	350	333	408	425	350	400	517
Ayutthaya2	242	200	192	350	333	408	425	350	400	517
Ayutthaya3	242	200	192	350	333	408	425	350	400	517
Ratchaburi1	350	342	358	517	508	575	600	567	583	692
Ratchaburi2	350	342	358	517	508	575	600	567	583	692
SamutSakorn1	342	317	325	483	458	533	558	517	533	642
SamutSakorn2	342	317	325	483	458	533	558	517	533	642
SamutSakorn3	342	317	325	483	458	533	558	517	533	642
Pattani	1,117	1,083	1,067	1,208	1,175	1,250	1,267	1,250	1,242	1,292
Songkla	1,125	1,092	1,075	1,225	1,192	1,275	1,292	1,275	1,258	1,325
Bangkok1	317	283	275	442	408	475	508	458	467	592
Bangkok2	317	283	275	442	408	475	508	458	467	592
Bangkok3	317	283	275	442	408	475	508	458	467	592
Samutprakarn1	358	317	300	450	425	492	517	467	483	583
Samutprakarn2	358	317	300	450	425	492	517	467	483	583
Chachoengsao1	400	358	317	467	417	492	500	458	458	558
Chachoengsao2	400	358	317	467	417	492	500	458	458	558
Chachoengsao3	400	358	317	467	417	492	500	458	458	558
ChonBuri1	417	383	358	517	483	550	567	525	533	633
ChonBuri2	417	383	358	517	483	550	567	525	533	633
ChonBuri3	417	383	358	517	483	550	567	525	533	633
ChonBuri4	417	383	358	517	483	550	567	525	533	633
Rayong1	475	425	392	533	483	542	558	525	525	625
Rayong2	475	425	392	533	483	542	558	525	525	625
Rayong3	475	425	392	533	483	542	558	525	525	625
Rayong4	475	425	392	533	483	542	558	525	525	625
Rayong5	475	425	392	533	483	542	558	525	525	625
Rayong6	475	425	392	533	483	542	558	525	525	625
Rayong7	475	425	392	533	483	542	558	525	525	625
Rayong8	475	425	392	533	483	542	558	525	525	625

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Lamphun	625	550	625	675	708	717	667	617	533	467
Pichit	483	408	458	483	492	500	442	417	358	292
KhonKaen	250	175	175	250	275	283	242	192	125	67
Saraburi1	483	408	417	417	400	400	342	350	350	300
Saraburi2	483	408	417	417	400	400	342	350	350	300
Ayutthaya1	533	450	475	467	458	450	392	400	392	333
Ayutthaya2	533	450	475	467	458	450	392	400	392	333
Ayutthaya3	533	450	475	467	458	450	392	400	392	333
Ratchaburi1	708	633	642	633	608	600	542	558	567	517
Ratchaburi2	708	633	642	633	608	600	542	558	567	517
SamutSakorn1	650	583	583	567	550	542	483	500	517	467
SamutSakorn2	650	583	583	567	550	542	483	500	517	467
SamutSakorn3	650	583	583	567	550	542	483	500	517	467
Pattani	1,250	1,208	1,167	1,108	1,033	1,025	992	1,058	1,142	1,125
Songkla	1,275	1,233	1,192	1,133	1,050	1,042	1,017	1,092	1,167	1,150
Bangkok1	583	508	517	500	475	467	408	433	408	408
Bangkok2	583	508	517	500	475	467	408	433	408	408
Bangkok3	583	508	517	500	475	467	408	433	408	408
Samutprakarn1	583	517	508	492	467	450	400	425	450	408
Samutprakarn2	583	517	508	492	467	450	400	425	450	408
Chachoengsao1	542	475	458	425	392	375	325	367	400	375
Chachoengsao2	542	475	458	425	392	375	325	367	400	375
Chachoengsao3	542	475	458	425	392	375	325	367	400	375
ChonBuri1	625	558	542	517	483	475	417	458	492	458
ChonBuri2	625	558	542	517	483	475	417	458	492	458
ChonBuri3	625	558	542	517	483	475	417	458	492	458
ChonBuri4	625	558	542	517	483	475	417	458	492	458
Rayong1	600	533	517	467	433	417	367	417	425	442
Rayong2	600	533	517	467	433	417	367	417	425	442
Rayong3	600	533	517	467	433	417	367	417	425	442
Rayong4	600	533	517	467	433	417	367	417	425	442
Rayong5	600	533	517	467	433	417	367	417	425	442
Rayong6	600	533	517	467	433	417	367	417	425	442
Rayong7	600	533	517	467	433	417	367	417	425	442
Rayong8	600	533	517	467	433	417	367	417	425	442

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	31	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**
Lamphun	433	375	483	517	450	442	442	450	408	567
Pichit	267	242	292	317	258	233	225	225	167	317
KhonKaen	42	50	50	83	25	25	42	58	83	183
Saraburi1	275	233	267	275	233	217	200	175	150	183
Saraburi2	275	233	267	275	233	217	200	175	150	183
Ayutthaya1	317	267	317	317	292	267	250	225	192	233
Ayutthaya2	317	267	317	317	292	267	250	225	192	233
Ayutthaya3	317	267	317	317	292	267	250	225	192	233
Ratchaburi1	500	450	492	492	458	442	425	400	367	383
Ratchaburi2	500	450	492	492	458	442	425	400	367	383
SamutSakorn1	442	400	442	442	408	392	375	350	317	325
SamutSakorn2	442	400	442	442	408	392	375	350	317	325
SamutSakorn3	442	400	442	442	408	392	375	350	317	325
Pattani	1,125	1,117	1,083	1,067	1,067	1,058	1,033	1,017	1,008	900
Songkla	1,150	1,142	1,100	1,083	1,092	1,083	1,058	1,042	1,025	933
Bangkok1	383	350	375	375	342	325	308	283	258	250
Bangkok2	383	350	375	375	342	325	308	283	258	250
Bangkok3	383	350	375	375	342	325	308	283	258	250
Samutprakarn1	392	350	375	375	350	333	317	292	267	242
Samutprakarn2	392	350	375	375	350	333	317	292	267	242
Chachoengsao1	375	350	342	333	325	308	292	267	258	175
Chachoengsao2	375	350	342	333	325	308	292	267	258	175
Chachoengsao3	375	350	342	333	325	308	292	267	258	175
ChonBuri1	450	408	417	417	408	383	367	342	325	267
ChonBuri2	450	408	417	417	408	383	367	342	325	267
ChonBuri3	450	408	417	417	408	383	367	342	325	267
ChonBuri4	450	408	417	417	408	383	367	342	325	267
Rayong1	433	417	408	392	392	375	358	333	333	242
Rayong2	433	417	408	392	392	375	358	333	333	242
Rayong3	433	417	408	392	392	375	358	333	333	242
Rayong4	433	417	408	392	392	375	358	333	333	242
Rayong5	433	417	408	392	392	375	358	333	333	242
Rayong6	433	417	408	392	392	375	358	333	333	242
Rayong7	433	417	408	392	392	375	358	333	333	242
Rayong8	433	417	408	392	392	375	358	333	333	242

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	41	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**
Lamphun	608	292	325	350	342	383	392	417	417	433
Pichit	367	58	108	117	100	133	133	192	175	183
KhonKaen	208	275	308	292	275	258	250	333	300	267
Saraburi1	233	167	158	125	108	75	58	117	83	25
Saraburi2	233	167	158	125	108	75	58	117	83	25
Ayutthaya1	292	142	108	83	83	50	42	58	25	17
Ayutthaya2	292	142	108	83	83	50	42	58	25	17
Ayutthaya3	292	142	108	83	83	50	42	58	25	17
Ratchaburi1	433	258	208	200	208	208	217	117	150	192
Ratchaburi2	433	258	208	200	208	208	217	117	150	192
SamutSakorn1	375	250	192	175	192	175	175	100	117	150
SamutSakorn2	375	250	192	175	192	175	175	100	117	150
SamutSakorn3	375	250	192	175	192	175	175	100	117	150
Pattani	917	1,017	967	942	958	925	933	875	883	883
Songkla	942	1,033	975	950	958	933	933	875	883	892
Bangkok1	308	225	183	167	167	142	142	100	100	100
Bangkok2	308	225	183	167	167	142	142	100	100	100
Bangkok3	308	225	183	167	167	142	142	100	100	100
Samutprakarn1	283	258	217	192	192	158	167	133	117	108
Samutprakarn2	283	258	217	192	192	158	167	133	117	108
Chachoengsao1	175	308	283	258	250	217	208	208	183	158
Chachoengsao2	175	308	283	258	250	217	208	208	183	158
Chachoengsao3	175	308	283	258	250	217	208	208	183	158
ChonBuri1	308	317	283	258	258	233	225	192	183	183
ChonBuri2	308	317	283	258	258	233	225	192	183	183
ChonBuri3	308	317	283	258	258	233	225	192	183	183
ChonBuri4	308	317	283	258	258	233	225	192	183	183
Rayong1	267	375	342	317	317	275	275	258	250	225
Rayong2	267	375	342	317	317	275	275	258	250	225
Rayong3	267	375	342	317	317	275	275	258	250	225
Rayong4	267	375	342	317	317	275	275	258	250	225
Rayong5	267	375	342	317	317	275	275	258	250	225
Rayong6	267	375	342	317	317	275	275	258	250	225
Rayong7	267	375	342	317	317	275	275	258	250	225
Rayong8	267	375	342	317	317	275	275	258	250	225

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	51	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**
Lamphun	450	475	500	483	517	525	542	483	467	450
Pichit	258	267	292	267	292	300	317	250	242	225
KhonKaen	417	417	425	392	417	408	433	367	350	325
Saraburi1	192	175	183	158	175	167	192	125	108	92
Saraburi2	192	175	183	158	175	167	192	125	108	92
Ayutthaya1	133	125	133	108	133	125	158	83	67	42
Ayutthaya2	133	125	133	108	133	125	158	83	67	42
Ayutthaya3	133	125	133	108	133	125	158	83	67	42
Ratchaburi1	58	50	25	67	58	75	50	92	108	125
Ratchaburi2	58	50	25	67	58	75	50	92	108	125
SamutSakorn1	83	50	25	33	2	8	17	42	58	83
SamutSakorn2	83	50	25	33	2	8	17	42	58	83
SamutSakorn3	83	50	25	33	2	8	17	42	58	83
Pattani	833	817	783	800	767	767	750	808	817	833
Songkla	833	817	783	800	767	767	750	808	817	833
Bangkok1	133	92	92	75	67	50	83	42	42	58
Bangkok2	133	92	92	75	67	50	83	42	42	58
Bangkok3	133	92	92	75	67	50	83	42	42	58
Samutprakarn1	167	125	117	100	92	75	108	75	75	92
Samutprakarn2	167	125	117	100	92	75	108	75	75	92
Chachoengsao1	250	217	208	200	175	167	192	158	167	167
Chachoengsao2	250	217	208	200	175	167	192	158	167	167
Chachoengsao3	250	217	208	200	175	167	192	158	167	167
ChonBuri1	200	167	142	150	117	100	125	125	133	142
ChonBuri2	200	167	142	150	117	100	125	125	133	142
ChonBuri3	200	167	142	150	117	100	125	125	133	142
ChonBuri4	200	167	142	150	117	100	125	125	133	142
Rayong1	275	242	225	175	200	183	200	200	208	217
Rayong2	275	242	225	175	200	183	200	200	208	217
Rayong3	275	242	225	175	200	183	200	200	208	217
Rayong4	275	242	225	175	200	183	200	200	208	217
Rayong5	275	242	225	175	200	183	200	200	208	217
Rayong6	275	242	225	175	200	183	200	200	208	217
Rayong7	275	242	225	175	200	183	200	200	208	217
Rayong8	275	242	225	175	200	183	200	200	208	217

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	61	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**
Lamphun	458	467	492	525	550	575	567	583	583	600
Pichit	217	217	250	267	292	317	325	333	333	358
KhonKaen	317	292	333	283	333	333	358	375	383	400
Saraburi1	83	50	92	75	117	133	142	150	158	175
Saraburi2	83	50	92	75	117	133	142	150	158	175
Ayutthaya1	33	33	58	100	117	142	133	142	150	167
Ayutthaya2	33	33	58	100	117	142	133	142	150	167
Ayutthaya3	33	33	58	100	117	142	133	142	150	167
Ratchaburi1	133	167	142	217	175	208	175	167	167	183
Ratchaburi2	133	167	142	217	175	208	175	167	167	183
SamutSakorn1	92	108	83	158	117	150	117	117	108	117
SamutSakorn2	92	108	83	158	117	150	117	117	108	117
SamutSakorn3	92	108	83	158	117	150	117	117	108	117
Pattani	842	842	808	817	775	767	733	725	717	708
Songkla	842	842	808	825	783	775	742	742	733	725
Bangkok1	58	58	8	75	50	92	67	75	75	92
Bangkok2	58	58	8	75	50	92	67	75	75	92
Bangkok3	58	58	8	75	50	92	67	75	75	92
Samutprakarn1	92	75	42	75	25	58	33	42	42	50
Samutprakarn2	92	75	42	75	25	58	33	42	42	50
Chachoengsao1	158	133	117	75	58	25	58	67	83	92
Chachoengsao2	158	133	117	75	58	25	58	67	83	92
Chachoengsao3	158	133	117	75	58	25	58	67	83	92
ChonBuri1	150	150	117	117	67	75	42	25	17	4
ChonBuri2	150	150	117	117	67	75	42	25	17	4
ChonBuri3	150	150	117	117	67	75	42	25	17	4
ChonBuri4	150	150	117	117	67	75	42	25	17	4
Rayong1	217	192	175	150	108	83	92	83	92	83
Rayong2	217	192	175	150	108	83	92	83	92	83
Rayong3	217	192	175	150	108	83	92	83	92	83
Rayong4	217	192	175	150	108	83	92	83	92	83
Rayong5	217	192	175	150	108	83	92	83	92	83
Rayong6	217	192	175	150	108	83	92	83	92	83
Rayong7	217	192	175	150	108	83	92	83	92	83
Rayong8	217	192	175	150	108	83	92	83	92	83

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	71	**72**	**73**	**74**	**75**	**76**	**77**	**78**	**79**	**80**
Lamphun	617	625	642	650	692	725	758	633	600	633
Pichit	375	383	400	400	433	467	500	367	383	417
KhonKaen	417	433	442	408	408	433	458	308	492	517
Saraburi1	192	200	217	208	242	275	300	183	258	283
Saraburi2	192	200	217	208	242	275	300	183	258	283
Ayutthaya1	183	192	208	217	258	283	317	217	217	250
Ayutthaya2	183	192	208	217	258	283	317	217	217	250
Ayutthaya3	183	192	208	217	258	283	317	217	217	250
Ratchaburi1	200	208	225	242	283	308	350	308	83	108
Ratchaburi2	200	208	225	242	283	308	350	308	83	108
SamutSakorn1	133	150	167	183	250	275	308	242	92	117
SamutSakorn2	133	150	167	183	250	275	308	242	92	117
SamutSakorn3	133	150	167	183	250	275	308	242	92	117
Pattani	692	683	658	675	675	650	633	775	692	658
Songkla	708	692	675	700	700	675	658	800	700	658
Bangkok1	100	108	125	150	192	217	250	183	150	192
Bangkok2	100	108	125	150	192	217	250	183	150	192
Bangkok3	100	108	125	150	192	217	250	183	150	192
Samutprakarn1	58	75	100	108	158	192	225	158	167	208
Samutprakarn2	58	75	100	108	158	192	225	158	167	208
Chachoengsao1	100	108	117	67	92	117	158	67	267	317
Chachoengsao2	100	108	117	67	92	117	158	67	267	317
Chachoengsao3	100	108	117	67	92	117	158	67	267	317
ChonBuri1	8	17	42	67	75	67	175	158	125	133
ChonBuri2	8	17	42	67	75	67	175	158	125	133
ChonBuri3	8	17	42	67	75	67	175	158	125	133
ChonBuri4	8	17	42	67	75	67	175	158	125	133
Rayong1	92	83	58	8	33	58	92	100	208	208
Rayong2	92	83	58	8	33	58	92	100	208	208
Rayong3	92	83	58	8	33	58	92	100	208	208
Rayong4	92	83	58	8	33	58	92	100	208	208
Rayong5	92	83	58	8	33	58	92	100	208	208
Rayong6	92	83	58	8	33	58	92	100	208	208
Rayong7	92	83	58	8	33	58	92	100	208	208
Rayong8	92	83	58	8	33	58	92	100	208	208

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	81	**82**	**83**	**84**	**85**	**86**	**87**	**88**	**89**	**90**
Lamphun	842	917	1,017	1,083	1,092	1,100	1,083	1,117	1,175	1,192
Pichit	650	725	808	875	875	917	900	925	967	983
KhonKaen	750	817	858	933	933	1,025	1,000	1,008	1,042	1,050
Saraburi1	517	592	667	708	717	792	767	783	825	833
Saraburi2	517	592	667	708	717	792	767	783	825	833
Ayutthaya1	475	550	625	667	675	750	725	742	783	792
Ayutthaya2	475	550	625	667	675	750	725	742	783	792
Ayutthaya3	475	550	625	667	675	750	725	742	783	792
Ratchaburi1	333	408	492	567	575	608	600	608	658	675
Ratchaburi2	333	408	492	567	575	608	600	608	658	675
SamutSakorn1	358	425	517	567	583	625	608	625	675	683
SamutSakorn2	358	425	517	567	583	625	608	625	675	683
SamutSakorn3	358	425	517	567	583	625	608	625	675	683
Pattani	483	417	325	233	208	358	367	300	242	192
Songkla	483	400	308	217	200	317	325	258	158	150
Bangkok1	433	508	583	625	633	708	683	700	742	750
Bangkok2	433	508	583	625	633	708	683	700	742	750
Bangkok3	433	508	583	625	633	708	683	700	742	750
Samutprakarn1	467	542	617	658	667	742	717	733	775	783
Samutprakarn2	467	542	617	658	667	742	717	733	775	783
Chachoengsao1	558	633	708	750	758	833	808	825	867	875
Chachoengsao2	558	633	708	750	758	833	808	825	867	875
Chachoengsao3	558	633	708	750	758	833	808	825	867	875
ChonBuri1	517	583	667	708	717	783	775	775	800	808
ChonBuri2	517	583	667	708	717	783	775	775	800	808
ChonBuri3	517	583	667	708	717	783	775	775	800	808
ChonBuri4	517	583	667	708	717	783	775	775	800	808
Rayong1	600	675	750	792	800	875	850	867	908	917
Rayong2	600	675	750	792	800	875	850	867	908	917
Rayong3	600	675	750	792	800	875	850	867	908	917
Rayong4	600	675	750	792	800	875	850	867	908	917
Rayong5	600	675	750	792	800	875	850	867	908	917
Rayong6	600	675	750	792	800	875	850	867	908	917
Rayong7	600	675	750	792	800	875	850	867	908	917
Rayong8	600	675	750	792	800	875	850	867	908	917

Table A2: Distances between landfills and industrial estates in Thailand (km) (continue)

Industrial Estate	Landfill									
	91	**92**	**93**	**94**	**95**	**96**	**97**	**98**	**99**	**100**
Lamphun	1,183	1,250	1,258	1,267	1,275	1,300	1,292	1,325	1,408	1,375
Pichit	967	1,017	1,033	1,042	1,058	1,075	1,058	1,092	1,175	1,133
KhonKaen	1,017	1,058	1,083	1,083	1,117	1,125	1,067	1,117	1,200	1,142
Saraburi1	817	850	875	875	908	908	875	908	1,000	958
Saraburi2	817	850	875	875	908	908	875	908	1,000	958
Ayutthaya1	775	808	833	833	867	867	833	867	958	917
Ayutthaya2	775	808	833	833	867	867	833	867	958	917
Ayutthaya3	775	808	833	833	867	867	833	867	958	917
Ratchaburi1	658	717	733	742	758	775	783	792	883	875
Ratchaburi2	658	717	733	742	758	775	783	792	883	875
SamutSakorn1	667	725	742	750	767	783	792	808	892	883
SamutSakorn2	667	725	742	750	767	783	792	808	892	883
SamutSakorn3	667	725	742	750	767	783	792	808	892	883
Pattani	150	75	92	75	133	100	17	25	117	100
Songkla	117	50	42	33	75	33	75	75	100	142
Bangkok1	733	767	792	792	825	825	792	825	917	875
Bangkok2	733	767	792	792	825	825	792	825	917	875
Bangkok3	733	767	792	792	825	825	792	825	917	875
Samutprakarn1	767	800	825	825	858	858	825	858	950	908
Samutprakarn2	767	800	825	825	858	858	825	858	950	908
Chachoengsao1	858	892	917	917	950	950	917	950	1,042	1,000
Chachoengsao2	858	892	917	917	950	950	917	950	1,042	1,000
Chachoengsao3	858	892	917	917	950	950	917	950	1,042	1,000
ChonBuri1	792	842	867	867	900	900	875	900	1,000	958
ChonBuri2	792	842	867	867	900	900	875	900	1,000	958
ChonBuri3	792	842	867	867	900	900	875	900	1,000	958
ChonBuri4	792	842	867	867	900	900	875	900	1,000	958
Rayong1	900	933	958	958	992	992	958	992	1,083	1,042
Rayong2	900	933	958	958	992	992	958	992	1,083	1,042
Rayong3	900	933	958	958	992	992	958	992	1,083	1,042
Rayong4	900	933	958	958	992	992	958	992	1,083	1,042
Rayong5	900	933	958	958	992	992	958	992	1,083	1,042
Rayong6	900	933	958	958	992	992	958	992	1,083	1,042
Rayong7	900	933	958	958	992	992	958	992	1,083	1,042
Rayong8	900	933	958	958	992	992	958	992	1,083	1,042

Table A3: Distances between provinces and landfills (km)

	UN1	UN2	UN3	UN4	UN5	UN6	UN7	UN8	UN9	LN1	LN2	LN3	LN4	LN5	LN6	LN7	LN8
lf1	49	123	189	288	230	263	205	205	255	329	370	370	444	468	510	436	542
lf2	16	82	156	247	181	230	177	164	173	288	329	329	403	427	468	395	501
lf3	230	238	304	329	255	49	90	197	164	279	370	255	411	468	452	362	452
lf4	74	33	90	164	95	214	140	82	148	197	238	255	312	337	378	304	415
lf5	95	74	12	115	95	296	222	132	205	197	197	279	279	284	353	296	407
lf6	185	115	99	62	8	238	173	66	156	107	132	189	214	238	279	214	321
lf7	247	173	148	33	66	263	197	99	132	58	74	156	148	181	214	148	255
lf8	279	222	205	95	111	247	197	127	123	4	82	95	115	173	173	99	210
lf9	312	238	226	103	132	263	222	148	148	33	74	99	90	156	148	78	185
lf10	378	329	337	238	230	226	222	214	160	132	214	45	193	279	197	107	173
lf11	345	279	247	123	164	308	259	189	189	74	74	123	58	123	111	90	156
lf12	370	304	263	148	197	353	312	230	234	115	66	168	16	74	82	90	156
lf13	399	333	271	160	234	427	370	275	296	185	90	255	86	8	132	173	214
lf14	353	288	230	132	181	822	822	255	288	205	132	304	205	164	271	267	345
lf15	822	822	822	189	263	822	822	312	362	271	177	362	230	160	284	300	362
lf16	822	822	822	230	304	353	822	362	822	316	230	411	292	234	353	366	427
lf17	822	822	822	263	337	822	822	822	822	337	255	427	321	255	378	386	452
lf18	822	822	822	263	337	822	822	822	822	329	238	822	292	222	345	370	822
lf19	822	822	822	296	370	822	822	822	822	362	267	822	321	255	370	390	822
lf20	822	822	822	822	822	822	822	822	822	822	822	822	822	358	822	822	822
lf21	822	822	822	822	822	822	822	822	822	822	822	822	822	399	822	822	822
lf22	822	822	822	822	822	822	822	822	822	822	362	822	822	325	822	822	822
lf23	822	822	822	822	822	822	822	822	822	822	822	822	822	370	822	822	822
lf24	822	822	822	822	822	822	822	822	822	822	822	822	822	395	822	822	822
lf25	822	822	822	822	822	822	822	822	822	822	822	822	822	411	822	822	822
lf26	822	822	822	822	822	822	822	822	822	822	822	822	822	423	822	822	822
lf27	822	822	822	822	822	822	822	822	822	822	822	822	822	370	822	822	822
lf28	822	822	822	822	822	822	822	822	822	822	822	822	822	333	822	822	822
lf29	822	822	822	349	822	822	822	822	822	427	329	822	358	275	390	822	822
lf30	822	822	822	288	362	822	822	822	822	366	267	822	292	214	329	378	415
lf31	822	822	822	263	337	822	822	822	822	337	238	822	267	185	304	345	386
lf32	822	822	822	205	279	822	822	822	822	271	168	349	197	119	238	275	316
lf33	822	822	822	312	386	822	822	822	822	378	275	822	288	210	321	374	399
lf34	822	822	822	337	411	822	822	822	822	403	304	822	312	230	341	399	415
lf35	822	822	822	279	353	822	822	822	822	341	242	822	255	173	288	337	366
lf36	822	822	822	271	345	822	822	822	822	329	230	822	236	156	267	321	343
lf37	822	822	822	275	349	822	822	822	822	329	230	822	226	148	255	312	329
lf38	822	822	822	288	362	822	822	822	822	333	234	822	230	148	247	312	321
lf39	822	822	822	255	329	822	822	822	822	288	193	353	177	99	197	259	271
lf40	822	822	822	822	822	822	822	822	822	822	822	822	822	255	316	822	822
lf41	822	822	822	822	822	822	822	822	822	822	822	822	822	296	366	822	822
lf42	444	374	341	214	263	390	358	292	279	164	140	185	58	119	12	82	82
lf43	822	822	390	263	312	822	822	337	321	205	193	218	107	156	37	115	53
lf44	822	822	407	279	329	822	822	353	345	230	205	238	115	156	49	136	74
lf45	822	822	390	271	321	822	822	349	345	222	193	242	107	136	45	140	90
lf46	822	822	822	288	349	822	822	378	374	259	214	279	132	140	82	173	123
lf47	822	822	822	288	349	822	822	382	378	263	214	288	136	136	82	181	136
lf48	822	822	822	353	403	822	822	822	822	308	279	300	189	181	123	205	111
lf49	822	822	822	345	395	822	822	822	822	304	263	308	181	193	119	205	132
lf50	822	822	822	341	403	822	822	822	822	321	263	341	185	173	140	234	177

Table A3: Distances between provinces and landfills (continue)

	UN1	UN2	UN3	UN4	UN5	UN6	UN7	UN8	UN9	LN1	LN2	LN3	LN4	LN5	LN6	LN7	LN8
lf51	822	822	822	822	822	822	822	822	822	356	341	329	255	288	185	247	136
lf52	822	822	822	822	822	822	822	822	822	374	358	358	267	292	201	271	168
lf53	822	822	822	822	822	822	822	822	822	399	378	382	288	321	222	292	189
lf54	822	822	822	822	822	822	822	822	822	382	353	370	263	288	201	275	177
lf55	822	822	822	822	822	822	822	822	822	415	386	403	296	312	230	308	205
lf56	822	822	822	822	822	822	822	822	822	419	386	411	298	312	234	312	218
lf57	822	822	822	822	822	822	822	822	822	427	403	419	316	335	247	329	222
lf58	822	822	822	822	822	822	822	822	822	370	337	370	251	263	185	271	177
lf59	822	822	822	822	822	822	822	822	822	362	325	366	238	247	173	263	167
lf60	822	822	822	822	822	822	822	822	822	345	302	345	218	224	156	247	156
lf61	822	822	822	822	822	822	822	822	822	345	300	348	218	221	156	247	160
lf62	822	822	822	822	822	822	822	822	822	353	296	370	222	210	168	263	189
lf63	822	822	822	822	822	822	822	822	822	382	329	389	251	247	193	284	205
lf64	822	822	822	822	822	822	822	822	822	822	337	822	267	240	226	323	259
lf65	822	822	822	822	822	822	822	822	822	822	370	822	296	275	247	341	263
lf66	822	822	822	822	822	822	822	822	822	822	386	822	316	292	271	370	296
lf67	822	822	822	822	822	822	822	822	822	822	822	822	321	304	270	362	279
lf68	822	822	822	822	822	822	822	822	822	822	822	822	333	318	279	370	288
lf69	822	822	822	822	822	822	822	822	822	822	822	822	337	325	279	370	288
lf70	822	822	822	822	822	822	822	822	822	822	822	822	349	337	292	382	296
lf71	822	822	822	822	822	822	822	822	822	822	822	822	359	349	304	395	304
lf72	822	822	822	822	822	822	822	822	822	822	822	822	370	362	316	407	316
lf73	822	822	822	822	822	822	822	822	822	822	822	822	395	382	339	427	341
lf74	822	822	822	822	822	822	822	822	822	822	822	822	822	370	349	822	362
lf75	822	822	822	822	822	822	822	822	822	822	822	822	822	407	386	822	407
lf76	822	822	822	822	822	822	822	822	822	822	822	822	822	427	415	822	432
lf77	822	822	822	822	822	822	822	822	822	822	822	822	822	458	448	822	464
lf78	822	822	822	822	822	822	822	822	822	822	822	822	822	321	335	822	372
lf79	822	822	822	822	822	822	822	822	822	822	822	822	822	395	312	822	282
lf80	822	822	822	822	822	822	822	822	822	822	822	822	822	427	345	822	312
lf81	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf82	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf83	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf84	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf85	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf86	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf87	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf88	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf89	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf90	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf91	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf92	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf93	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf94	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf95	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf96	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf97	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf98	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf99	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf100	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822

Table A3: Distances between provinces and landfills (continue)

	NE1	NE2	NE3	NE4	NE5	NE6	NE7	NE8	NE9	NE10	NE11	NE12	NE13	NE14	NE15	NE16	NE17	NE18	NE19
lf1	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf2	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf3	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf4	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf5	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf6	181	255	329	822	822	822	822	822	822	822	822	822	822	822	822	822	822	288	822
lf7	156	230	288	304	822	822	822	822	822	822	822	822	822	822	822	822	296	238	822
lf8	197	263	329	822	822	822	822	822	822	822	822	822	822	822	822	822	321	255	822
lf9	189	263	329	822	822	822	822	822	822	822	822	822	822	822	822	822	312	238	329
lf10	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf11	185	255	321	822	822	822	822	822	822	822	822	822	822	822	337	822	288	205	288
lf12	164	222	288	337	822	822	822	822	822	822	822	822	329	822	292	822	238	160	242
lf13	123	148	214	271	378	296	362	337	386	444	378	308	259	296	205	284	156	74	181
lf14	25	82	132	156	296	222	321	337	382	452	419	362	345	255	230	292	181	173	296
lf15	66	6	74	123	238	160	251	263	304	378	341	288	279	181	152	214	107	123	247
lf16	115	70	41	53	197	123	234	267	304	382	362	325	329	177	195	238	160	197	312
lf17	136	90	49	33	181	111	228	271	304	382	370	329	345	177	205	242	177	218	329
lf18	123	58	12	66	181	99	205	230	267	349	325	288	296	142	156	201	132	178	288
lf19	156	82	21	70	144	66	173	201	238	321	304	271	288	115	152	178	136	197	292
lf20	255	189	123	86	82	62	168	230	251	333	345	337	374	152	234	234	234	263	386
lf21	325	247	181	178	16	95	86	164	168	242	275	288	345	127	224	193	255	333	386
lf22	251	173	111	127	62	37	90	148	164	247	255	242	284	62	156	140	177	252	318
lf23	321	247	197	222	99	127	41	74	78	156	181	201	263	74	164	111	210	294	321
lf24	374	296	255	288	173	197	74	45	4	82	119	160	234	123	181	103	233	315	312
lf25	419	341	304	353	242	263	148	86	63	33	66	132	214	178	205	127	259	333	304
lf26	423	353	321	370	267	284	168	107	90	41	49	123	201	197	214	144	269	341	300
lf27	386	316	296	349	271	271	168	95	103	95	16	68	148	177	168	107	230	288	244
lf28	321	251	218	267	181	189	95	16	62	119	99	103	173	95	121	45	173	252	247
lf29	230	148	107	156	127	82	90	111	148	226	210	187	222	21	90	82	119	201	255
lf30	173	99	78	144	177	111	156	156	201	271	238	197	210	82	66	115	60	140	214
lf31	144	74	82	148	203	132	185	181	230	296	261	205	210	115	74	136	45	115	205
lf32	99	66	119	181	269	193	255	247	296	358	310	247	222	181	119	195	66	62	181
lf33	197	127	119	189	201	144	164	140	189	251	214	156	173	90	25	90	41	127	181
lf34	226	156	148	210	205	156	148	115	160	224	177	127	148	82	16	58	70	152	178
lf35	164	107	123	189	230	164	197	173	222	285	236	173	168	123	45	119	7	95	164
lf36	164	115	136	205	255	185	214	189	238	296	242	177	160	144	58	136	8	74	144
lf37	173	132	156	226	271	205	230	197	247	300	242	173	148	160	66	144	31	66	123
lf38	189	148	181	251	288	226	242	201	251	300	236	164	132	177	78	148	53	66	103
lf39	173	152	201	263	326	259	288	255	300	251	284	208	160	218	127	197	86	33	95
lf40	321	275	292	358	349	312	267	201	234	247	160	90	58	230	144	156	168	189	90
lf41	345	292	296	362	329	304	242	168	197	205	115	45	41	214	148	136	187	222	140
lf42	238	284	353	822	822	822	822	822	822	822	822	822	329	822	822	822	275	189	230
lf43	288	325	386	822	822	822	822	822	822	822	822	822	329	822	822	822	304	222	230
lf44	292	321	386	822	822	822	822	822	822	822	822	822	312	822	822	822	296	214	214
lf45	271	304	362	822	822	822	822	822	822	822	822	822	296	822	822	822	271	189	193
lf46	279	296	358	822	822	822	822	822	822	822	822	822	259	822	822	822	255	181	160
lf47	271	288	349	822	822	822	822	822	822	822	822	822	247	822	822	822	242	173	148
lf48	358	378	822	822	822	822	822	822	822	822	822	822	312	822	822	822	337	259	218
lf49	329	345	822	822	822	822	822	822	822	822	822	822	271	822	822	822	300	226	181
lf50	308	312	822	822	822	822	822	822	822	822	822	822	214	822	822	822	255	185	127

Table A3: Distances between provinces and landfills (continue)

	NE1	NE2	NE3	NE4	NE5	NE6	NE7	NE8	NE9	NE10	NE11	NE12	NE13	NE14	NE15	NE16	NE17	NE18	NE19
lf51	822	822	822	822	822	822	822	822	822	822	822	822	366	822	822	822	822	333	286
lf52	822	822	822	822	822	822	822	822	822	822	822	822	353	822	822	822	822	331	269
lf53	822	822	822	822	822	822	822	822	822	822	822	822	353	822	822	822	822	341	274
lf54	822	822	822	822	822	822	822	822	822	822	822	822	329	822	822	822	822	316	251
lf55	822	822	822	822	822	822	822	822	822	822	822	822	333	822	822	822	822	337	255
lf56	822	822	822	822	822	822	822	822	822	822	822	822	321	822	822	822	822	329	248
lf57	822	822	822	822	822	822	822	822	822	822	822	822	345	822	822	822	822	353	277
lf58	822	822	822	822	822	822	822	822	822	822	822	378	296	822	372	822	353	288	216
lf59	822	822	822	822	822	822	822	822	822	822	822	368	290	822	364	822	341	274	205
lf60	822	822	822	822	822	822	822	822	822	822	822	362	279	822	349	822	325	255	193
lf61	822	822	822	822	822	822	822	822	822	822	822	349	261	822	337	822	312	244	181
lf62	341	353	822	822	822	822	822	822	822	822	822	312	226	822	304	822	285	222	144
lf63	378	390	822	822	822	822	822	822	822	822	822	331	249	822	335	822	316	259	173
lf64	362	351	822	822	822	822	822	822	822	822	325	259	177	822	276	316	271	226	111
lf65	822	822	822	822	822	822	822	822	822	822	822	300	218	822	329	822	321	275	164
lf66	822	822	822	822	822	822	822	822	822	822	822	275	197	822	316	822	318	275	159
lf67	822	822	822	822	822	822	822	822	822	822	822	308	238	822	822	822	822	304	189
lf68	822	822	822	822	822	822	822	822	822	822	822	327	247	822	822	822	822	316	201
lf69	822	822	822	822	822	822	822	822	822	822	822	345	267	822	822	822	822	329	218
lf70	822	822	822	822	822	822	822	822	822	822	822	355	279	822	822	822	822	341	230
lf71	822	822	822	822	822	822	822	822	822	822	822	354	284	822	822	822	822	349	238
lf72	822	822	822	822	822	822	822	822	822	822	822	360	288	822	822	822	822	359	245
lf73	822	822	822	822	822	822	822	822	822	822	822	366	288	822	822	822	822	378	260
lf74	822	822	822	822	822	822	822	822	822	822	822	318	249	822	822	822	822	353	230
lf75	822	822	822	822	822	822	822	822	822	822	822	304	238	822	822	822	822	370	242
lf76	822	822	822	822	822	822	822	822	822	822	822	329	255	822	822	822	822	397	267
lf77	822	822	822	822	822	822	822	822	822	822	822	362	271	822	822	822	822	423	292
lf78	822	822	822	822	822	822	822	822	822	822	263	197	95	822	271	288	289	279	110
lf79	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	370
lf80	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	403
lf81	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf82	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf83	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf84	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf85	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf86	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf87	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf88	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf89	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf90	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf91	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf92	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf93	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf94	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf95	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf96	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf97	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf98	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf99	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf100	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822

Table A3: Distances between provinces and landfills (continue)

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	W1	W2	W3	W4	W5	W6	W7	W8
lf1	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf2	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf3	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf4	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf5	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf6	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf7	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf8	822	822	822	822	288	316	255	263	329	230	312	822	822	822	822	822	822	288
lf9	822	822	822	822	263	288	226	234	300	205	288	822	822	822	822	822	822	263
lf10	822	822	822	822	292	345	263	304	337	226	247	337	822	822	822	822	822	279
lf11	325	304	300	341	226	251	193	193	263	173	259	304	822	822	822	822	822	226
lf12	288	275	263	308	193	210	160	152	230	148	255	279	822	822	337	333	316	205
lf13	288	275	255	263	197	181	177	132	222	181	300	288	822	822	341	341	316	222
lf14	822	822	822	822	353	337	333	288	378	333	822	822	822	822	822	822	822	822
lf15	822	822	822	822	822	312	822	822	822	822	822	822	822	822	822	822	822	822
lf16	822	822	822	822	822	822	822	822	822	329	822	822	822	822	822	822	822	822
lf17	822	822	822	822	822	822	822	822	822	403	822	822	822	822	822	822	822	822
lf18	822	822	822	822	822	822	378	325	822	427	822	822	822	822	822	822	822	822
lf19	822	822	822	822	822	822	403	341	822	395	822	822	822	822	822	822	822	822
lf20	822	822	822	822	822	822	822	822	822	415	822	822	822	822	822	822	822	822
lf21	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf22	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf23	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf24	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf25	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf26	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf27	822	822	822	822	822	822	822	358	403	822	822	822	822	822	822	822	822	822
lf28	822	822	822	822	822	822	822	353	411	822	822	822	822	822	822	822	822	822
lf29	822	822	822	822	822	358	403	331	411	822	822	822	822	822	822	822	822	822
lf30	822	822	378	419	353	312	348	279	362	366	822	822	822	822	822	822	822	822
lf31	822	822	362	403	337	292	321	259	345	337	822	822	822	822	822	822	822	822
lf32	822	822	316	366	325	247	263	205	296	279	822	370	822	822	822	822	390	822
lf33	382	386	345	390	337	288	329	259	337	353	822	822	822	822	822	822	822	370
lf34	382	386	349	386	345	288	337	267	341	366	822	822	822	822	822	822	822	378
lf35	353	356	321	366	304	255	292	228	310	316	822	382	822	822	822	822	399	341
lf36	337	337	304	345	284	238	275	210	290	296	822	366	822	822	822	822	378	321
lf37	321	316	284	329	263	222	257	189	271	279	822	345	822	822	822	822	358	304
lf38	292	296	263	304	247	197	242	173	251	271	822	329	822	822	822	822	337	284
lf39	263	288	234	279	210	168	197	132	218	222	337	292	822	822	822	337	308	242
lf40	271	288	247	271	267	201	275	214	247	312	822	321	822	822	822	337	308	304
lf41	312	329	288	312	316	251	325	263	296	362	822	362	822	822	822	378	353	353
lf42	222	205	201	247	127	160	14	115	164	74	181	205	822	308	255	263	247	132
lf43	185	160	164	201	90	140	58	107	127	33	132	156	822	267	205	214	201	82
lf44	160	140	144	181	66	115	35	90	104	8	136	140	822	255	197	197	181	66
lf45	164	148	140	189	70	107	37	74	99	29	156	150	822	267	210	210	189	78
lf46	136	123	115	156	41	66	25	41	74	58	168	136	822	255	205	189	168	72
lf47	140	127	115	160	49	66	41	25	80	70	183	144	822	263	210	197	173	86
lf48	95	70	86	111	41	99	55	74	66	66	107	62	822	181	119	121	107	66
lf49	95	74	66	111	2	63	37	80	33	71	144	82	822	203	152	140	119	33
lf50	99	99	66	115	58	78	68	49	45	111	197	123	822	234	193	164	140	90

Table A3: Distances between provinces and landfills (continue)

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	W1	W2	W3	W4	W5	W6	W7	W8
lf51	122	95	132	136	115	168	127	191	119	123	58	58	251	126	62	90	103	78
lf52	86	62	103	99	108	154	130	182	101	140	97	25	228	105	45	58	64	85
lf53	78	60	106	86	123	160	148	196	107	160	163	33	205	86	41	37	47	101
lf54	60	37	81	75	99	136	126	173	82	139	164	7	222	108	66	48	41	82
lf55	55	48	86	62	125	148	155	192	99	173	147	36	197	86	64	16	19	111
lf56	45	44	79	48	123	140	155	189	95	173	159	48	197	95	78	17	7	115
lf57	76	70	107	74	148	244	175	218	123	189	156	56	245	62	56	2	33	132
lf58	36	7	48	58	77	103	107	144	52	130	141	29	259	136	97	66	48	72
lf59	41	16	41	62	62	90	95	130	41	119	142	37	279	148	111	78	58	62
lf60	58	37	46	80	42	74	74	108	22	99	142	51	287	168	123	101	80	49
lf61	59	42	39	81	41	62	72	99	9	101	154	65	300	180	140	108	84	57
lf62	64	59	31	81	62	33	87	86	29	123	193	99	263	205	171	132	103	90
lf63	26	41	6	41	82	73	111	123	41	148	188	78	337	168	148	97	66	99
lf64	99	119	74	97	130	76	152	126	97	190	259	154	822	236	177	164	136	160
lf65	66	90	64	58	136	103	164	158	99	204	246	128	822	189	183	125	99	159
lf66	99	123	92	89	164	123	193	177	127	230	279	163	822	222	214	154	127	189
lf67	74	99	82	56	158	127	185	185	119	222	253	132	822	222	181	123	99	173
lf68	81	107	92	58	168	200	197	200	130	231	255	136	822	238	197	140	115	181
lf69	75	123	90	74	167	205	201	205	132	229	275	152	822	251	210	152	127	181
lf70	85	132	107	86	181	218	212	220	141	242	279	160	822	263	222	164	140	189
lf71	96	140	115	90	191	230	222	230	152	255	288	168	822	267	226	168	144	201
lf72	107	148	127	99	204	240	234	242	164	263	296	177	822	279	238	181	156	212
lf73	132	164	155	105	228	205	256	263	189	288	321	197	822	300	259	201	177	238
lf74	152	181	164	127	238	201	267	257	199	302	325	205	822	300	259	201	177	255
lf75	201	226	205	181	279	238	308	292	242	345	378	259	822	345	304	247	222	300
lf76	226	255	234	205	308	263	337	318	267	370	403	279	822	374	333	275	251	325
lf77	259	288	267	238	341	296	370	352	302	403	436	312	822	407	366	308	284	362
lf78	197	222	185	185	247	189	265	228	210	304	370	255	822	358	316	259	234	275
lf79	132	214	156	148	210	234	238	278	187	255	204	123	111	33	90	66	90	197
lf80	164	164	189	189	242	261	263	307	214	288	234	156	76	58	119	99	123	230
lf81	822	822	822	822	822	822	822	822	822	822	822	822	157	288	280	337	822	822
lf82	822	822	822	822	822	822	822	822	822	822	822	822	222	362	345	403	822	822
lf83	822	822	822	822	822	822	822	822	822	822	822	822	316	822	440	822	822	822
lf84	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf85	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf86	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf87	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf88	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf89	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf90	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf91	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf92	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf93	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf94	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf95	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf96	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf97	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf98	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf99	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf100	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822

Table A3: Distances between provinces and landfills (continue)

	E1	E2	E3	E4	E5	E6	E7	E8	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
lf1	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf2	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf3	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf4	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf5	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf6	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf7	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf8	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf9	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf10	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf11	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf12	345	822	296	255	822	822	822	329	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf13	300	822	822	230	822	345	822	304	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf14	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf15	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf16	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf17	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf18	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf19	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf20	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf21	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf22	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf23	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf24	329	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf25	333	822	370	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf26	316	822	362	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf27	267	822	308	345	822	822	822	333	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf28	308	822	329	366	822	822	822	374	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf29	353	822	362	378	822	822	822	407	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf30	329	822	325	333	822	822	822	374	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf31	321	822	312	316	822	822	822	366	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf32	304	822	288	284	822	822	403	337	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf33	288	415	288	304	822	386	378	337	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf34	275	403	279	304	822	378	366	329	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf35	275	395	271	279	822	370	370	321	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf36	263	378	255	261	822	351	353	304	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf37	247	362	234	242	822	333	337	284	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf38	222	337	210	222	370	308	312	263	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf39	222	329	201	193	374	296	312	247	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf40	127	255	152	238	279	238	210	189	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf41	160	288	197	189	304	271	230	230	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf42	312	345	255	205	822	315	380	288	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf43	296	312	230	177	822	279	349	255	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf44	275	288	210	156	822	255	329	234	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf45	263	288	201	148	822	255	323	228	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf46	224	255	164	109	822	218	288	193	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf47	214	255	156	107	822	219	280	189	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf48	242	226	177	121	345	197	279	185	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf49	214	218	148	86	329	185	259	160	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf50	164	205	103	52	300	168	228	136	822	822	822	822	822	822	822	822	822	822	822	822	822	822

Table A3: Distances between provinces and landfills (continue)

	E1	E2	E3	E4	E5	E6	E7	E8	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14
lf51	292	279	205	177	386	247	312	222	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf52	259	245	197	152	352	212	278	187	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf53	251	234	196	152	341	201	267	177	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf54	234	222	177	130	329	189	255	164	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf55	236	208	173	133	315	175	241	150	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf56	214	197	160	123	304	164	230	140	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf57	238	219	187	152	326	187	252	162	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf58	204	205	144	98	292	136	226	136	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf59	201	197	138	86	296	140	226	136	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf60	201	189	115	82	304	154	237	144	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf61	189	185	105	70	296	150	228	136	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf62	152	164	86	33	271	132	200	105	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf63	156	140	95	49	255	107	182	90	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf64	86	132	19	35	214	99	141	53	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf65	105	89	58	58	197	58	123	33	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf66	76	81	45	76	167	48	95	1	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf67	115	66	82	86	181	32	115	37	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf68	123	53	95	99	178	21	111	49	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf69	140	58	108	107	186	29	122	66	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf70	150	49	122	123	187	33	123	76	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf71	150	41	127	132	178	32	119	82	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf72	156	33	133	143	170	37	113	86	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf73	160	29	149	165	152	49	107	99	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf74	115	25	123	156	107	49	49	82	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf75	115	76	150	193	53	99	22	111	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf76	140	99	180	222	33	119	48	140	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf77	164	140	207	255	16	156	81	173	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf78	29	136	90	150	132	130	78	99	822	822	822	822	822	822	822	822	822	822	822	822	822	822
lf79	312	279	247	206	411	247	362	230	822	289	822	822	822	822	822	822	822	822	329	822	822	822
lf80	337	312	288	230	444	279	395	263	822	259	822	822	822	822	822	822	822	822	296	822	822	822
lf81	822	822	822	822	822	822	822	822	270	25	345	279	822	822	222	337	822	822	66	822	822	181
lf82	822	822	822	822	822	822	822	822	201	41	267	205	822	822	156	284	822	822	44	822	337	152
lf83	822	822	822	822	822	822	822	822	108	140	173	104	411	370	107	195	822	337	127	279	241	31
lf84	822	822	822	822	822	822	822	822	99	230	99	19	329	263	168	99	822	288	222	185	164	107
lf85	822	822	822	822	822	822	822	822	123	267	100	33	288	230	197	86	822	263	255	164	159	140
lf86	822	822	822	822	822	822	822	822	86	238	173	197	444	411	41	263	822	436	205	321	279	105
lf87	822	822	822	822	822	822	822	822	80	214	168	181	419	386	25	247	822	411	183	288	247	81
lf88	822	822	822	822	822	822	822	822	25	238	115	115	367	312	74	164	822	337	216	232	173	86
lf89	822	822	822	822	822	822	822	822	76	304	16	86	267	210	173	66	822	234	292	132	78	114
lf90	822	822	822	822	822	822	822	822	85	316	21	99	263	214	181	74	822	230	304	127	66	168
lf91	822	822	822	822	822	822	822	822	123	337	41	78	218	205	222	8	822	193	315	132	72	193
lf92	822	822	822	822	822	822	822	822	197	822	108	111	144	90	296	66	822	121	822	33	82	261
lf93	822	822	822	822	822	822	822	822	187	822	95	156	155	107	286	66	822	123	822	23	49	257
lf94	822	822	822	822	822	822	822	822	201	822	107	164	144	99	296	78	822	115	822	74	58	268
lf95	822	822	822	822	822	822	822	822	181	822	99	173	187	150	279	99	822	164	822	67	29	263
lf96	822	822	822	822	822	822	822	822	214	822	127	189	144	107	312	105	822	107	822	34	62	288
lf97	822	822	822	822	822	822	822	822	288	822	205	263	66	11	822	173	822	74	822	88	162	822
lf98	822	822	822	822	822	822	822	822	298	822	210	263	45	21	822	164	822	37	822	89	160	822
lf99	822	822	822	822	822	822	822	822	386	822	259	329	86	115	822	247	822	49	822	156	222	822
lf100	822	822	822	822	822	822	822	822	366	822	288	337	24	78	822	230	822	66	822	156	226	822

Table A4: Availability of each biomass in each province per year (ton)

	Rice straw	Rice husk	Bagasse	Cane trash	Corn-cob	Corn stalk	Tapioca rhizome	Para-wood root	Oil palm frond	Oil palm fiber	Palm empty bunch	Oil palm shell	Wood
M1	45,343	0	0	0	0	0	0	0	0	0	0	0	0
M2	70,200	0	0	0	0	0	0	0	0	0	0	0	0
M3	164,613	0	0	0	0	0	0	0	0	0	0	0	0
M4	18,858	0	0	0	0	0	0	0	0	0	0	0	0
M5	152,574	0	0	30,669	0	0	0	0	0	0	0	0	0
M6	118,935	0	0	184,394	0	60,685	11,787	0	0	0	0	0	0
M7	191,234	0	0	104,140	0	0	0	0	0	0	0	0	0
M8	258,518	0	0	147,683	0	183,698	55,507	0	0	0	0	0	0
M9	340,796	0	0	0	0	0	0	0	0	0	0	0	0
M10	422,105	0	0	72,403	0	5,287	36,152	0	0	0	0	0	0
E1	100,444	0	0	123,744	17,403	95,137	215,044	169	1,571	0	0	0	0
E2	5,404	0	0	30,566	0	0	129,418	51,051	34,168	0	0	0	0
E3	136,004	0	0	6,267	1,762	9,634	82,640	0	0	0	0	0	0
E4	98,361	0	0	0	0	0	0	0	0	0	0	0	0
E5	5,797	0	0	0	0	0	0	26,456	49,496	0	0	0	0
E6	21,584	0	0	123,477	95	518	155,248	6,930	188,623	0	0	0	0
E7	5,299	0	0	19,898	2,866	15,666	125,588	22,791	5,663	0	0	0	0
E8	265,571	0	0	65,062	1,388	7,589	164,560	3,056	7,810	0	0	0	0
LN1	200,264	0	0	166,898	5,087	27,807	439	0	0	0	0	0	0
LN2	416,779	0	0	174,797	17,995	98,374	83,128	0	0	0	0	0	0
LN3	40,718	0	0	9,980	35,399	193,515	696	0	0	0	0	0	0
LN4	458,247	0	0	55,890	3,841	21,000	1,704	0	0	0	0	0	0
LN5	236,795	0	0	172,940	76,270	416,945	11,496	0	0	0	0	0	0
LN6	671,518	0	0	644,443	33,414	182,661	103,057	0	0	0	0	0	0
LN7	326,592	0	0	400,641	15,536	84,928	213,746	0	0	0	0	0	0
LN8	143,770	0	0	174,332	15,560	85,064	93,530	0	0	0	0	0	0
UN1	285,395	76,445	0	923	25,583	139,856	2,586	0	0	0	0	0	0
UN2	118,856	31,836	0	0	16,804	91,863	216	0	0	0	0	0	0
UN3	41,428	11,097	0	0	11,053	60,423	0	0	0	0	0	0	0
UN4	150,922	40,425	0	106,902	2,861	15,642	2,026	0	0	0	0	0	0
UN5	55,682	14,915	0	3,779	4,036	22,063	471	0	0	0	0	0	0
UN6	20,299	5,437	0	0	143	781	0	0	0	0	0	0	0
UN7	131,701	35,277	0	2,619	3,975	21,727	0	0	0	0	0	0	0
UN8	88,490	23,703	0	35,162	2,565	14,023	252	0	0	0	0	0	0
UN9	34,891	9,346	0	0	4,018	21,963	0	0	0	0	0	0	0
NE1	51,602	0	0	70,792	14,223	77,750	59,461	0	0	0	0	0	0
NE2	105,089	0	0	26,265	3,259	17,816	20,503	0	0	0	0	0	0
NE3	225,721	0	0	408,718	1,164	6,366	81,708	29	0	0	0	0	0
NE4	125,510	0	0	7,787	196	1,069	20,577	299	0	0	0	0	0
NE5	113,744	0	0	10,169	0	0	4,594	0	0	0	0	0	0
NE6	225,794	0	0	19,376	0	0	27,367	0	0	0	0	0	0
NE7	44,249	0	0	76,122	0	0	38,244	0	0	0	0	0	0
NE8	117,390	0	0	5,989	0	0	22,362	0	0	0	0	0	0
NE9	114,122	0	0	5,089	0	0	14,489	0	0	0	0	0	0
NE10	371,968	0	0	0	1,989	10,875	37,541	0	0	0	0	0	0
NE11	322,131	0	0	31,090	5,687	0	24,764	0	0	0	0	0	0
NE12	374,870	0	0	21,193	0	0	17,676	0	0	0	0	0	0
NE13	353,764	0	0	70,947	35	190	94,303	0	0	0	0	0	0
NE14	233,091	0	0	260,875	0	0	168,068	0	0	0	0	0	0
NE15	234,827	0	0	34,985	0	0	54,110	0	0	0	0	0	0
NE16	345,045	0	0	16,965	0	0	52,718	0	0	0	0	0	0
NE17	314,533	0	0	493,681	486	2,655	111,276	0	0	0	0	0	0
NE18	134,165	0	0	299,021	7,934	43,374	181,864	0	0	0	0	0	0
NE19	370,616	0	0	447,729	0	272,790	912,772	0	0	0	0	0	0
W1	119,549	0	0	778,732	0	29,012	121,703	0	969	16	137	0	0
W2	207,810	0	0	114,303	0	0	0	0	0	0	0	0	0
W3	16,784	0	0	54,227	0	676	0	202	195,282	3,289	27,700	0	0
W4	127,979	0	0	26,113	0	866	1,356	0	0	0	0	0	0
W5	149,437	0	0	187,977	0	2,211	43,413	0	0	0	0	0	0
W6	1,693	0	0	0	0	0	0	0	0	0	0	0	0
W7	7,929	0	0	0	0	0	0	0	0	0	0	0	0
W8	464,868	0	0	559,912	0	20,941	13,346	0	0	0	0	0	0
S1	4,419	0	0	0	0	0	0	73,261	2,255,031	37,984	319,863	0	0
S2	7,873	0	0	0	0	0	0	17,024	1,369,787	23,073	194,296	0	0
S3	8,114	0	0	0	0	0	0	113,089	259,619	4,373	36,825	0	0
S4	112,067	0	0	0	0	0	0	99,536	116,085	1,955	16,466	0	0
S5	16,239	0	0	0	0	0	0	52,547	49,570	835	7,031	0	39,410
S6	28,937	0	0	0	0	0	0	23,718	0	0	0	0	17,789
S7	1,112	0	0	0	0	0	0	74,682	169,235	2,851	24,005	0	0
S8	73,743	0	0	0	0	0	0	42,879	2,770	47	393	0	0
S9	176	0	0	0	0	0	0	4,972	1,623	27	230	0	0
S10	9,239	0	0	0	0	0	0	60,341	1,817	31	258	0	45,255
S11	442	0	0	0	0	0	0	11,626	111,647	1,881	15,836	0	0
S12	62,914	0	0	0	0	0	0	128,403	42,219	711	5,988	0	0
S13	12,310	0	0	0	0	0	0	31,856	228,682	3,852	32,437	0	0
S14	12,933	0	0	0	0	0	0	124,638	1,947,903	32,810	276,298	0	0

Table A5: Total residues of each biomass in each province per year (ton)

	Rice straw	Rice husk	Bagasse	Cane trash	Corn-cob	Corn stalk	Tapioca rhizome	Para-wood root	Oil palm frond	Oil palm fiber	Palm empty bunch	Oil palm shell	Wood
M1	56,679	24,291	0	0	0	0	0	0	0	0	0	0	0
M2	87,750	37,607	0	0	0	0	0	0	0	0	0	0	0
M3	205,766	88,186	0	0	0	0	0	0	0	0	0	0	0
M4	23,573	10,103	0	0	0	0	0	0	0	0	0	0	0
M5	190,717	81,736	63,141	38,336	0	0	0	0	0	0	0	0	0
M6	148,668	63,715	379,634	230,492	22,202	75,856	14,734	0	0	0	0	0	0
M7	239,042	102,447	214,405	130,175	0	0	0	0	0	0	0	0	0
M8	323,147	138,492	304,053	184,603	67,206	229,622	69,383	0	0	0	0	0	0
M9	425,995	182,569	0	0	0	0	0	0	0	0	0	0	0
M10	527,632	226,128	149,064	90,503	1,934	6,608	45,189	0	0	0	0	0	0
E1	125,555	53,809	254,767	154,680	34,806	118,921	268,805	212	1,964	265	446	56	635
E2	6,755	2,895	62,931	38,208	0	0	161,772	63,813	182,269	5,755	9,693	1,212	191,440
E3	170,006	72,859	12,903	7,834	3,525	12,043	103,299	0	0	0	0	0	0
E4	122,951	52,693	0	0	0	0	0	0	0	0	0	0	0
E5	7,247	3,106	0	0	0	0	0	33,070	61,869	8,337	14,041	1,755	99,210
E6	26,980	11,563	254,218	154,346	190	648	194,060	8,663	235,779	31,772	53,510	6,689	25,988
E7	6,624	2,839	40,966	24,872	5,731	19,582	156,985	28,488	7,078	954	1,606	201	85,465
E8	331,963	142,270	133,952	81,328	2,776	9,486	205,700	3,820	9,763	1,316	2,216	277	11,459
LN1	250,330	107,284	343,614	208,623	10,173	34,759	549	0	0	0	0	0	0
LN2	520,974	223,275	359,876	218,496	35,991	122,968	103,910	0	0	0	0	0	0
LN3	50,897	21,813	20,546	12,474	70,798	241,893	871	0	0	0	0	0	0
LN4	572,809	245,490	115,068	69,863	7,683	26,250	2,130	0	0	0	0	0	0
LN5	295,993	126,854	356,053	216,175	152,541	521,181	14,370	0	0	0	0	0	0
LN6	839,397	359,742	1,326,794	805,553	66,827	228,327	128,821	0	0	0	0	0	0
LN7	408,240	174,960	824,850	500,802	31,071	106,160	267,182	0	0	0	0	0	0
LN8	179,712	77,019	358,919	217,915	31,121	106,329	116,913	0	0	0	0	0	0
UN1	356,744	152,890	1,900	1,154	51,167	174,820	3,232	0	0	0	0	0	0
UN2	148,570	63,673	0	0	33,608	114,829	270	0	0	0	0	0	0
UN3	51,785	22,194	0	0	22,106	75,529	0	0	0	0	0	0	0
UN4	188,652	80,851	220,093	133,628	5,723	19,553	2,533	0	0	0	0	0	0
UN5	69,603	29,830	7,780	4,724	8,072	27,578	589	0	0	0	0	0	0
UN6	25,373	10,874	0	0	286	976	0	0	0	0	0	0	0
UN7	164,626	70,554	5,393	3,274	7,949	27,159	0	0	0	0	0	0	0
UN8	110,612	47,405	72,392	43,952	5,130	17,528	315	0	0	0	0	0	0
UN9	43,613	18,691	0	0	8,035	27,454	0	0	0	0	0	0	0
NE1	64,502	27,644	145,749	88,491	28,445	97,187	74,327	0	0	0	0	0	0
NE2	131,361	56,298	54,075	32,831	6,518	22,270	25,628	0	0	0	0	0	0
NE3	282,151	120,922	841,479	510,898	2,329	7,957	102,135	36	0	0	0	0	107
NE4	156,888	67,238	16,032	9,734	391	1,337	25,721	374	0	0	0	0	1,121
NE5	142,180	60,934	20,936	12,711	0	0	5,742	0	0	0	0	0	0
NE6	282,242	120,961	39,892	24,220	0	0	34,209	0	0	0	0	0	0
NE7	55,312	23,705	156,721	95,152	0	0	47,805	0	0	0	0	0	0
NE8	146,737	62,887	12,330	7,486	0	0	27,952	0	0	0	0	0	0
NE9	142,652	61,137	10,477	6,361	0	0	18,112	0	0	0	0	0	0
NE10	464,961	199,269	0	0	3,979	13,594	46,927	0	0	0	0	0	0
NE11	402,664	172,570	0	0	11,375	38,863	30,955	0	0	0	0	0	0
NE12	468,587	200,823	43,632	26,491	0	0	22,095	0	0	0	0	0	0
NE13	442,204	189,516	146,068	88,684	70	238	117,879	0	0	0	0	0	0
NE14	291,364	124,870	537,096	326,094	0	0	210,085	0	0	0	0	0	0
NE15	293,534	125,800	72,027	43,731	0	0	67,637	0	0	0	0	0	0
NE16	431,306	184,845	34,927	21,206	0	0	65,897	0	0	0	0	0	0
NE17	393,167	168,500	1,016,401	617,101	972	3,319	139,095	0	0	0	0	0	0
NE18	167,706	71,874	615,631	373,776	15,869	54,218	227,330	0	0	0	0	0	0
NE19	463,270	198,544	921,795	559,661	99,801	340,987	1,140,965	0	0	0	0	0	0
W1	149,436	64,044	1,603,272	973,415	10,614	36,265	152,129	0	1,211	163	275	34	0
W2	259,763	111,327	235,329	142,879	0	0	0	0	0	0	0	0	0
W3	20,980	8,992	111,643	67,783	247	845	0	253	244,102	32,893	55,399	6,925	759
W4	159,974	68,560	53,762	32,641	317	1,082	1,695	0	0	0	0	0	0
W5	186,796	80,055	387,012	234,972	809	2,763	54,266	0	0	0	0	0	0
W6	2,116	907	0	0	0	0	0	0	0	0	0	0	0
W7	9,911	4,247	0	0	0	0	0	0	0	0	0	0	0
W8	774,780	332,049	1,152,761	699,891	7,661	26,176	16,682	0	0	0	0	0	0
S1	5,524	2,367	0	0	0	0	0	91,576	2,818,789	379,837	639,725	79,966	274,729
S2	9,841	4,217	0	0	0	0	0	21,281	1,712,233	230,726	388,592	48,574	63,842
S3	10,143	4,347	0	0	0	0	0	141,362	324,524	43,730	73,651	9,206	424,085
S4	140,084	60,036	0	0	0	0	0	124,421	145,106	19,553	32,932	4,116	373,262
S5	20,299	8,699	0	0	0	0	0	65,683	61,962	8,350	14,062	1,758	197,050
S6	36,171	15,502	0	0	0	0	0	29,648	0	0	0	0	88,944
S7	1,391	596	0	0	0	0	0	93,353	211,544	28,506	48,010	6,001	280,058
S8	92,179	39,505	0	0	0	0	0	53,598	3,463	467	786	98	160,795
S9	221	94	0	0	0	0	0	6,215	2,029	273	460	58	18,644
S10	11,549	4,950	0	0	0	0	0	75,426	2,272	306	516	64	226,277
S11	553	237	0	0	0	0	0	14,533	0	18,806	31,673	3,959	43,598
S12	78,643	33,704	0	0	0	0	0	160,504	52,773	7,111	11,977	1,497	481,511
S13	15,387	6,594	0	0	0	0	0	39,820	285,852	38,519	64,874	8,109	119,459
S14	16,167	6,929	0	0	0	0	0	155,797	2,434,878	328,104	552,596	69,075	467,392

Table A6: Conversion of units

1 CF	0.00108	GJ
1 BCF	$1.05 * 10^{15}$	J
1 BCF	25.07	ktoe
1 MMscf	0.02457	ktoe
1 MMbbl	158.99	million litres
1 million litres	0.86	ktoe
1 kcal	4,186	J
	3.968	Btu
1 toe	10.093	Gcal
	42.244	GJ
	$40.047 * 10^{6}$	Btu
	1270	m^3 of Natural Gas
	7.4	bbl
	2.3	MT of Coal
1 ktoe	0.0448763	BCF
	1.327625	MW
	11.63	GWh
1 MW	24,000	kWh
1kWh	3,600	kJ