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Bioenergy Supply Chain Simulation and Improvement based-on Thailand Alternative Energy Development Plan (AEDP)

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МАГИСТЕРСКАЯ ДИССЕРТАЦИЯ

Моделирование и улучшение цепочки поставок биотоплива на основе плана развития альтернативной энергетики Таиланда

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Abstract

Alternative energy penetration has been growing over the past decade. Thailand, as well, has been aware of global warming and decreasing of fossil fuels reservoir problems. The country has developed and proclaimed the Alternative Energy Development Plan (AEDP) as a part of energy development plans to reduce energy-intensive, utilize more residue resources, and reduce Greenhouse gases emission. According to the AEDP, the country has achieved many target alternative energy consumptions. However, electricity generated from biomass and biogas; and bioethanol produced from biomass have not been accomplished. There are 398 MW of electricity and 0.75 ML/day of bioethanol production capacity Thailand requires to accomplish the AEDP. Hence, this study was conducted to identify the causes that make the AEDP has not been accomplished including the amount of biomass and energy production capacity needed and additionally provide some suggestions to improve the bioenergy supply chain.

Mathematical programming was performed to optimize the supply chain by Python PuLP for linear programming. Monthly profile of 77-province suppliers, 17 biomasses, 427 bioenergy plants with 5 different energy conversion technologies were considered. The result showed that Thailand currently has biomass resources to produce electricity from biomass for 2550.4 MW; electricity from biogas (from energy crops) for 35.65 MW; and bioethanol from molasses and cassava for 4.79 ML/day which can satisfy the AEDP bioethanol consumption target. Bottlenecks in the supply chain were improved by changing an objective function from minimizing total cost to minimize maximum inventory level. This makes the percentage of overall power plants operation increase by 24.13% and inventory utilization increase by 30.32%, though the total cost increases by 124.77 billion THB.

To accomplish all AEDP targets, more biomass and new power plants are needed. For additional biomass, the optimal result showed that growing additional 4.65 billion tons of sugarcane is able to produce sufficient energy to satisfy the AEDP, while 1,634.82 MW capacity biomass power plant and 51.8 MW capacity biogas power plant need to be installed at Saraburi province as well. Finally, we suggest that using high methane content fuel such as solid waste instead of agricultural biomass will reduce this additional biomass.

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Моделирование и улучшение цепочки поставок биотоплива на основе плана развития альтернативной энергетики Таиланда

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Реферат

За последнее десятилетие возрос спрос на альтернативную энергетику. В Таиланде проблемы глобального потепления и снижения резервуаров ископаемого топлива являются актуальными. В связи с этим в стране был разработан и обнародован план развития альтернативной энергетики (AEDP) как составная часть стратегии энергетического развития с целью сокращения выбросов парниковых газов и использования энергоемких технологий. В соответствии с данным планом, в стране были достигнуты целевые показатели потребления альтернативной энергии. Однако, попытки выработать электричество из биомассы и биогаза, и получить биоэтанол из биомассы не были достигнуты. Для реализации плана AEDP Таиланду нужно достичь показателей емкости производимых 398 МВт электроэнергии и 0,75 Мл/день биоэтанола. Это исследование было проведено с целью определения причин которые не позволяют реализовать план AEDP исходя из количества биомассы и емкости производимой электроэнергии, а также предлагает пути улучшения цепочки поставки биоэнергии.

Был проведен программный расчет для оптимизации цепочки поставки биоэнергии при помощи программной библиотеки Python PuLP. Был рассмотрен ежемесячный профиль поставщиков из 77 провинций, 17 видос биомассы, 427 биоэнергетических установок с 5 различными технологиями преобразования электроэнергии. Результат расчета показал, что в Таиланде имеются ресурсы для производства электроэнергии из биомассы на 2550,4 МВт и биогаза (энергетических культур) на 35,65 МВт, биоэтанола из мелассы и маниоки на 4,79 Мл/день, что может удовлетворить цель потребления биоэтанола предложенного в рамках плана AEDP. Узкие места в цепочке поставки были улучшены путем замены минимизации полных затрат на минимизацию максимального уровня запасов. Это позволило увеличить проценты общей эксплуатации электростанций на 24,13% и использования запасов на 30,32% при увеличении полных затрат на 124,77 миллиардов бат.

Чтобы достичь всех целевых показателей плана AEDP нужно больше биомассы и новых электростанций. Что касается дополнительного количества биомассы, оптимальный результат показал, что выращивание дополнительных 4.65 миллиардов тонн сахарного тростника может выработать достаточно энергии для удовлетворения требований AEDP. С этой целью в провинции Сарабури должны быть установлены работающие на биомассе и биогазе электростанции с мощностями 1634,82 МВт и 51,8 МВт соответственно. В заключении, было предложено использовать топливо с высоким содержанием метана, такое как твердые отходы, вместо сельскохозяйственной биомассы, что приведет к сокращению дополнительной биомассы.

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Abbreviation and Definition

Abbreviation

MOE	**M**inistry **o**f **E**nergy of the Kingdom of Thailand
DEDE	**D**epartment of **A**lternative **E**nergy **D**evelopment and **E**fficiency
EGAT	**E**lectricity **G**enerating **A**utorized of **T**hailand
EPPO	**E**nergy **P**olicyand **P**lanning **O**ffice
DMF	**D**epartment of **M**ineral **F**uels
OAE	**O**ffice of **A**gricultural **E**conomics
TIEB	**T**hailand **I**ntegrated **E**energy **B**lueprint
PDP	**P**ower **D**evelopment **P**lan
EEDP or **EEP**	**E**nergy **E**fficiency **D**evelopment **P**lan
AEDP	**A**lternative **E**nergy **D**evelopment **P**lan

Definition

Biomass	Biomass is a material derived from plants, waste or algae. It is used as a fuel to produce energy.
Bioenergy	Bioenergy is energy produced from using biomass. In this thesis, the term of bioenergy refers to electrical energy from biomass, and biogas (methane) digested from biomass; and bioethanol fermented from molasses and cassava.
THB	Thai currency which 1 USD = 31.14 THB (exchange rate at 1^{st} May 2021)
Capacity factor or **Plant factor**	The ratio between the real energy produced by maximum possible energy production of bioenergy plant. For instance, a power plant produce electrcity at 70 MWh while it can actually produce electricity up to 100 MWh, this make the capacity factor of this power plant = 0.7.

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Chapter 1

Introduction

1.1 Problem statement

In several years, Thailand has attempted to control and alleviate energy and ecological problem including people being. With an increasing of energy price ([19]), lower fossil fuels reservoir ([16]), as well as natural disaster and pollution from greenhouse gases emission. This causes renewable energy has been interested since it emits lower carbon dioxide (CO_2) and more environmentally friendly. There are expectations that renewable energy penetration will have grown significantly ([23]) and become the mainstream replacing fossil fuels. With this vision, Thailand has joined many related associations; including Asia-Pacific Economic Cooperation (APEC), ASEAN Economic Community (AEC), as well as the Paris Agreement. Following the APEC, Thailand agrees to reduce energy-intensive per GDP by 30% by 2036 comparing to the year 2010 ([35], [34]). Following the ASEAN, Thailand agrees to buy and sell renewable energy with member countries.

Adjust to the country's context, Thailand has developed the national energy development plan called "Thailand Integrated Energy Blueprint (TIEB)" which is responsible by the Ministry of Energy (MOE) of the kingdom of Thailand. The TIEB has been reviewed and improved every year to make the context suitable for the current situation of Thailand in economics, security, and environment. It consists of an energy operational plan and goal description categorized into 5 plans; Power Development Plan (PDP), Energy Efficiency Development Plan (EEDP or EEP), Alternative Energy Development Plan (AEDP), Oil Plan, and Gas Plan. All the plans' context is associated.

The AEDP describes the alternative energy operational plan and consumption ratio goal for 20 years ahead. Real alternative energy consumption results so far have been achieved. However, comparing the real consumption in 2020 and the targeted consumption in 2021, some types of alternative energy have not been achieved yet as seen in Table 1.1 [14]. The electricity consumption from small hydro power, biomass, biogas, solid waste, and bioethanol have not been achieved, while electricity consumption from wind power and biodiesel have already been achieved. The electricity consumption from small hydropower is 26.69% away from the 2021 goal, the electricity consumption from biomass, biogas, solid waste, and bioethanol consumption are 11.14%, 34.46%, 33.79%, and 15.62% respectively away from the 2021 goal. While the electricity consumption from wind power is already 217.23 % of the 2021 goal. However, even though specific types of alternative energy consumption have not reached the 2021 goal, but if we consider the total electricity produced from alternative energy, Thailand has already reached its target. The electricity from wind power compensates for the rest of alternative energy from other types.

Table 1.1: Real and targeted alternative energy consumption according to AEDP

Alternative energy: Energy type	Alternative energy: resource	unit	2020 real consumption	2021 target consumption	Error from target (%)
Electricity	Total	MW	11972.65	11871	0.86
		ktoe	2241.233		
	Solar energy	MW	2982.62	2993	-0.35
	Wind	MW	1506.821	475	217.23
	Small hydro power	MW	190.39	259	-26.49
	Biomass	MW	3501.18	3940	-11.14
	Biogas (including from energy crop)	MW	547.238	835	-34.46
	Biogas (from energy crop)	MW		387	
	Solid waste	MW	324.44	490	-33.79
	Large hydro power	MW	1919.662	2906	0.47
Heat	Total	ktoe	5616.815		
	Solar energy	ktoe	7.915		
	Biomass	ktoe	5004.14		
	Biogas	ktoe	515.88		
	Solid waste	ktoe	88.88		
	etc	ktoe			
Biofuel	Total	ktoe	1762.776	2055	-14.22
	Bioethanol	ML/day	4.042	4.79	-15.62
		ktoe		892	
	Biodiesel	ML/day	5.072	3.58	41.68
		ktoe		1162	

Therefore, this thesis attempts to identify the possible root causes of the problem that make the real electricity consumption from biomass, biogas (from energy crops), and bioethanol have not reached the year-2021 AEDP goal. We use Python programming language to do mathematical programming to simulate the logistic activities of Thailand's bioenergy supply chain. The analytical data consists of the amount of biomass needed, production capacity, and logistics flow of the supply chain. We will simulate the current bioenergy supply chain, and study how we can improve the supply chain so that the target consumption would be satisfied.

1.2 Objectives

1. To make mathematical model and simulate Thailand's bioenergy (biomass, biogas (from energy crops), ethanol) supply chain.
2. To investigate the problems that make the real bioenergy (biomass, biogas (from energy crops), ethanol) consumption lower than the target in the year 2021 regarding the AEDP.
3. To make suggestions to improve Thailand's bioenergy supply chain to accomplish AEDP goals in 2021.

1.3 Scope of study

Even though the alternative energies that have not been reached the goal are electricity produced from small hydropower, biomass, biogas, solid waste; and bioethanol production. This thesis studies in the scope of electricity produced from biomass, biogas from energy crops, and bioethanol production from cassava and molasses only. Thus this thesis does not include the small hydropower, biogas from non-energy-crops resources, and solid waste.

The biomass feedstocks are provided from all provinces in Thailand and no biomass imported from any other countries. Hence, all electricity and bioethanol from biomass are produced domestically. This thesis considers only biomass derived from Thailand's 6 major economical crops which are rice, sugarcane, corn, cassava, oil palm, and coconut. Thus, there are totally 17 biomass types considered in this thesis as shown in Table 1.2.

In the supply chain optimization, this thesis assumes that retailers who buy electricity can supply all of the electricity buying from bioenergy power plants to the end consumers. Besides, this thesis does not consider the limitation of electrical transmission lines. Thus, we can do a balance between electricity supplying from power plants and retailers without considering the transmission line network.

1.4 Methodology

Conducting bioenergy supply chain optimization and simulation can be done in several methods such as mathematical programming and simulation software. However, this thesis uses Python version 3.9 to do the mathematical programming. Lenevo™ ideapad330 64-bit is used to generate codes. The problem and constraints are linear. Most necessary biomass and power plants related data is collected from the Department of Alternative Energy Development and Efficiency (DEDE) and the Ministry of Energy (MOE) official website. The detail about data collection will

Table 1.2: List of biomass considered in this thesis

Crop	Biomass
1. rice	1. straw 2. husk
2. sugarcane	3. leaves 4. bagasse 5. molasses
3. corn	6. leaves and tops 7. corncob
4. cassava	8. peeled cassava 9. rhizome 10. fiber 11. peel
5. oil palm	12. bunches 13. fiber 14. shell
6. coconut	15. bunches 16. bracts 17. shells

be described more in section 3.4. Research tools and data collection methods are classified as the following;

1. Optimization by using Linear Programming.

2. Programming by Python programming language version 3.7.

3. The related python programming packages are;

   - PuLP
   - Numpy
   - Pandas
   - Matplotlib

4. Biomass and power plants related data is collected from Department of Alternative Energy Development and Efficiency (DEDE) ([9]) and Ministry of Energy (MOE) ([32]).

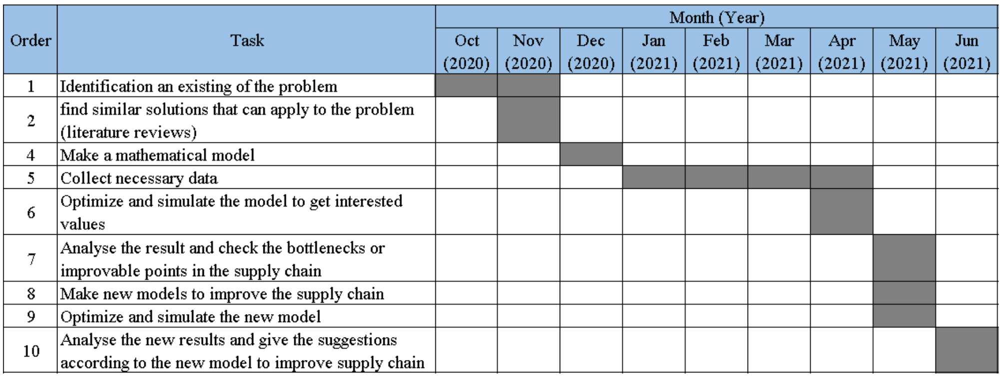
5. The distance between each component are calculate by using python OSRM (Open Source Routing Machine) package.

The thesis studying work steps consist of 10 steps as the following;

1. Identification an existing of the problem.

2. Check whether there is already an existing solution for the problem. If not, find similar solutions that can apply to the problem.
3. Make a mathematical model to solve the problem by referring from the similar solutions.
4. Collect necessary data.
5. Optimize and simulate the model to get interested values.
6. Analyse the result and check the bottlenecks or improvable points in the supply chain.
7. Make new models to improve the supply chain.
8. Optimize and simulate the new model.
9. Analyse the new results and give the suggestions according to the new model to improve supply chain

The workflow and schedule of the research approach is shown in Figure 1.1



Order	Task	Month (Year)								
		Oct (2020)	Nov (2020)	Dec (2020)	Jan (2021)	Feb (2021)	Mar (2021)	Apr (2021)	May (2021)	Jun (2021)
1	Identification an existing of the problem									
2	find similar solutions that can apply to the problem (literature reviews)									
4	Make a mathematical model									
5	Collect necessary data									
6	Optimize and simulate the model to get interested values									
7	Analyse the result and check the bottlenecks or improvable points in the supply chain									
8	Make new models to improve the supply chain									
9	Optimize and simulate the new model									
10	Analyse the new results and give the suggestions according to the new model to improve supply chain									

Figure 1.1: Thesis work-plan schedule

1.5 Research organization

This thesis consists of 6 chapters. Chapter 1 is an introduction stating about problem statement and an overview of the thesis work. Chapter 2 is literature reviews stating Thailand's background and its energy development plan, and related bioenergy supply chain optimization studies. Chapter 3 is the research methodology. Chapter 4 is current Thailand's bioenergy supply chain results. Chapter 5 is an improved supply chain simulation results. And chapter 6 is the conclusion and discussion.

Chapter 2

Literature Review and Related Research

2.1 Thailand background and biomass potential

Thailand locates in the Southeast Asia continent which is a tropical zone. It is fruitful and has various tropical agricultural products. Its mainstream comes from exporting in the agricultural sector and industrial sector. Thailand's major crops consist of rice, sugarcane, corn, cassava, para rubber tree, oil palm, and coconut. There are about 60 million tons of biomass per year ([9]) from these crops left that can be potentially used to produce energy. However, most agriculturists have not fully utilized this left biomass.

Rice is the most common food for Thai and Asian people. Whole rice trees are collected, separated grain, and pass it through a milling process to produce white rice. Some agriculturists use a sickle to harvest, some use automatic tractors. Biomasses that occur from rice harvesting and milling are rice husk and rice straw.

Sugarcane is used to produce sugar. The sugarcane is burnt before harvested. there are cut by sickle above its root and trimmed its leaves out before delivered to a sugar manufacturing process. In the process, sugarcane is extracted its juice and left only its bagasse. Not all sugarcane juice is processed into sugar. Some of them are left as molasses. Hence biomass that occurs from sugarcane harvesting is sugarcane leaves. And biomasses that occur from the sugar manufacturing process is sugarcane bagasse and molasses.

Corns planted in Thailand are categorized into 2 types; one is for human's food, and another one is for livestock feeding. Corn is collected only their corn-ears. And after corn is eaten, there will be corncobs left. Hence, the total biomasses that occur from corn are corn' leaves, trunks, and corncobs.

Cassava is used for both food and non-food industries. The used part is roots. Its trunks with leaves can be used to re-plant the cassava again. Cassava's roots are peeled before fed into manufacturing process. Hence, the biomass that occurs from harvesting is only the cassava' rhizomes. And from the industrial manufacturing process, the biomasses that occur are peels and their fibers.

Oil palm is mostly used to produce cooking oil. Its bunches are collected and delivered to the palm oil manufacturing process. The oil palm is extracted oil from its fruit and leave its bunches, fibers, and shells as a waste. Hence, biomasses that occur from the palm oil manufacturing process are bunches, fibers, and shells.

Coconut bunches are collected from the coconut trees. young coconut can be eaten fresh. The old ones are used to produce coconut milk. The biomasses derived from coconuts are coconut brunches, bracts, and shells.

The total biomass types acquired from these crops and their ratio is shown in Table 2.1

Table 2.1: List of Crops and their derived biomass

Crop	Biomass	Ratio of green biomass per harvested crop (tons of biomass per ton of harvested crop)	Moisture (%)
1. rice	1. straw 2. husk	0.49 0.21	10 12
2. sugarcane	3. leaves 4. bagasse 5. molasses	0.17 0.28 0.05	9.2 50.73
3. corn	6. leaves and tops 7. corncob	1.84 0.24	42 40
4. cassava	8. peeled cassava 9. rhizome 10. fiber 11. peel	0.72 0.2 0.06 0.28	 40 59.4 59.4
5. oil palm	12. bunches 13. fiber 14. shell	0.32 0.19 0.04	58.6 38.5 12
6. coconut	15. bunches 16. bracts 17. shells	0.29 0.33 0.25	12 12 12
		* 1 rai = 1600 sq.m.	

According to [9], the leftover biomass potential was evaluated. There was 42.68% of rice straw, 10.84% of corn' leaves and tops, 2.71% of cassava' rhizomes, 47.17% of oil palm's bunches, and 19.40% of coconut's bunches utilized. Their productivity and utilization are shown in Table 2.2.

Moreover, from [33], it reported that most heat-consumed-from-renewable-energy industries are agricultural which are sugar, palm oil, cassava starch, processed wood, rice mills, and livestock farm industries. Of which sugar manufacturers consume 99% heat which is from bagasse (99.96%) and rice husk (0.04%). Rice millers consume 85% heat which is from rice husk (99.24%). Processed wood manufacturers consume 95% heat which is from wood-chip (95.04%) and sawdust (4.91%). Oil palm manufacturers consume 90% heat which is from oil palm fibers (84.27%) and shells (8.96%).

Table 2.2: Biomass productivity, utility, and leftover

Biomass	Productivity (tons)	Utility (tons)	Leftover (tons)
rice straw	19,005,628.14	8,112,801.26	10,892,826.89
rice husk	8,145,269.20	8,006,283.36	138,985.84
sugarcane leaves	17,016,248.08	1,845,487.74	15,170,760.34
bagasse	28,026,761.54	28,026,761.54	0
corn leaves and tops	9,315,603.52	465,780.18	8,849,823.34
corncobs	1,215,078.72	1,094,081.58	120,997.14
cassava rhizomes	6,045,508.40	164,196.52	5,881,311.88
cassava fiber	1,813,652.52	1,813,652.52	0
cassava peels	8,463,711.76	8,463,711.76	0
oil palm bunches	4,099,859.52	1,891,985.90	2,207,873.62
oil palm fibers	2,434,291.59	2,434,291.59	0
oil palm shell	512,482.44	512,482.44	0
coconut bunches	292,909.57	56,824.46	236,085.11
coconut bracts	333,310.89	329,976.78	3,334.11
coconut shells	252,508.25	230,540.03	21,968.22

2.2 Alternative Energy Development Plan (AEDP)

Thailand has improved energy production and consumption efficiency consecutively. To manage remaining domestic resources, reduce energy import from other countries including Greenhouse gases emission. By the responsibility of Thailand's Ministry of Energy (MOE), it launched the country's energy development plan called ”Thailand Integrated Energy Blueprint (TIEB)”. This plan had been reviewed yearly and the officially version is of the year 2015. In the present, it has been categorized into 5 plans; Power Development Plan (PDP), Energy Efficiency Development Plan (EEDP), Alternative Energy Development Plan (AEDP), Oil Plan, and Gas Plan. They prioritize on energy security, economy, and ecology perspectives to support Thailand's 20-year National Economic and Social Development Plan ([40]) associated with people and urban growth rate, fuel diversification, living cost, including environmental impacts ([35]).

According to Power Development Plan ([35]), Thailand was predicted that it will have the final energy consumption at 182,720 ktoe in the year 2036. However, according to the Energy Efficiency Development Plan (EEDP) ([34]), Thailand has attempted to reduce an energy intensive (EI) (energy consumption per GDP) by 30% in the year 2036 comparing to the year 2010, of which it makes the final energy consumption should be reduce to 131,000 ktoe, which is an electrical energy for 277,789 ktoe, thermal energy for 68,413 ktoe, and biofuel for 34,798 ktoe. In an electricity consumption term, there will be 19,634.4 MW from alternative energy which is about 20 % of total electricity production.

According to the Alternative Energy Development Plan (AEDP) [33], its alternative energy consumption goal in the year 2015, 2021, and 2036 is shown in Table 2.3.

Table 2.3: Alternative energy consumption goals in the year 2015, 2021, and 2036

Alternative energy: Energy type	Alternative energy: resource	unit	Targeted consumption: 2015	2021	2036
Electricity	Total	MW	7962	11871	19864.4
		ktoe			5588
	Solar energy	MW	1419	2993	6000
	Wind	MW	233	475	3002
	Small hydro power	MW	172	259	376
	Biomass	MW	2726	3940	5570
	Biogas (including from energy crop)	MW	372	835	1280
	Biogas (from energy crop)	MW		387	680
	Solid waste	MW	131	490	550
	Large hydro power	MW	2906	2906	2906.4
Heat	Total	ktoe			25088
	Solar energy	ktoe			1200
	Biomass	ktoe			22100
	Biogas	ktoe			1283
	Solid waste	ktoe			495
	etc	ktoe			10
Biofuel	Total	ktoe	1942	2055	8712.43
	Bioethanol	ML/day	3.5	4.79	11.3
		ktoe	879	892	2104
	Biodiesel	ML/day	3.4	3.58	14
		ktoe	1063	1162	4405
	Pyrolysis oil	ML/day			0.53
	Compressed bio-methane gas	tons/day			4800
	etc	ktoe			10
Alternative energy production		ktoe			39388.67
Final energy consumption		ktoe			131000
% of alternative energy consumption		%			30

However, Thai government has promoted alternative energy production to private sector. The government has changed electricity buying from small power plants (SPP) and very small power plants (VSPP) from adder system to feed-in-tariff (FiT) system of which it has made many private companies being interested to invest in alternative energy production. However, there are some issues that Thai government, with the responsibility of Ministry of Energy, have to hurriedly improve. From an evaluation of Electricity Generating Authorization of Thailand (EGAT) ([35], [36]), the current electrical transmission lines cannot carry all traditional and alternative energy generated with their maximum production capacity. Thence, there are several transmission lines construction projects being operated.

2.3 Considered issues in bioenergy supply chain optimization

Bioenergy supply chain optimizations were studied in many contexts. Some consider 1 type of biomass, some consider multi-type. Some tried to optimize the amount of input biomass for each time-step, some optimize the location of the power plant instead. Each study has different objective and constraints. However, [3] indicated issues we have to consider in supply chain optimization as the following.

2.3.1 Activities

Crops cultivation

From soil preparation to crops harvesting, there are many activities in this process. Soil preparation is the first step, agriculturists have to soften the soil, get rid of the weed, adjust moisture, pH balance, and nutrient of the soil before planting crops seed or sprouts. This process requires work labours, water, and fertilization.

The next step is seed or sprouts planting. Each type of crop has a different harvesting method. Rice, sugarcane, corn , and cassava are annuals plant. They can be harvested once. So, they have to be re-planted again to give another product set. Unlike the previous ones, oil palm and coconut are perennials plants. They have a long life and give agricultural products along their cycle. Hence, rice, sugarcane, corn, and cassava have higher work labour cost but lower fertilizing cost. In contrast, oil palm, para rubber tree, and coconut have lower labour cost but higher fertilizing cost. The cost, however, quite high only in the early stages of the plants but it will become cheaper when plants are more mature.

After the plants are ready to be harvested, the next step is harvesting.

Biomass collection

Biomass can be obtained from crops residues and industrial process. Agricultural biomass such as rice straw, corn leaves, cassava rhizomes, sugarcane leaves, and coconut bunches and bracts are collected from the agriculturists' field. These biomasses contain a high amount of moisture. Usually, these biomasses are dried under strong sunlight to reduce their moisture value before being sold to bioenergy production plants. Industrial biomasses such as rice husk, sugarcane bagasse and molasses, corncobs, cassava residues, and oil palm residues are a by-product of the related process in industries. To utilize these biomasses, the industries have to either install their own energy production process or sell them to other bioenergy production factories.

Pre-processing

Before converting the biomass to energy, they have to be pre-processed to make the combustion process more efficient. In biomass-to-electricity conversion process. Wood biomass is usually dried to reduce moisture and palletized to increase its density making the combustion process more efficient. Other biomasses are passed through the Torrefaction process to reduce moisture. In some country such as in US ([29], [71]), there are factories built to pre-process biomass specifically. However, in Thailand, the pre-process are installed inside the bioenergy production factories. We will discuss each energy conversion technologies further in section 2.6.

Storage

The storage unit is made to keep biomass before they are fed into the bioenergy production process. It can be located near suppliers for centralization purpose or near factories. It can be just an open empty area or have a roof covered and air fan depending on the biomass type and weather. However, the storage has to have the ability to control moisture which significantly affects stored biomass.

Transportation

Transportation takes a role to deliver biomass from suppliers to bioenergy production plants. Transportation usually operates in 3 modes; roadway, railway, or waterway; or a combination of them. Depending on biomass type; conditions; and distance, choosing a proper transportation mode is essential. The roadway is suitable for a short and medium distance at less than 500 km and in narrow aisles. The railway is suitable for long-distance at about 500-1000 km. And the waterway is suitable for a very long distance that further than 1000 km. However, the roadway is the fastest but the highest cost among these three modes. Oppositely, the waterway is the slowest yet cheapest mode.

2.3.2 Classification of objective functions

Objective functions and decision constraints of the optimization are needed to be considered. The objective function expresses the main goal of the business. Different objective functions give different optimal variables value which is a trade-off among them. Hence, entrepreneurs have to choose their main objective. The objective functions are usually classified as whether to minimize an overall cost in the supply chain, to maximize business' profit, or to maximize a net present value (NPV). However, some studies optimized multi-objective and benchmark them ([71], [30]). In bioenergy optimization, there have other objectives such as a carbon-dioxide emission minimization ([71]), land-used minimization ([30]) as well, etc which we will see some examples in the further section.

2.3.3 Classification of decision making

In [3], the paper classified the decision level of supply chain management into strategic, tactic, and operational levels.

The strategic decisions aim to find long-term goals. They focus on finding the right size, type, and location of facilities whether production factories, biomass supplier and transportation mode.

The tactical decisions aim to find a mid-term goal. They focus on logistics management such as finding the right amount of biomass, production, transportation over a time period.

The operational decisions aim to find a short-term goal. They are mostly day-by-day logistic planning including vehicles planning and scheduling.

Overall decision levels are simply shown in fig 2.1

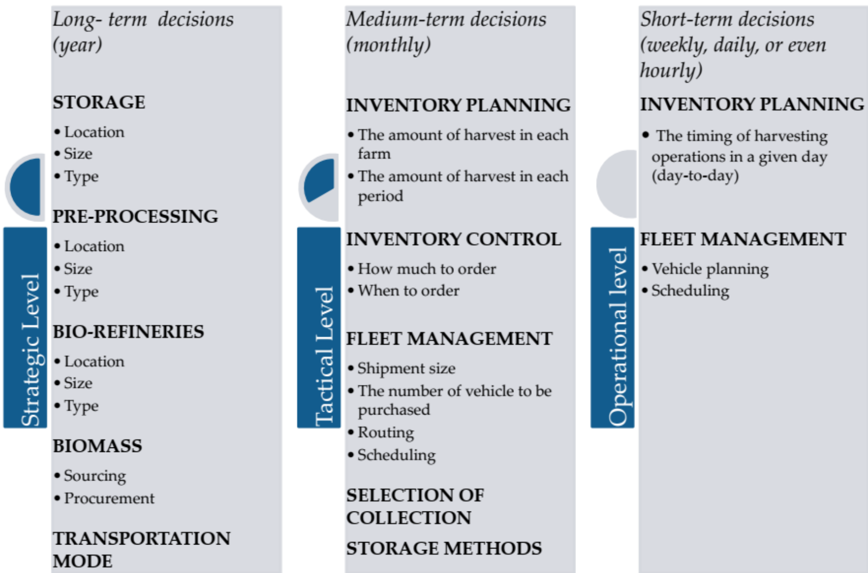


Figure 2.1: Decision levels in supply chain management

2.3.4 Classification of solution methods

Bioenergy supply chain optimization comes up with several optimization methods. Even though these methods are based on mathematical programming. However, there are several tools developed to help researchers optimize the supply chain easier.

Mathematical programming

Mathematical programming is the basic and the most utilized method. It consists of variables, objective function, and a set of constraints. These components are written in mathematical term. The mathematical models can be divided into 4 categories; Linear programming (LP), Integral programming (IP), Mixed Integer Linear Programming (MILP), and Non-linear Programming (NP).

Heuristics

Heuristic uses a practical method or shortcuts to produce solutions. This method is flexible and very fast. However, there do not guarantee that the solutions are optimal. But they are sufficient given a short limited time.

Multi-criteria decision analysis

Multi-criteria decision analysis is a method that optimizes the problem in different objective functions and compares them. This method aims to guide decision-makers assisting them to choose their preferred choice.

GIS-based

A Geographic Information System (GIS) is a computational based system that capture, store, manage, retrieve, analyze, and display spatial or geographical information. This system interacts with its user in a map-like interface. The user can input the locations of facilities in the system and specify necessary parameters. Then it will optimize and simulate such as time, transportation, route selection, amount of supplies, inventory level, etc in a specific time period over the running duration.

Simulation

Simulation software makes optimization tasks easier and animatedly visually. They can compute a complex task while visualizing output over a specific time period. The software' interface is more user-friendly than the mathematical programming method. However, it requires a lot of information as well as a lot of runs to find the precise optimal values

2.4 Related bioenergy optimization studies

Several studies studied bioenergy supply chain optimization. There are many studies conducted a biofuel supply chain optimization in the US. [3] did an overview and critical outlook of biofuel supply chain optimization. They gave an outlook of logistic activities including what biofuel supply chain optimization can vary in terms of objectives, decision levels, and methodologies. the paper focused on forest and wood chip biomass. As well as [29], they did a mathematical model of biofuel supply chain optimization focusing on cellulosic bioethanol and gave some other concerns in supply chain management such as land usage change, environment and social impacts, and governmental policies. [71] did switchgrass-based bioethanol supply chain optimization with different harvesting methods by using Mixed Integer Linear Programming (MILP). Their objective function is to minimize the total annual cost that occurs in the supply chain intending to find a suitable facilities location. [70] did a biofuel simulation by using Arena Simulation Software to minimize the feedstocks delivery cost, energy consumption, and Greenhouse gases emission. The simulation model provided several economic and environmental performance measures for each condition. [5] studied an effect of feedstock quality on overall cost and supply chain modelling. They proposed two-stage stochastic modelling of moisture content to optimize different scenarios.

Biomass and biogas supply chain have similar ideas. Many biomass supply chain conducted in Asia and Thailand. [53] reviewed different biomass feedstocks in different countries and their state-of-art energy conversion technologies. [24] conducted a case study in Thailand. They did the biomass supply chain modelling using Mixed Integer Linear Programming (MILP) with an objective function to minimize an overall supply chain cost to find an amount of biomass a power plant should order. They also considered a perishing of biomass. [26] presented a methodology to set up fuel supply strategies and determine the connected risks of different circumstances that will affect biomass quality and price, as well as a biomass potential in Northeast of Thailand. [59] presented the impact of the expansion of biomass production on the changes in economic variables and also carbon dioxide emission. The paper used regression calculation by Annex 12 Methodological tool. [67] studied the potential of using rubberwood residues for electricity generation in the southern part of Thailand. [25] did an overview of biogas production including feedstocks potential in Zimbabwe and state-of-art of biogas production. [30] did multi-goal linear programming (MGLP) to optimize biogas supply chain using artichoke in Europe, with objective functions to minimize land use of artichoke's area and Net Present Value (NPV) of existing plants.

To summarize these studies, we make Table 2.4 to compare them by their bioenergy system, objective function, decision-making level, and methodology as we mentioned in 2.3. However, These studies considered separated bioenergy system. But in our case, we integrate biofuel, biomass, and biogas together of which we have to apply these studies together.

Table 2.4: Bioenergy literature reviews comparison

Paper	Bioenergy systems	Objective function	Decision level	Methodology
[29]	bioethanol	minimize total cost	tactical	MILP
[71]	bioethanol	minimize total cost	strategic	MILP
[70]	bioethanol	minimize total cost and CO_2 emission	operational	simulation
[5]	bioethanol	minimize total cost	-	2-stage stochastic programming
[24]	biomass	minimize total cost	tactical	MILP
[30]	biogas	minimize land use and NPV	strategic	LP

2.5 Bioenergy supply chain in Thailand

A supply chain is a network between economical players to produce and distribute a specific product to the consumer. In the supply chain, there generally consists of suppliers, producers, consumers, and transporters. In some cases, there is possible not to have producers if those products are non-processed. The suppliers are who supply raw material. In our case, They are agriculturists and some factories that have biomass as a by-product from their main production processes. The producers are those who receive the raw material from suppliers and process them to make new products. Consumers are those who consume the products they buy from the producers. However, neither raw materials nor products can move. Hence, the transporters deliver these items from one place to another. Moreover, there are possibly facilitators in the supply chain as well.

Logistic activities are the key for every supply chain modelling. To manage well supply chain, we have to identify logistic activities that happen in the supply chain. Let's see the suppliers first. Here to obtain biomass, the agriculturists need to start by planting crops, nurture and fertilize them properly, and harvest them in harvesting season. Different types of crop need different cultivation and harvesting method of which makes the cost of the crops differently. However, the cost of biomass is not dependent on only cultivation cost, but also its dryness and heat capacity. The considered crops and their biomass were already mentioned in section 2.1

The second player in the supply chain is the transporter. In Thailand, we usually use a 10-

wheel truck to do this job. It costly efficient when a distance of transportation is less than 500 km and can fit to narrow local roads which bioenergy factories usually locate. The 10-wheel truck has 16 tons load capacity. Its width x length x height dimension is 2.3 x 7.2 x 2.2 m^3. The model of the 10-wheel truck is shown in Fig 2.2. Nevertheless, liquid biomass such as molasses cannot be transported by a 10-wheel truck. As for molasses, it is transported by petroleum tank trunk. Its capacity is 20,000 liters. However, this 10-wheel truck can be trailed by another car. But in our case, we use only an un-trailed one. The truck works by carrying biomass from suppliers whether they are from agriculturists or manufacturers to energy producer.

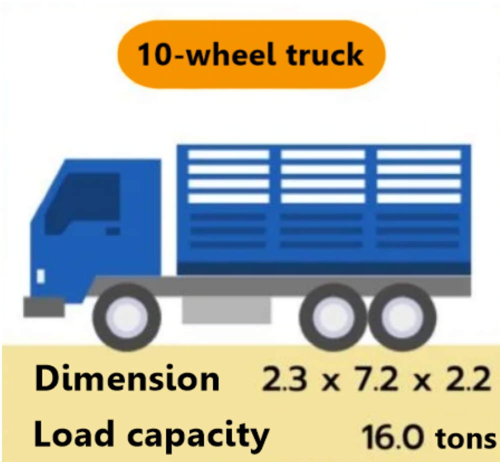


Figure 2.2: 10-wheel truck model

Since the truck has a weight and dimension limit per one trip, hence to calculate transportation cost, we have to consider the volume-matrix weight of the biomass which we will do in section 3.4

The third player is a bioenergy producer. As we already mentioned before, in this thesis, we consider electricity production from biomass and biogas; and bioethanol production. Hence, we have 3 different factory types; biomass power plants, biogas power plant, and bioethanol plant. The power plants receive biomass from the supplier which is carried by the transporters. The biomass is unloaded at the power plants' warehouse and waited to be fed into the energy production process inside the power plants. This prepared biomass is then called "feedstocks". Usually, in Thailand, the bioenergy power plants have an empty area as an open warehouse to place the unloaded biomass. One advantage of doing this is utilizing sunlight to dry biomass. When the plants need to use some feedstocks, they will pull from an inventory.

To produce electricity in biomass power plants, the feedstocks are pulled from inventory, then pass through a complex electricity production process and finally generate electricity. There are 3 different biomass power plant technologies used in Thailand; direct firing, gasification, and co-generation. In the biogas power plant, the feedstocks pulled from inventory are necessary to put to an anaerobic process to produce biogas before passing the biogas to the electricity production process to produce electricity. The bioethanol plant used only high-carbohydrate biomass such as molasses and cassavas to produce bioethanol. The feedstocks will need to put in the fermentation process to produce bioethanol. We will describe more detail about these bioenergy production technologies in section 2.6.

The fourth player is consumers who consume energy. The consumers include household, industrial, commercial, and government sectors. However, since we try to achieve the national target consumption. Thence, we have to balance energy target consumption to all energy produced annually for each alternative energy type.

Thailand bioenergy supply chain work flow diagram is shown in Fig 2.3.

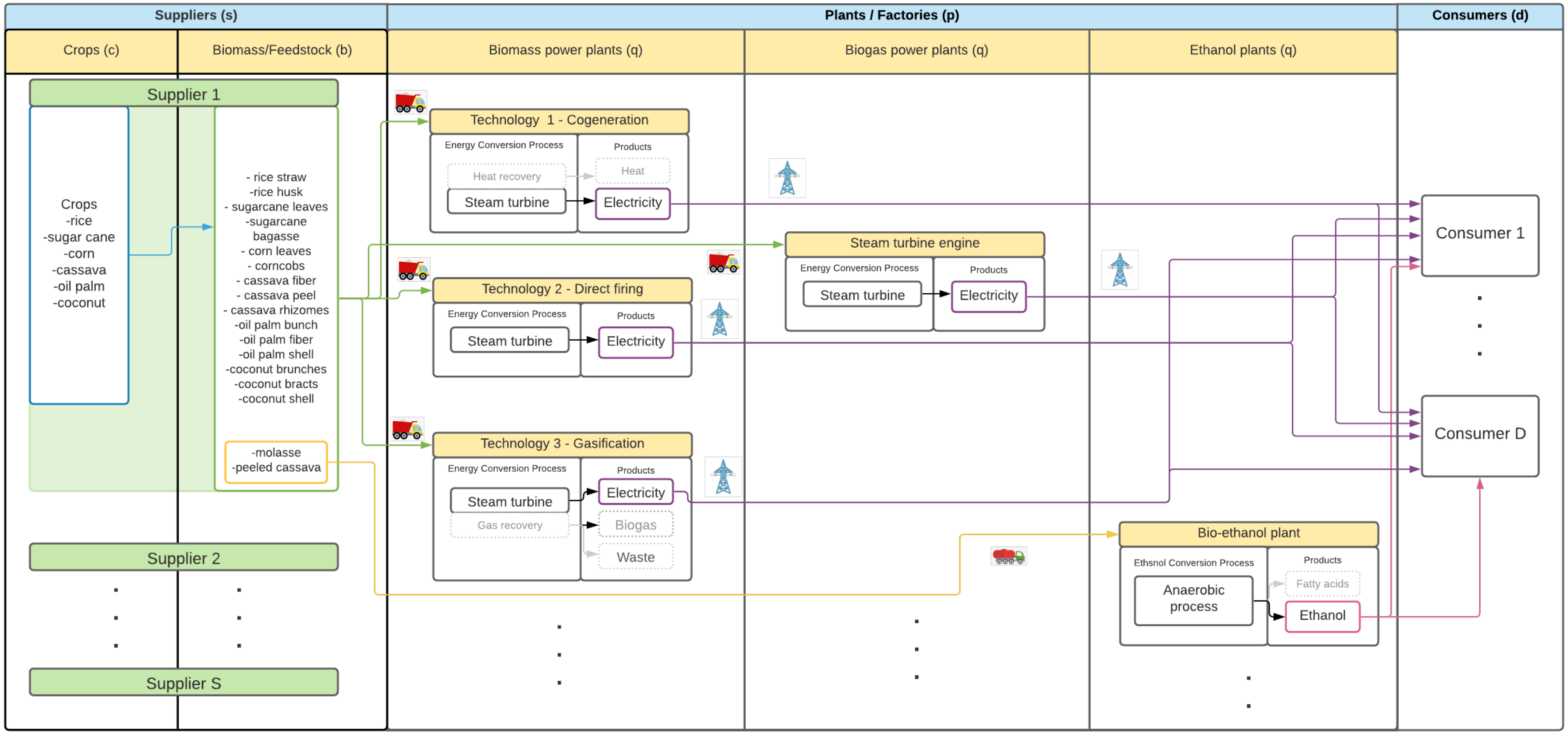


Figure 2.3: Thailand’s bioenergy supply chain diagram

2.6 Bioenergy production technologies

Electricity generation technologies from biomass used in Thailand are direct firing (direct combustion/ direct fired), gasification, and cogeneration, while electricity generation processes from biogas is direct firing, and bioethanol production process is fermentation/anaerobic process. The different production technologies give different energy efficiencies. In the following subsections, we will clarify each technology.

2.6.1 Direct firing

Direct firing a traditional method. It is the most simple process in produce electricity. However, its energy efficiency is the least. The direct firing process diagram is shown in Figure 2.4 ([18]). The process can be simply divided into 3 parts. The first part is biomass feedstock pre-treatment. This process dries out moisture within the biomass. The temperature used in this process is 200-320 degree Celsius. Then the pre-treated biomass will be fed into a combustion chamber afterwards. In some types of feedstock such as wood, the pre-treated biomass will be pelletized to increase a density before feed into the combustion chamber. This method increases the combustion efficiency up to 25%–30%. ([22])

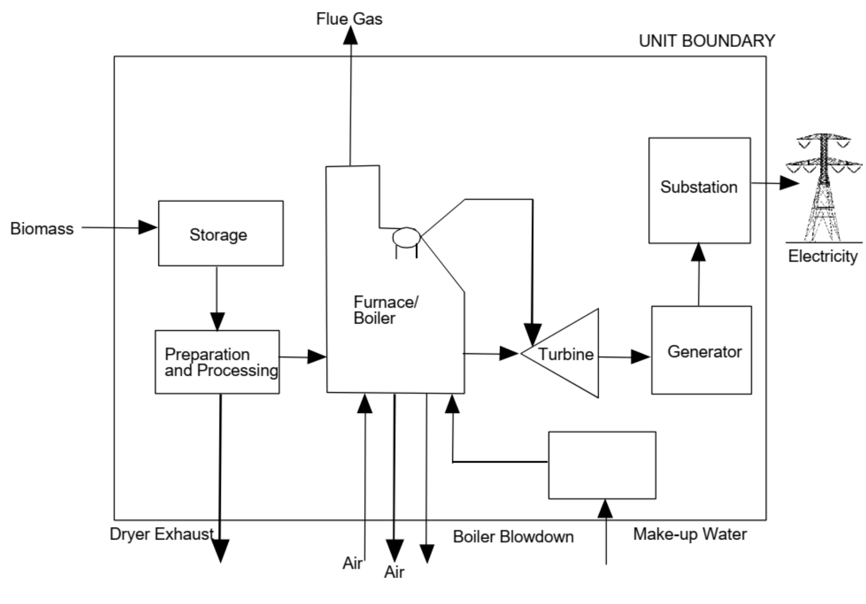


Figure 2.4: Direct firing process diagram ([18])

The second part is the combustion process. The pre-treated biomass will be combusted with oxygen at temperature 900 degree Celsius [18], heating inflow water to a vapour state. The vapour then passes through a condenser to increase pressure, and feed to a turbine to generate electricity.

The third part is the steam turbine engine which is connected to a generator. Here, the vapour temperature drops down to about 500 degree Celsius with the pressure at 15 -20 MPa depended on different commercial technologies. An overall heat cycle is the Rankine Cycle. The total energy efficiency since the beginning of the process of electricity generation is 20%-35%. The more modern structure give the more energy efficiency which depended on different commercial technology. However, in this thesis, we will consider the energy efficiency at 30% (stroker system) or with the ratio $8.33x10^{-5}$ MWh/MJ (convert from 0.3 MJ out put/MJ input, with $1 Joule = 2.777810^{-4} Wh$).

2.6.2 Gasification

The gasification process is the most used technology to produce electricity from biomass since this process does not generate only electricity, but also capture flue gases such as nitrogen, hydrogen, methane, carbon dioxide, and use them for further benefits.

The gasification power plant structure consists of 4 parts. The first part is the pretreatment process. Like the direct firing, this process is to dry out moisture within the biomass to increase the combustion efficiency. The second part is the pyrolysis process. In this pyrolysis process, the biomass is given heat without oxygen condition to prevent the biomass from combustion and causes it to be chemically altered. The biomass is heated at temperature 200-300 degree Celsius [22]. Here, the process produces pyrolysis oil, flue gases, and biochar. Then, the pyrolyzed biomass will be fed to the third part, a gasification process.

The gasification process is similar to the pyrolysis one. The biomass is heated without oxygen at temperature 600-800 degree Celsius [43]. There, the flue gases are more produced. The inflow water has heat exchanging in this process (in some structures also have heat exchanging at the pyrolysis process as well). The water is heated up to vapour, then is condensed by a condenser before delivered to the gas turbine engine which is the fourth part. The turbine engine, which is connected to the generator, is driven by the condensed steam to generate electricity. The gasification process diagram is shown in Figure 2.5 [20]. The overall energy efficiency of the gasification process is in range 37%-45% [8] depended on different commercial technologies. However, in this thesis, we will consider the energy efficiency of this process at 45% or with the conversion ratio $1.25x10^{-4}$ MWh/MJ (convert from 0.45 MJ output/MJ input, with $1J = 2.777810^{-4} Wh$).

2.6.3 Co-generation

The co-generation process (or also known as Combined Heat and Power: CHP) is an approach that uses heat residue which is normally wasted in conventional power generation. The heat is recovered, then used to heat the biomass or biofuel to produce bioenergy. The co-generation avoids losses that could be incurred from a separate generation of heat and power. Compared with a conventional method, the co-generation systems can operate at total energy efficiency (heat and

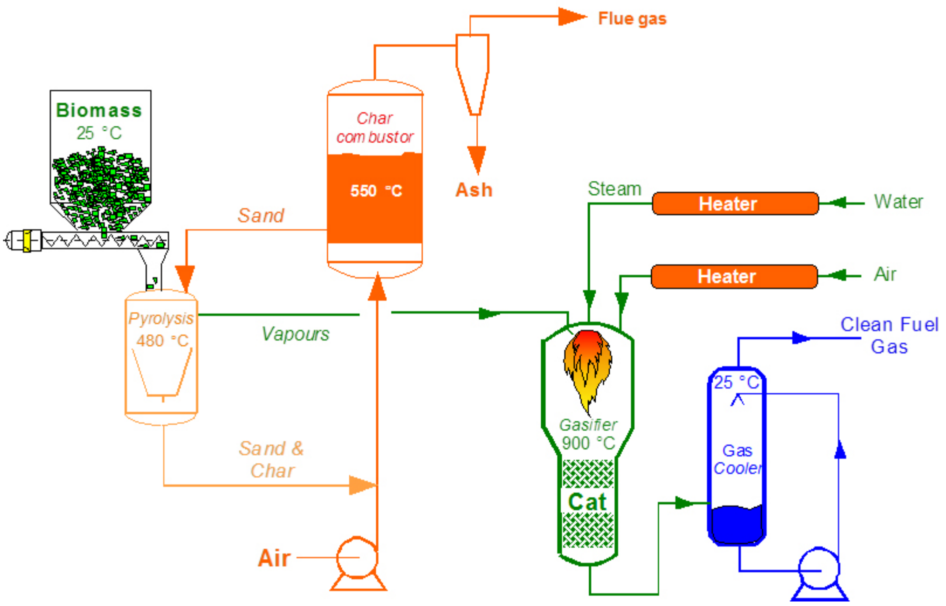


Figure 2.5: Gasification process diagram ([20])

electricity) levels at 80%, while the conventional method can operate just at 45%.

However, en energy efficiency ratio between thermal efficiency and electric efficiency is various depended on the objective of energy production. Some co-generation structures give 60%:20% heat: electricity ratio, while some structures give 45%:40% heat: electricity ratio. Nevertheless, in this thesis, we want to optimize electricity. So, we will use the electricity efficiency at 40% or with the conversion ratio $1.11x10^{-4}$ MWh/MJ (convert from 0.40 MJ output/MJ input, with $1J = 2.777810^{-4}Wh$).

2.6.4 Anaerobic digestion process

Anaerobic digestion is a biodegradation process by enzymes and microorganism in the absence of an oxygen environment (Figure 2.6 [7]. Initially, the biomass is hydrolyzed by enzymes (e.g. cellulase, amylase, protease, and lipase) into sugars, amino acid, and fatty acid. Next, fermentative bacteria, acidogens, convert these derivative products into carbon dioxide, hydrogen, ammonia, and organic acids. Then, acetogenic bacteria further convert these substances to acetate, carbon dioxide, and hydrogen. Finally, they are converted to methane and carbon dioxide by methanogens.

The anaerobic digestion conventionally operates in 2 different temperature level. Mesophilic digestion occurs at 30 - 38 Celsius and thermophilic digestion occurs at 49 - 57 degree Celsius. Thermophilic digestion always gives higher methane content.

The energy coefficient of biogas power plant is at 15%-25% ([41]). Here, we will use the coefficient at 15% which is $4.16x10^{-5}$ MWh/MJ (convert from 0.15 MJ output/MJ input, with $1J = 2.777810^{-4}Wh$).

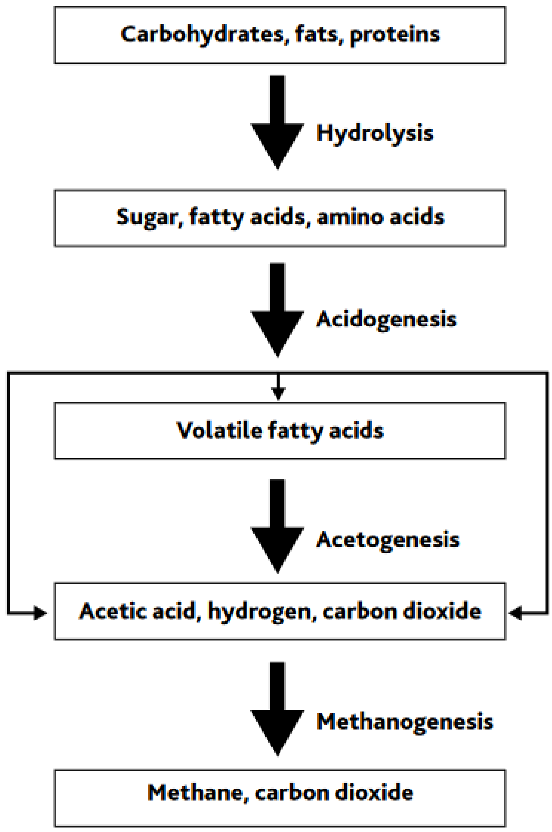


Figure 2.6: Anaerobic process diagram [7]

2.6.5 Fermentation

Fermentation is the conversion process of a plant's glucose (or carbohydrate) into alcohol or acid. In fermentation, yeast or bacteria are added to the biomass, which feeds on the sugars to produce ethanol and carbon dioxide. The ethanol is distilled and dehydrated to obtain a higher concentration of alcohol to achieve the required purity for use as automotive fuel. Besides this, the solid residue from the fermentation process can be used as cattle feed and in the case of sugarcane, can be used as a fuel for boilers or subsequent gasification. Figure 2.7 [55] shows the bioethanol production process from biomass.

Finally, for all energy conversion technologies we have been discussed, we assume that these plants have to spend 15% time to do preventive maintenance. Hence their maximum operational time is 85% [21] which means that energy produced from plants cannot exceed 85% of the labelled maximum energy production capacity.

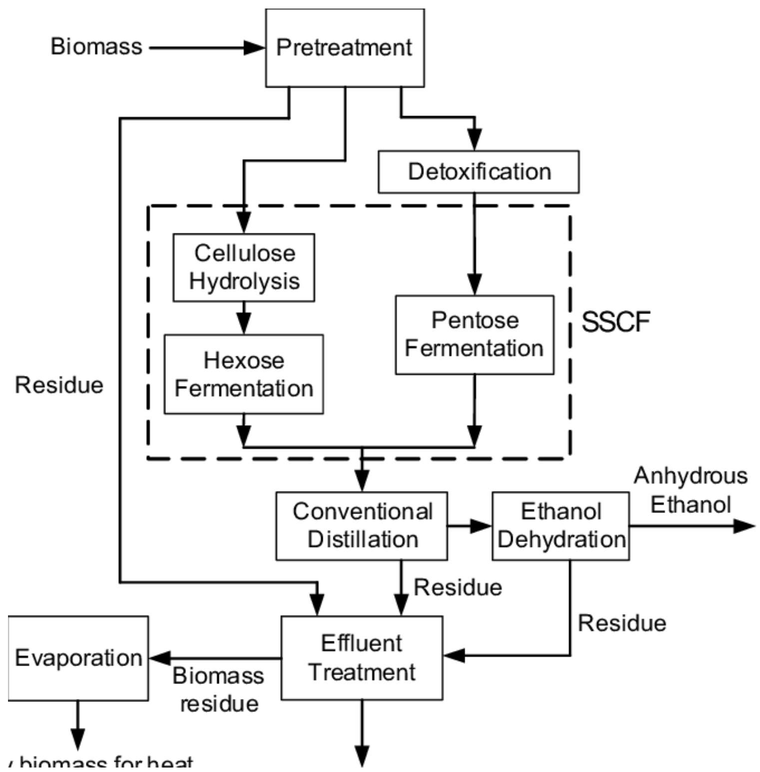


Figure 2.7: Fermentation process diagram [55]

Chapter 3

Research Methodology

3.1 Operational plan

To accomplish this study, we have to start by identifying players and logistics activities occurring in the supply chain. Then, we have to make a mathematical model associating with the logistic activities and context of the supply chain. Next, we collect all related data to input as parameters in the mathematical model. Afterwards, we do linear programming to obtain the optimal values and decision variables. Finally, we analyze the result and improve the supply chain model. The thesis approach workflow shows in Figure 3.1.

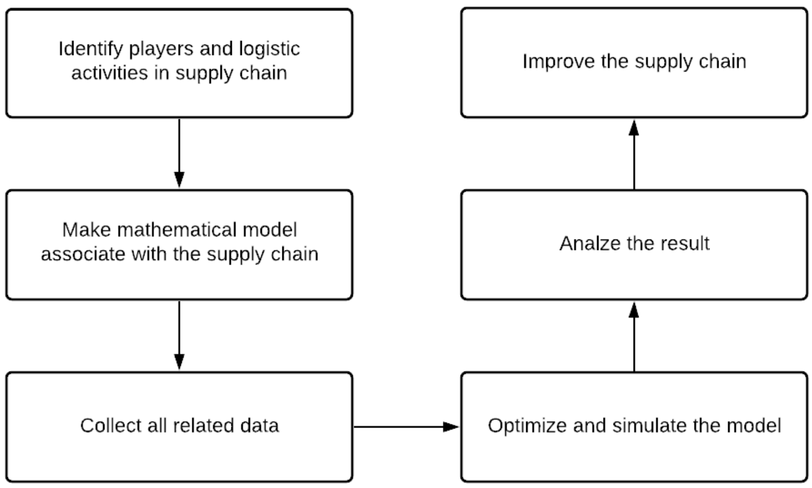


Figure 3.1: Operational workflow

3.2 Players and logistic activities in supply chain

In section 2.3, we already know what should we have to take into account when we do a bioenergy supply chain optimization. However, the players and logistics activities are different depended on the context of each country. As we mentioned in section 2.5, Realistically, for Thailand, we have 6 players in the bioenergy supply chain; the first one is suppliers who produce crops and agricultural residues including some manufacturers who have biomass and biowaste as their by-product; the second player is the transporter who deliver biomass from the suppliers to power plants and bioethanol plants, and deliver bioethanol from bioethanol plants to consumers; the third player is biomass power plants, biogas power plants, and bioethanol plants to produce electricity and bioethanol; the fourth player is the first-step distributor who transmits electricity from power plants to retailers; the fifth player is retailers who buy electricity from power plants and then sell it to consumers; the last player is the consumers who consume electricity and bioethanol. However, since we cannot access all data. Hence, we simplify our supply chain.

In our supply chain model, we assume that the retailer provides all electricity to the consumers within the retailer's jurisdiction. So here, we consider retailers as the consumers themselves, and we will not consider the electricity distribution between consumers and retailers since we are unable to access the specific location and voltage of the electrical grid. Thus, the simplified supply chain model has 4 players, and their workflow is shown in Figure 2.3. Another issue is we do not know the bioethanol demand for each consumer. Thus, we consider only the total bioethanol production.

One supplier is assumed to be one province. Hence, we will have totally 77 suppliers. Each supplier provides different types and different amount of biomass. The transportation mode used in Thailand is the 10-wheel truck. The power plant's production technologies are either direct-firing, co-generation, or gasification. Each power plant has only one technology. The bioethanol plants use an anaerobic process. And we consider retailers as the consumers themselves as stated before.

3.3 Mathematical model

In our case, we consider an annual profile with a monthly time-step. There are 77 suppliers supplying the different amount of 17 biomasses. There are totally 427 bioenergy plants which are 215 biomass power plants, 185 biogas power plants, and 27 bioethanol plants. And, there are 5 different energy productions technologies. Here, q=1,2,3 represent direct-firing, gasification, and co-generation technologies respectively of biomass power plants; while q=4 represents anaerobic digestion of biogas power plants, and q=5 represents the fermentation process of bioethanol plants.

Decision-making variables are; the amount of biomass delivered from different suppliers to different plants at each time-step; the amount of biomass inputted into the energy production process at each plant and time-step; inventory level and its maximum at each plant.

Parameters consist of biomass available at each supplier, distance between suppliers and plants, Plants' maximum energy production capacity, energy conversion factors, energy efficiencies, capacity factors, and costs.

The notation of indices, variables, and parameters are shown in Table 3.1, Table 3.2, and Table 3.3 respectively.

Table 3.1: Indices notation

Symbol	Description
t	Set of time step t (1,2,...,365)
s	Set of supplier s
b	Set of biomass type b
p	Set of plant p
q	Set of plant technology q

Table 3.2: Variables notation

Variable	Unit	Description
X^{B}_{bspqt}	tons	Amount of biomass type b delivered from supplier s to plant p (which uses technology q) at time t
X^{P}_{bpqt}	tons	Amount of biomass type b fed into production process of plant p (which uses technology q) at time t
I_{bpqt}	tons	Inventory level of biomass b at plant p (which uses technology q) at time t
I^{max}_{pq}	tons	Maximum Inventory level at plant p (which uses technology q) at time

Table 3.3: Parameters notation

Parameter	Unit	Description
B^{max}_{bst}	ton	Amount of biomass type b available from supplier s at time t
L_{spq}	km	Distance from supplier s to plant p (which uses technology q)
Elc^{max}_{pq}	MW	Maximum electricity production capacity of plant p (which uses technology q)
Eth^{max}_{pq}	Litres/day	Maximum ethanol production capacity of plant p (which uses technology q)
$D^{Elc,B}$	MWh	National electricity consumption from biomass
$D^{Elc,G}$	MWh	National electricity consumption from biogas
D^{Eth}_{t}	Litres/day	Amount of ethanol consumption at time t
f^{B-Eth}_{b}	Liters/ton	Coefficient for converting biomass b to ethanol
$f^{B-H,B}_{b}$	MJ/ton	Heat capacity of converting biomass type b to heat
$f^{B-H,G}_{b}$	MJ/ton	Heat capacity of converting methane from biomass type b to heat
f^{H-Elc}_{q}	MWh/MJ	Coefficient for converting heat to electricity with technology q

Table 3.3: Parameters notation

Parameter	Unit	Description
C_b^{TV}	THB/ton.km	Transportation variable cost of biomass type b
C_{pq}^{O-Elc}	THB/MWh	Electricity operational cost of power plant p (which uses technology q)
C_{pq}^{O-Eth}	THB/Litre	Ethanol operational cost from biomass of plant p(which uses technology q)
C_{bst}^{B}	THB/ton	Material cost of biomass type b
C_b^{h}	%	Holding cost biomass type b = 10 % of biomass cost
pf_q	%	Percentage of plant's operational time by total time in a day
N_t	days	Number of days in month t|

The objective function is to minimize an annual total cost (equation 3.1). The total cost consist of biomass cost (equation 3.2), transportation cost (equation 3.3), plants' operational cost (equation 3.4), and holding cost (inventory cost) (equation 3.5).

$$\begin{aligned} Min\ Z = &\ Annual\ biomass\ cost + Annual\ transportation\ cost \\ &+ Annual\ operational\ cost + Annual\ holding\ cost \end{aligned} \tag{3.1}$$

$$Annual\ biomass\ cost\ = \sum_{b,s,p,q,t} (C_{bst}^{B} \cdot X_{bspqt}^{B}) \tag{3.2}$$

$$Annual\ transportation\ cost\ = \sum_{b,s,p,q,t} (C_b^{TV} \cdot X_{bspqt}^{B} \cdot L_{spq}) \tag{3.3}$$

$$\begin{aligned} Annual\ operational\ cost = &\sum_{p,q=1,2,3,t} (C_{pq}^{OElc} \cdot (f_q^{H-Elc} * \sum_b (X_{bpqt}^{P} * f_b^{B-Elc,B})) \\ &+ \sum_{p,q=4,t} (C_{pq}^{OElc} \cdot (f_q^{H-Elc} * \sum_b (X_{bpqt}^{P} * f_b^{B-Elc,G})) \\ &+ \sum_{p,q=5,t} (C_{pq}^{OEth} \cdot \sum_b (X_{bpqt}^{P} * f_b^{B-Eth})) \sum_b (X_{bpqt}^{P} * f_b^{B-Eth})) \end{aligned} \tag{3.4}$$

$$Annual\ holding\ cost\ = \sum_{p,q,t} (\sum_b (I_{bpqt} \cdot C_b^{h})) \tag{3.5}$$

The annual biomass is a sumproduct of biomass cost C_b^B [THB/ton] and amount of biomass delivered to plants X^{B}_{bspqt} [tons]. The annual transportation cost is a sumproduct of transportation variable cost of each biomass type C^{TV}_{b} [THB/ton.km], amount of biomass delivered to plants X^{B}_{bspqt} [tons], and distance between suppliers and plants L_{spq} [km]. The annual energy operational cost is split into three parts; electricity production from biomass (first term of equation 3.4), electricity production from biogas (second term of equation 3.4), and bioethanol production (third term of equation 3.4). The electricity operational cost from biomass power plants is a sumproduct of biomass power plant's operational cost $C^{O,Elc}_{pq}$ [THB/MWh] and electricity produced $f^{H-Elc}_{q} * \sum_{b}(X^{P}_{bpqt} * f^{B-Elc,B}_{b})$. The electricity operational cost from biogas power plants is a sumproduct of biogas power plant's operational cost $C^{O,Elc}_{pq}$ [THB/MWh] and electricity produced $f^{H-Elc}_{q} * \sum_{b}(X^{P}_{bpqt} * f^{B-Elc,G}_{b})$. The bioethanol operational cost is a sumproduct of bioethanol plant's operational cost $C^{O,Eth}_{pq}$ [THB/liter] and bioethanol produced. The holding cost is a sumproduct of holding cost of each biomass C^{h}_{b} [THB/ton] and inventory level I_{bpqt} [tons].

Constraints we have to take into account are limitations of logistic activities in the supply chain. First, we have a limitation of biomass availability. So, we cannot deliver biomass to plants more than suppliers have (inequality 3.6)

$$0 \leq \sum_{p,q} X^{B}_{bspqt} \leq B^{max}_{bst} \qquad \forall b, s, t \tag{3.6}$$

However, each plant has the limitation of biomass received at each time-step, it cannot exceed the plant's maximum inventory level (inequality 3.7).

$$0 \leq \sum_{b} I_{bpqt} \leq I^{max}_{pq} \qquad \forall p, q, t \tag{3.7}$$

After biomass delivered to plants and be kept inside the inventory, now it becomes a feedstock inputted to the energy production process. In each time-step, there is a change in inventory level all the time. The change of inventory level is as in equation 3.8. The inventory level at current time $I_{b,p,q,t}$ is equal to the previous time-step inventory level $I_{b,p,q,t-1}$ plus the biomass getting from supplier $\sum_{s} X^{B}_{bspqt}$, then subtract by the biomass used for energy production process X^{P}_{bpqt}. While the feedstocks pulled from inventory cannot exceed the inventory level (inequality 3.9).

$$\begin{aligned} I_{b,p,q,t} &= \sum_{s} X^{B}_{bspqt} - X^{P}_{bpqt} \qquad \forall b, p, q, t = 0 \\ I_{b,p,q,t} &= I_{b,p,q,t-1} + \sum_{s} X^{B}_{bspqt} - X^{P}_{bpqt} \qquad \forall b, p, q, t \neq 0 \end{aligned} \tag{3.8}$$

$$
\begin{aligned}
&X^P_{b,p,q,t} \leq \sum_s X^B_{bspqt} \qquad \forall b,p,q,t=0 \\
&X^P_{b,p,q,t} \leq I_{b,p,q,t-1} + \sum_s X^B_{bspqt} \qquad \forall b,p,q,t \neq 0
\end{aligned} \tag{3.9}
$$

Each plant has its maximum energy production capability, where the maximum production capacity of power plants is Elc_p^{max} [MW] and the maximum bioethanol production is Eth_p^{max} [liters/day]. Hence, the plants cannot produce energy more than their limit. The energy production constraint for biomass and biogas power plants are shown in inequality 3.10, respectively, and for bioethanol plants is shown in inequality 3.12.

$$
f_q^{H-Elc} * \sum_b (Xp_{b,p,q=1,2,3,t} * f_b^{B-H,B}) \leq Elc_p^{max} * pf_{q=1,2,3} * 24 * N_t \;\; \forall p,t \tag{3.10}
$$

$$
f_q^{H-Elc} * \sum_b (Xp_{b,p,q=4,t} * f_b^{B-H,G}) \leq Elc_p^{max} * pf_{q=4} * 24 * N_t \;\; \forall p,t \tag{3.11}
$$

$$
\sum_b (Xp_{b,p,q=5,t} * f_b^{B-Eth}) \leq Eth_p^{max} * pf_{q=5} * N_t \;\; \forall p,t \tag{3.12}
$$

The energies produced have to be matched with demands. Electricity produced from biomass matches with national electricity from biomass demand (equation 3.13). Electricity produced from biogas matches with national electricity from biogas demand (equation 3.14). And bioethanol produced matches with national bioethanol demand (equation 3.15).

$$
\sum_{p,t} \sum_b (Xp_{b,p,q=1,2,3,t} * f_b^{B-Elc,B}) = D^{Elc,B} * 24 * N_t \tag{3.13}
$$

$$
\sum_{p,t} \sum_b (Xp_{b,p,q=4,t} * f_b^{B-Elc,B}) = D^{Elc,G} * 24 * N_t \tag{3.14}
$$

$$
\sum_p (Xp_{b,p,q=5,t} * f_b^{B-Eth}) = D_t^{Eth} * N_t \qquad \forall t \tag{3.15}
$$

And finally, the last constraint (inequality 3.16) is to ensure that all variables are non-negative.

$$
X^B_{bspqt}, \quad X^P_{bpqt}, \quad I_{b,p,q,t}, \quad I_p^{max} \geq 0 \tag{3.16}
$$

3.4 Data collection

Biomass

Regarding the parameters used for our optimization model as shown in Table 3.3, we have to collect the data for each supplier, power plant, bioethanol plant, energy production technology, consumer, at each time-step. Biomass and energy plants related data are collected from Department of Alternative Energy Development and Efficiency (DEDE) ([12]) and Ministry of Energy (MOE) [37]. The available biomass is totally 17 type as shown in Table 1.2. These amount of crops available in each province data is collected from an official website of the Office of Agricultural Economics (OAE) ([13]), which the data is in year 2019. Then we acquire the amount of biomass available by multiplying the amount of crops with biomass ratio coefficient as shown in Table 2.1. Their green biomass (weight including moisture content) prices are shown Table 3.4 ([24], [50]). Their heat capacities are shown in Table 3.5 ([10]). And their methane component and heat equivalent are shown in Table 3.6 ([65], [68]). The methane density is at 0.657 kg/m^3 (with molar mass 16.043 g/mol), and its specific heat capacity; c_v = 27.4 J/mol.K or 1.709 kJ/kg.K ; c_p = 35.8 J/mol.K or 2.232 kJ/kg.K ([62]). The amount of biomass available data in each province is attached in the file "monthly suppliers profile.csv" [27].

Table 3.4: Green biomass price

Biomass	Price (THB/ton)
1. rice straw	2000
2. rice husk	1500
3. sugarcane leaves	800
4. bagasse	500
5. molasses	10410 [31]
6. corn leaves and tops	1500
7. corncob	500
8. peeled cassava	2700 [1]
9. cassava rhizome	1800
10. cassava fiber	3300
11. cassava peels	2800
12. oil palm bunch	50
13. oil palm fiber	1500 [58]
14. oil palm shell	3200
15. coconut bunch	1000
16. coconut bract	5000
17. coconut shell	1000

For bioethanol production, there are only 2 biomasses used which are molasses and peeled cassava. The molasses to bioethanol coefficient is 3.8 kg/liter of bioethanol. And peeled cassava to bioethanol coefficient is 5.975 kg/liter of bioethanol ([61]).

Table 3.5: List of Crops and their derived biomass

Biomass	Heat capacity (MJ/ton of biomass)
1. rice straw	12330
2. rice husk	13520
3. sugarcane leaves	15480
4. bagasse	7370
5. molasses	No usage in heat conversion. Use only for bioethanal conversion.
6. corn leaves and tops	9830
7. corncob	9620
8. peeled cassava	No usage in heat conversion. Use only for bioethanal conversion.
9. cassava rhizome	5490
10. cassava fiber	1470
11. cassava peels	1490
12. oil palm bunch	7240
13. oil palm fiber	11400
14. oil palm shell	16900
15. coconut bunch	15400
16. coconut bract	16230
17. coconut shell	17930

Distances

The geographical coordinate of each supply chain component is identified from google map. The distance among them is calculated from using python-OSRM package. The distance between suppliers and bioenergy plants is attached in the file ”distance.csv”.

Transportation

As we already stated before. Thailand uses a 10-wheel truck as a transportation mode to transport biomass and use petroleum tank truck to transport molasses. According to [56], variable cost consists of fuel cost, tires cost, and maintenance cost. The fuel consumption rate of the 10-wheel truck is 5 km/Liter. Here, we consider that the truck uses diesel. Its price is 24.09 THB/liter (price on 1 May 2021). Hence, the fuel consumption price is 4.818 THB/km. The tires cost is 8,000 THB/tire which makes totally 80,000 THB for all 10 tires. Each tire has 70,000 km lifespan. Thus, the tires cost is 1.143 THB/km. And finally, the maintenance cost is averagely 0.6 THB/km. Therefore, the total variable cost is **6.561 THB/km**.

However, to calculate each biomass transportation cost in the unit of THB/km.ton, we have to consider the amount of biomass that the truck can load for one trip. Since the truck has 2.3 x 7.2 x 2.2 m^3 cargo dimension and 16 tons maximum weight capacity while the petroleum tank truck has 20,000 L capacity, we have to choose whether the loaded biomass' weight per truck is limited

Table 3.6: Methane acquired from biomass

Biomass	Methane content (m^3/ kg of biomass)	Heat equivalent (MJ/ ton biomass)
1. rice straw	0.226 [65]	108.0402
2. rice husk	0.019 [65]	9.0830
3. sugarcane leaves	0.148 [39]	70.7520
4. bagasse	0.185 [49]	88.4400
5. molasses	0.324 [15] No usage in biogas conversion. Use only for bioethanal conversion.	154.8896
6. corn leaves and tops	0.199 [69]	95.1327
7. corncob	0.1 [68]	47.8054
8. peeled cassava	0.262 [57](No usage in biogas conversion. Use only for bioethanal conversion.)	125.2502
9. cassava rhizome	0.09676 [46]	46.2565
10. cassava fiber	0.167 [57]	79.8350
11. cassava peels	0.078 [57]	37.2882
12. oil palm bunch	0.1996 [6]	95.4196
13. oil palm fiber	0.1664 [6]	79.5482
14. oil palm shell	No usage in biogas conversion.	0
15. coconut bunch	No usage in biogas conversion.	0
16. coconut bract	No usage in biogas conversion.	0
17. coconut shell	No usage in biogas conversion.	0

by the truck's maximum weight capacity or its cargo dimension. To know that, biomass' densities are needed. The biomass densities are shown in Table 3.7. Here we consider one truck carries only one type of biomass. So, if the biomass weight at maximum truck weight capacity does not exceed its cargo dimension, then we consider 16 tons biomass for one truck. In contrast, if the biomass weight at maximum truck weight capacity exceeds its cargo dimension, then we consider weight at track's maximum cargo volume for one truck instead.

The following steps are an approach to calculate the transportation cost of biomass.

1. Determine the 10-wheel truck's variable cost in unit of THB/km.

2. Calculate the maximum weight of biomass that the truck can load by comparing between the limitation of truck's cargo dimension and weight capacity as we mentioned earlier.

3. Divide step 1 by step 2 to get a variable transportation cost in unit of THB/km/ton.

The calculated variable biomass transportation cost is shown in Table 3.8.

Table 3.7: Biomass densities

Biomass	Density (kg/m^3 of biomass)
1. rice straw	178.255 [73]
2. rice husk	356.065 [73]
3. sugarcane leaves	190.43 [44]
4. bagasse	160 [42]
5. molasses	1441 [38]
6. corn leaves and tops	81.61 [72]
7. corncob	182.38 [72]
8. peeled cassava	637.38 [4]
9. cassava rhizome	238 [66]
10. cassava fiber	712.50 [17]
11. cassava peels	247.87 [4]
12. oil palm bunch	380 [60]
13. oil palm fiber	250[60]
14. oil palm shell	400 [60]
15. coconut bunch	355 [48]
16. coconut bract	151.91 [54]
17. coconut shell	920.53 [54]

Power plants and bioethanol plants

The list and production capability for biomass power plants, biogas power plants, and bioethanol plants are collected from the website of the Department of Alternative Energy Development and Efficiency (DEDE) ([11]). Used technologies and other information for each plant are investigated separately. The energy conversion coefficient for direct-firing, gasification, and co-generation are 8.33×10^{-5} , 1.25×10^{-4} , and 1.11×10^{-4} MWh/MJ respectively as we already clarified in section 2.6.

Plants' operational cost is calculated in term of a Levelized Cost of Energy (LCOE). Depending on the technology, LCOE considers investment, operation, maintenance, and feedstocks cost together and appraise it in the unit of currency per energy (USD/kWh). According to [21], an investment LCOE of direct-firing is 0.04-0.13 USD/kWh, gasification is 0.11-0.28 USD/kWh, and co-generation is 0.07-0.29 USD/kWh. In this thesis, we use their median values as representative of the corresponding technologies and convert currency unit to THB with 1 USD = 31.14 THB. Hence, the investment LCOE of direct-firing is 2.6469 THB/kWh = 2,646.90 THB/MWh, gasification is 5.7609 THB/kWh = 5,760.90 THB/MWh, and co-generation is 5.6052 THB/kWh = 5,605.20 THB/MWh. However, these LCOEs consider only an investment cost. Operation and maintenance cost is accounted for 20% of the investment LCOE. We will not include the material cost in the LCOE cost since we already accounted it separately. Thus, the investment, operation and maintenance LCOE of direct-firing, gasification, and co-generation are 3,176.28 THB/MWh, 6,913.08 THB/MWh, and 6,726.24 THB/MWh respectively. Biogas power plants have a total

Table 3.8: Variable transportation cost

Biomass	Variable cost (THB/km.ton of biomass)
1. rice straw	1.01
2. rice husk	0.51
3. sugarcane leaves	0.95
4. bagasse	1.13
5. molasses	0.23
6. corn leaves and tops	2.21
7. corncob	0.99
8. peeled cassava	0.41
9. cassava rhizome	0.76
10. cassava fiber	0.41
11. cassava peels	0.73
12. oil palm bunch	0.47
13. oil palm fiber	0.72
14. oil palm shell	0.45
15. coconut bunch	0.51
16. coconut bract	1.19
17. coconut shell	0.41

LCOE at 3,500.00 THB/MWh ([28]). And bioethanol plants have total LCOE at 7.2990 THB/liter ([52]).

The capacity factor determines the percent of energy generation by its possible maximum energy generation capability. Besides, we also have to consider maintenance as such no plant can use its full potential. Here, we consider all plants have to preserve preventive maintenance at least 15% ([21]) of their total time. So, all plants have their maximum capacity factor at 0.85.

All plants data including biomass, biogas power plants, and bioethanol plants is attached in file ”plants profile.csv” [27]. Their geographical locations are attached in file ”plants loc.csv” [27].

3.5 Optimization and analysis tools

To achieve this supply chain simulation, optimization tools are necessary. In this thesis, we use the mathematical programming method as we already showed in section 4.1. The model is Linear Programming (LP). And Python programming language version 3.9 is used for coding.

The related Python packages used for this thesis consist of Numpy, Pandas, CSV, PuLP, and Matplotlib. The Numpy is used for general mathematics and numerical array computation. The Pandas is used for a data structure. The CSV is used for working with a .csv file to import input parameters. The PuLP is used for doing Linear Programming and optimal result obtaining. And the last one, Matplotlib is used to generate graphs and diagrams to show the change of optimal variables along the time.

Chapter 4

Optimization result: bioenergy potential

4.1 Current bioenergy potential: the case 1

After a mathematical model was generated. However, the current biomass and/or plants profiles could not satisfy targeted demand according to the AEDP. The major question is how much maximum bioenergy potential Thailand has. To find this answer, we change 3 national consumption demand parameters which are electricity from biomass demand $D^{B,Elc}$; electricity from biomass demand $D^{G,Elc}$; and bioethanol demand D^{Eth} to variables instead, and change an objective function to maximize annual energy output as shown in equation 4.1. These 3 variables are limited their boundary up to the targeted consumptions which are 3940 MW, 387 MW, and 4.79 ML/day respectively. Here, we make the energy output in the unit MWh. Since $D^{B,Elc}$ and $D^{G,Elc}$ are in unit MW, we multiply them by 24. And since D^{Eth} is in unit liters/day, as one liter of bioethanol give energy equivalently $5.9313x10^{-3}$ MWh, we multiply it with the bioethanol demand variable, then sum them for all time-step. However, optimization constraints are still the same as we already showed in section .

$$Max\,\Gamma = (24 \cdot (D^{B,Elc} + D^{G,Elc}) + \sum_{t} (D^{Eth} \cdot 0.0059313) \cdot N_t)$$

The optimization took 4,564 seconds to optimize. The result showed that Thailand has the ability to produce bioenergy up to 33.02 TWh which is divided into; electricity from biomass at 2,550.4 MW; electricity from biogas at 35.65 MW; and bioethanol at 4.79 ML/day. However, according to AEDP, the current bioethanol potential can satisfy the target, but the current potential electricity from biomass and biogas cannot. There are 1389.6 MW and 351.35 MW of biomass and biogas respectively needed to reach the target. All Biomass types are used to generate energy.

Now, we changed an objective function back as we used to discuss in section 4.1 with the same constraints. We substitute national electricity demand from biomass $D^{B,Elc}$ to 2,550.4 MW, electricity demand from biogas $D^{G,Elc}$ to 35.65 MW, and bioethanol demand D^{Eth} to 4.79 ML/day to see how the supply chain behave when we produce energy at current maximum bioenergy potential. Let's call this case ”case 1”. The optimization took 2,378 seconds to optimize. The result showed that the total cost is 375.22 billion THB which are 185.94 billion THB for total biomass cost, 6.57 billion THB for total transportation cost, 16.78 billion THB for holding cost, 152.06 billion THB for biomass power plants' operational cost, 1.09 billion THB for biogas power plants' operational cost, and 12.76 billion THB for bioethanol plants' operational cost.

However, not all biomass types used for this case. Biomass types 14-16 are not used at any time step while type 17 are used for about 8% of its maximum available. Overall biomass usages are shown in figure 4.1

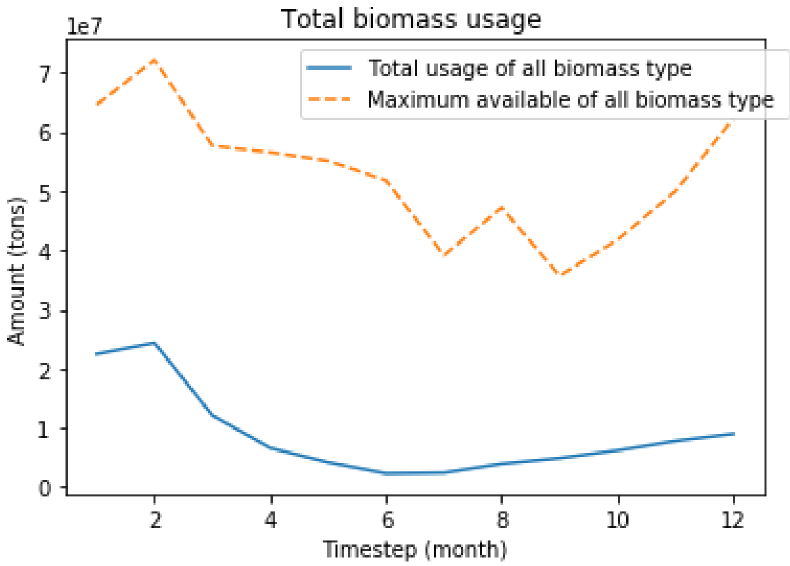
The capacity factor of all plants is at 0.89 in this case. the capacity factor of biomass power plants is 1.0. The capacity factor of biogas power plants is 0.1. And the capacity factor of bioethanol plants is 0.89. The energy produced from plants is shown in figure 4.2. All biomass power plants operate at their maximum potential to generate electricity. Bioethanol plants spend about 89% of their maximum potential to produce bioethanol to satisfy the target bioethanol demand. While biomass power plants spend only 10% to generate electricity.

An overall inventory level significantly fluctuates, especially in the early months. The reason is there is a low amount of biomass during the middle of the year, it is necessary to stock biomass to have enough feedstocks to produce energy to satisfy demands in this period. An inventory utilization of all plants is 41.58%, where inventory utilization of biomass power plants, biogas power plants, and bioethanol plants are 8.73%, 42.13%, and 35.14% respectively. A population variance of overall inventory level of all plants is $156.93 \times 10^{12}\ tons^2$. Biomass power plants, biogas power plants, and bioethanol plants population variances are 0, 4.55×10^{12}, and 68.06×10^9. Here, we can see that biomass power plants' inventory have no bottlenecks. The overall inventory level of all plants, biomass power plants, biogas power plants, and bioethanol plants are shown in figure 4.3.

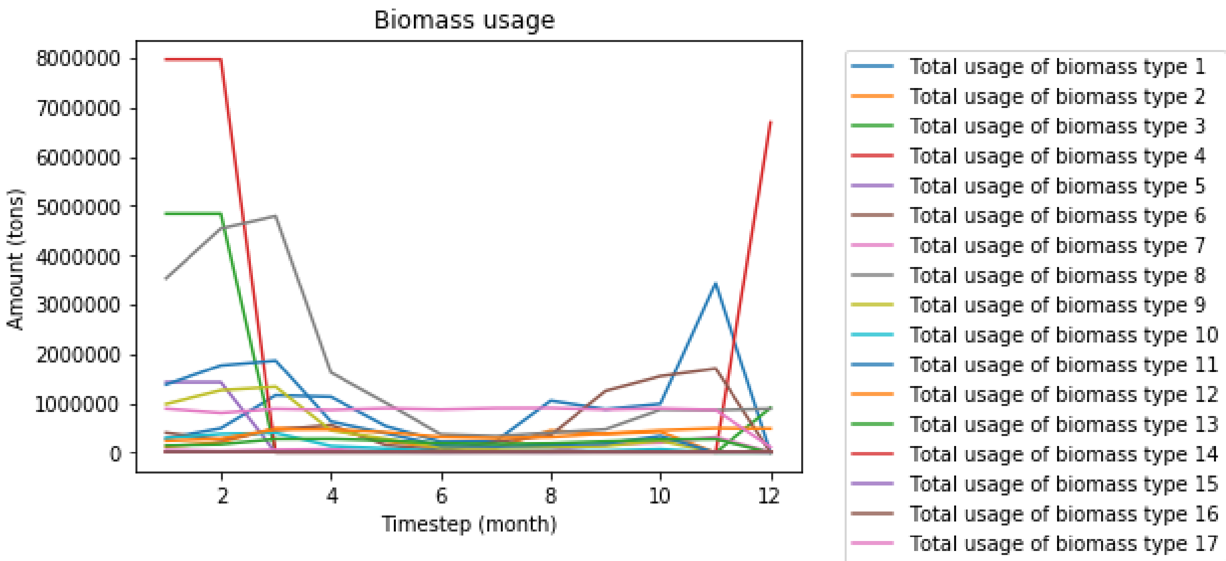
Even though biomass power plants and bioethanol plants spend their possible potential to satisfy demands, there are 55.67% of biogas power plants (103 plants out of 185 plants) do not operate in this case. However, realistically, all plants should operate since entrepreneurs already invest on building facilities. There is no sense to not utilize their assets. Hence, we improve our model to make all plants operate.

4.2 Improved supply chain at current bioenergy potential: the case 2

In the previous case, there is 55.67% of biogas power plants operate. There are 41.58% inventory utilization and $156.93 \times 10^{12} tons^2$ inventory populational variance. Here, we want to make all plants operate as much as possible and also reduce the variance of inventory level. So, we change the objective function to minimize the total maximum inventory level as shown in equation 4.2.

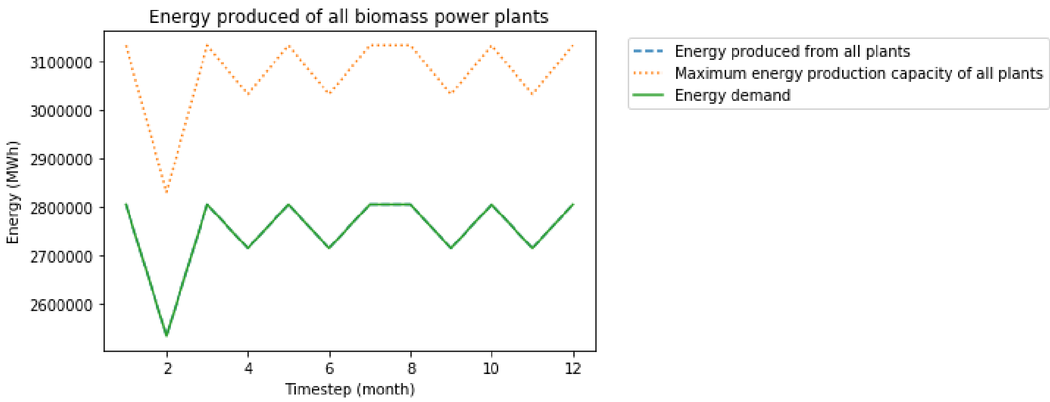


(a) Total biomass usage and its maximum available

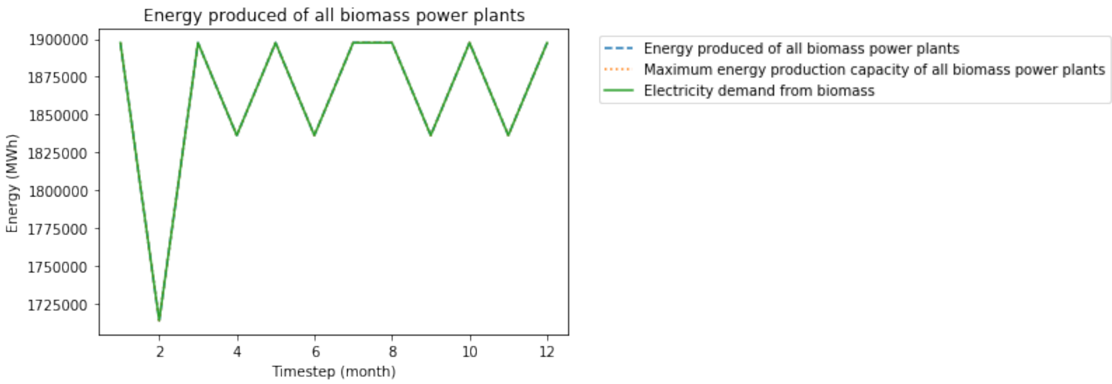


(b) Usage for each type of biomass

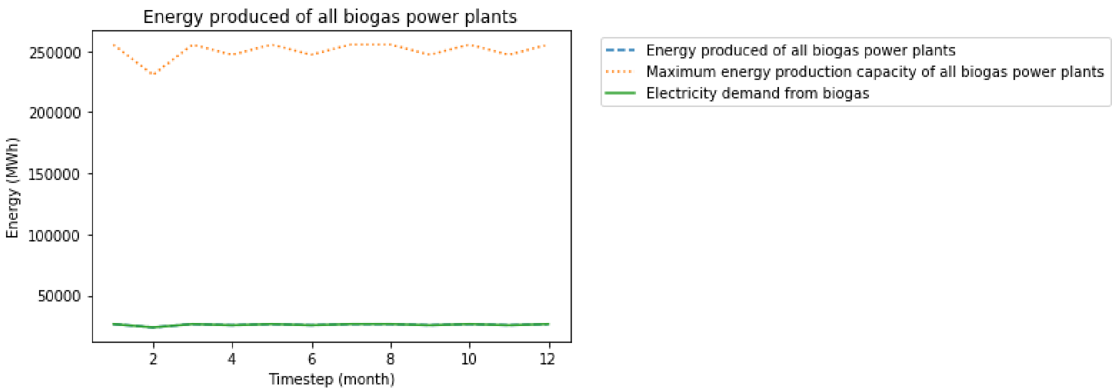
Figure 4.1: Case 1: Biomass usage



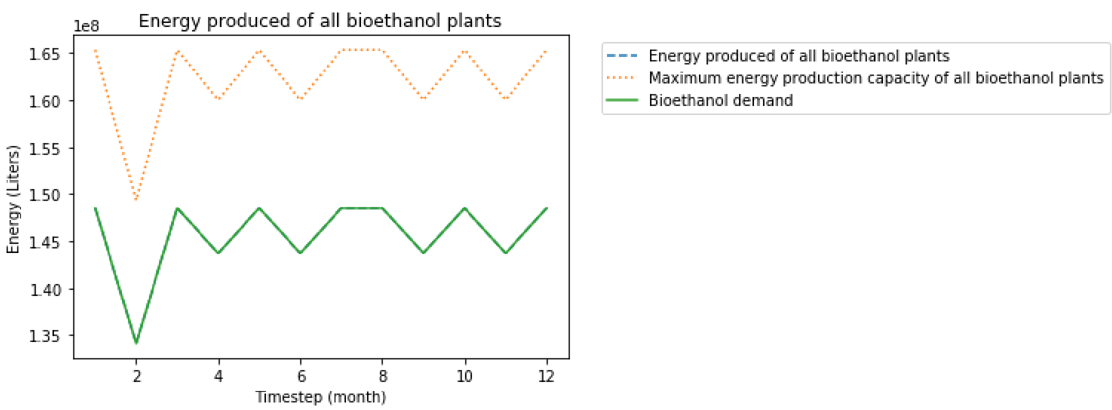
(a) Energy produced from all plants



(b) Energy produced from biomass power plants

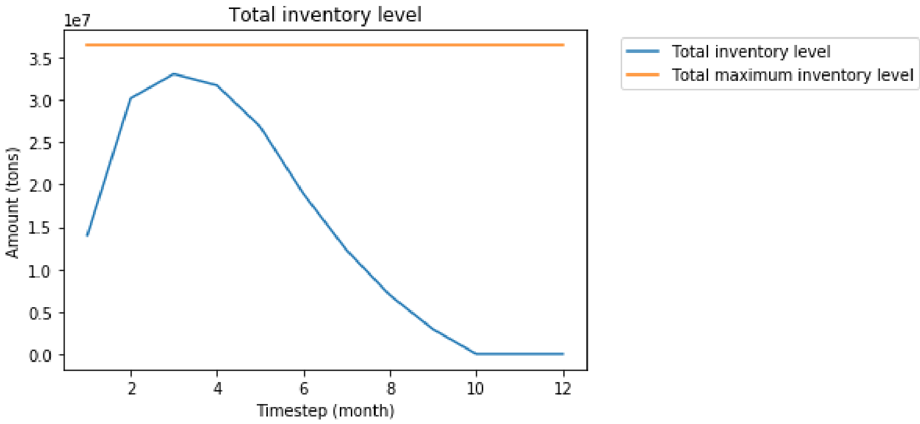


(c) Energy produced from biogas power plants

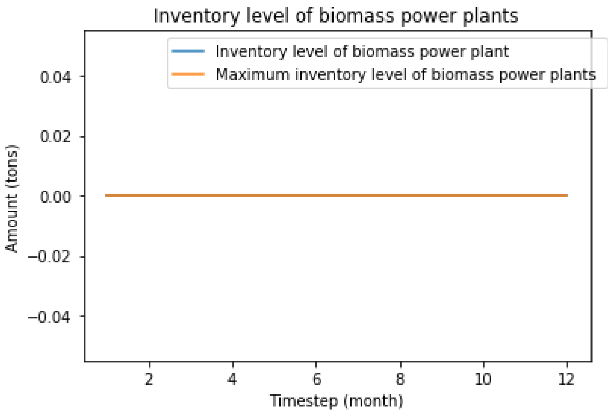


(d) Energy produced from bioethanol plants

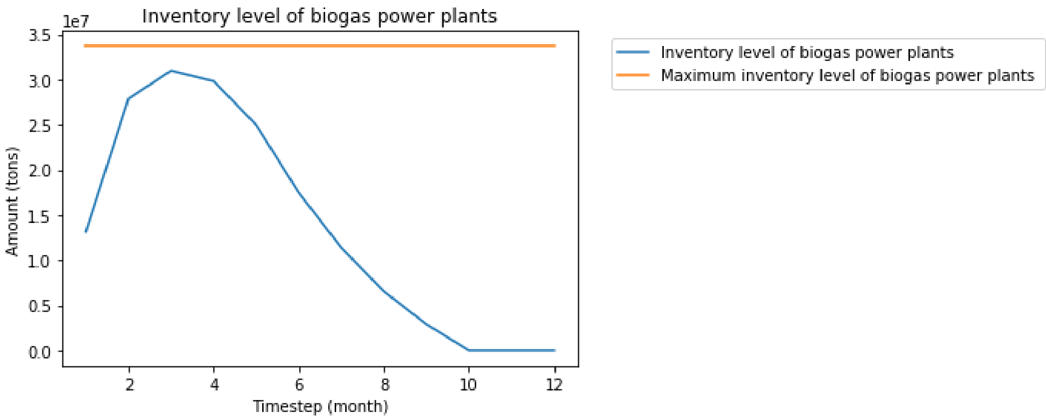
Figure 4.2: Case 1: Energy produced from plants



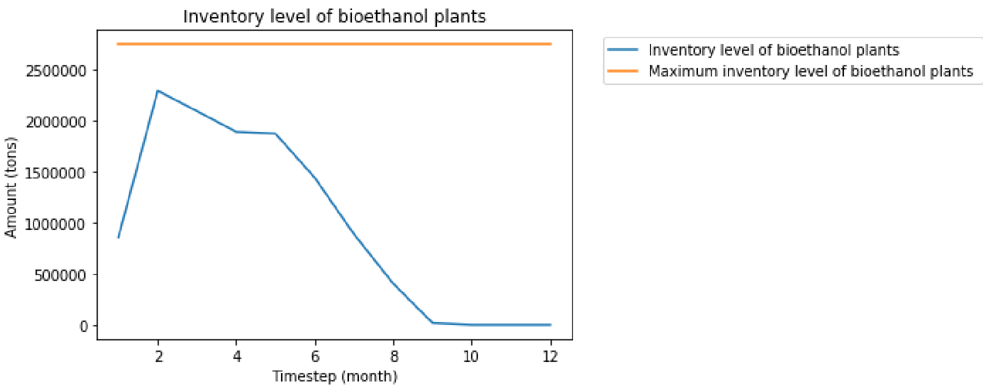
(a) Inventory level of all plants



(b) Inventory level biomass power plants



(c) Inventory level biogas power plants



(d) Inventory level bioethanol plants

Figure 4.3: Case 1: Inventory level of plants

$$Max\ \Theta = \sum_{p,q} I_{p,q}^{max}$$

Let's call this case "case 2". The optimization took 8,613 seconds to optimize. The result showed that the total cost is 499.99 billion THB which are 219.94 billion THB for total biomass cost, 76.47 billion THB for total transportation cost, 37.65 billion THB for holding cost, 152.06 billion THB for biomass power plants' operational cost, 1.09 billion THB for biogas power plants' operational cost, and 12.76 billion THB for bioethanol plants' operational cost.

However, similar to the previous case, not all biomass types are used. Biomass types 14-16 are not used at any time step while type 17 are used for about 8% of its maximum available. Overall biomass usages are shown in figure 4.4

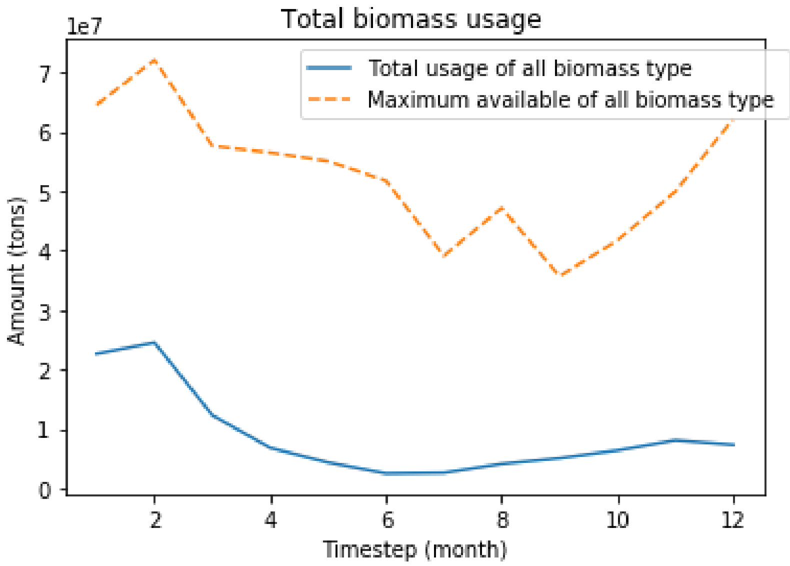
The capacity factor of all plants is 0.89 in this case. the capacity factor of biomass power plants is 1.0. the capacity factor of biogas power plants is 0.1. And the capacity factor of biomass power plants is 0.89. The energy produced from plants is shown in figure 4.5. All biomass power plants operate at their maximum potential to generate electricity. Bioethanol plants spend about 89% of their maximum potential to produce bioethanol to satisfy the target bioethanol demand, while biomass power plants spend 10% to generate electricity. However, unlike case 1, all biogas power plants operate.

An overall inventory level is significantly lower fluctuated from case 1. An inventory utilization of all plants is 71.90%, where inventory utilization of biomass power plants, biogas power plants, and bioethanol plants are 100.0%, 41.72%, and 54.93% respectively. A populational variance of overall inventory level of all plants is $91.74 \times 10^{12}\ tons^2$. Biomass power plants, biogas power plants, and bioethanol plants populational variances are $0\ tons^2$, $4.19 \times 10^{12}\ tons^2$, and $129.52 \times 10^9\ tons^2$. Here, we can see that biomass power plants' inventory have no bottlenecks. The overall inventory level of all plants, biomass power plants, biogas power plants, and bioethanol plants are shown in figure 4.6.

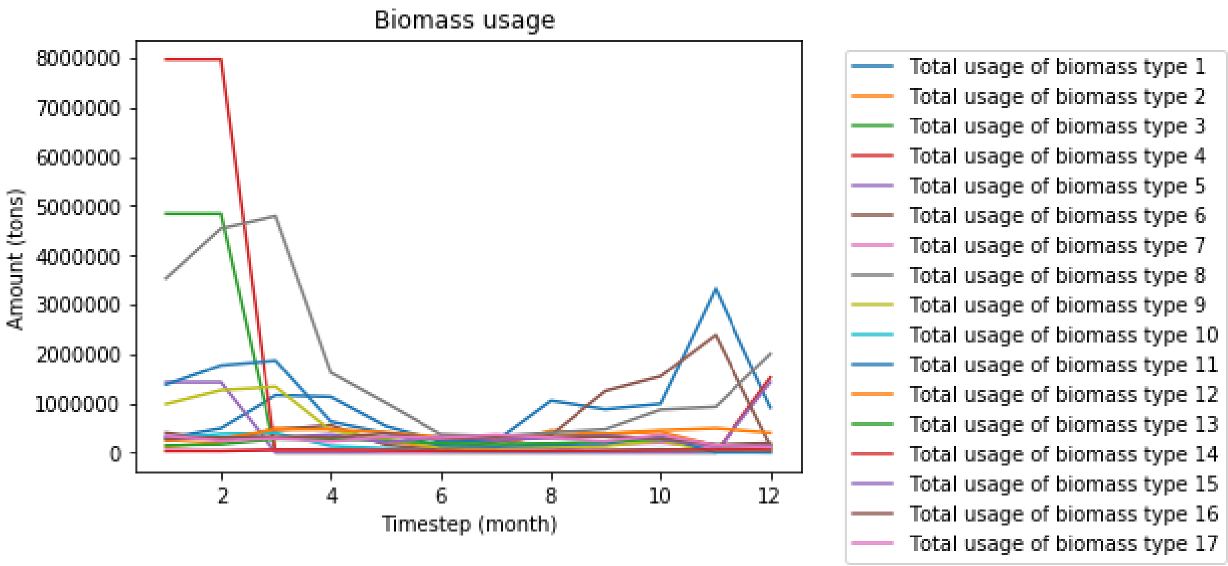
4.3 Case 1 and 2 comparison

According to the case 1 and case 2 results, case 1 has 124.77 billion THB total cost lower than case 2; where biomass material cost, transportation cost, and holding cost are 33.94, 69.9, and 20.87 billion THB lower than case 2 respectively. However, biomass power plants, biogas power plants, and bioethanol plants' operational costs stay the same since they produce the same amount of energy. The cost comparison of case 1 and 2 is shown in figure 4.7.

Since both cases produce the same amount of energy, hence overall energy production stays the same of which makes the capacity factor stay the same consequently as shown in figure 4.8.

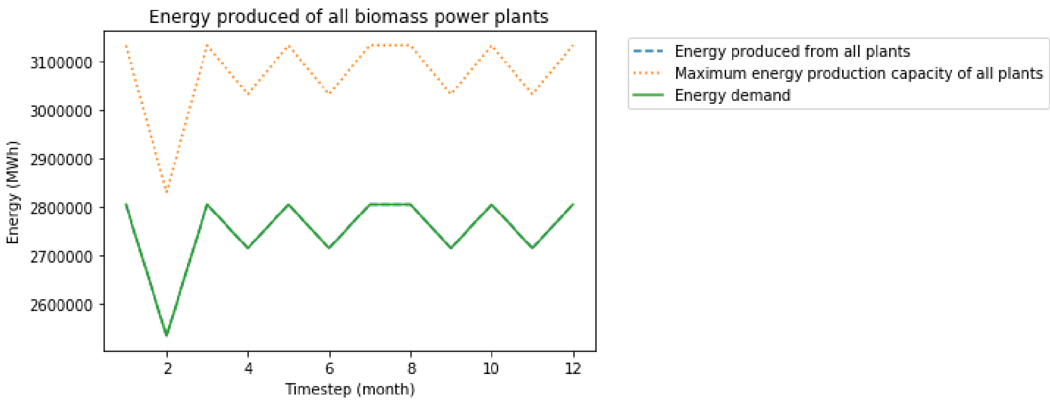


(a) Total biomass usage and its maximum available

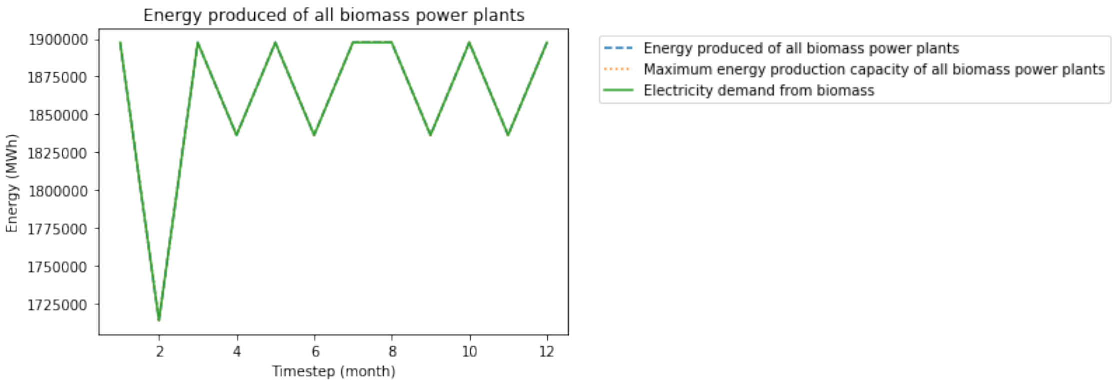


(b) Usage for each type of biomass

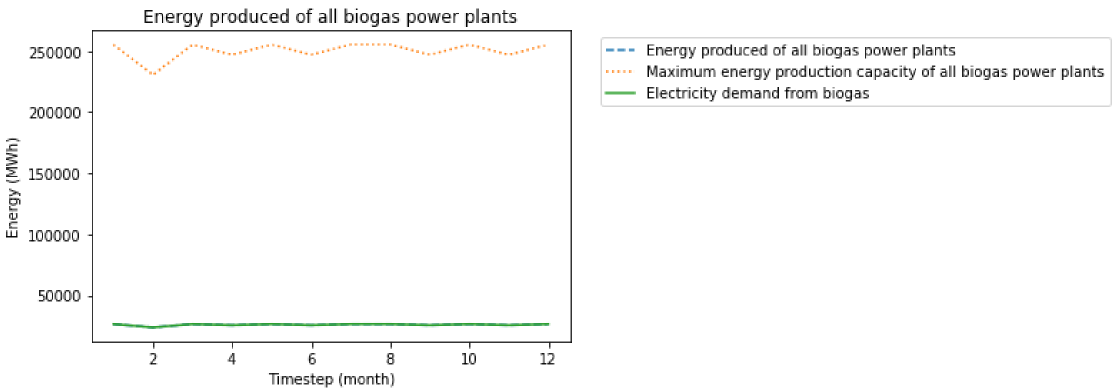
Figure 4.4: Case 2: Biomass usage



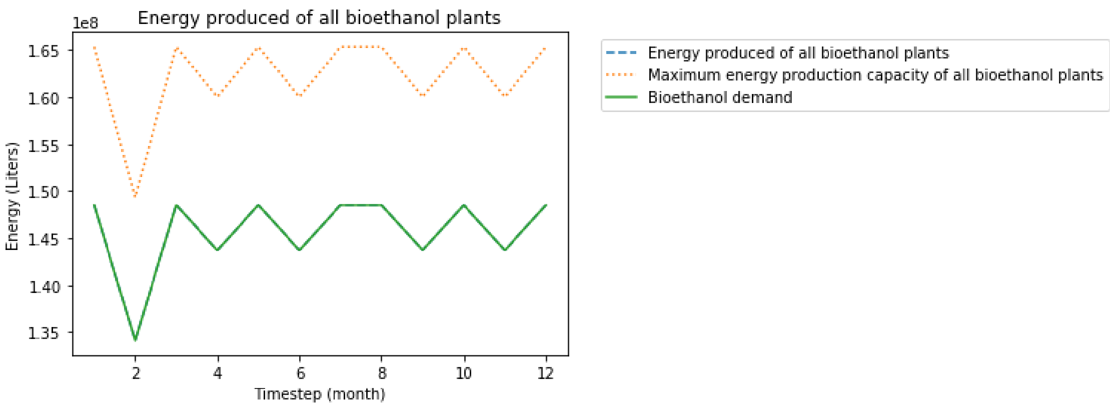
(a) Energy produced from all plants



(b) Energy produced from biomass power plants

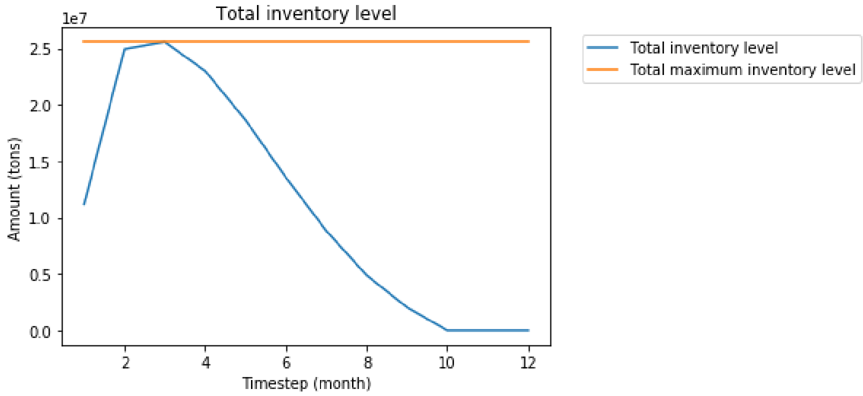


(c) Energy produced from biogas power plants

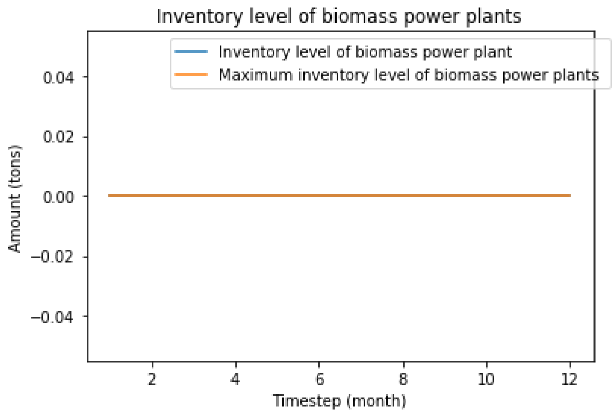


(d) Energy produced from bioethanol plants

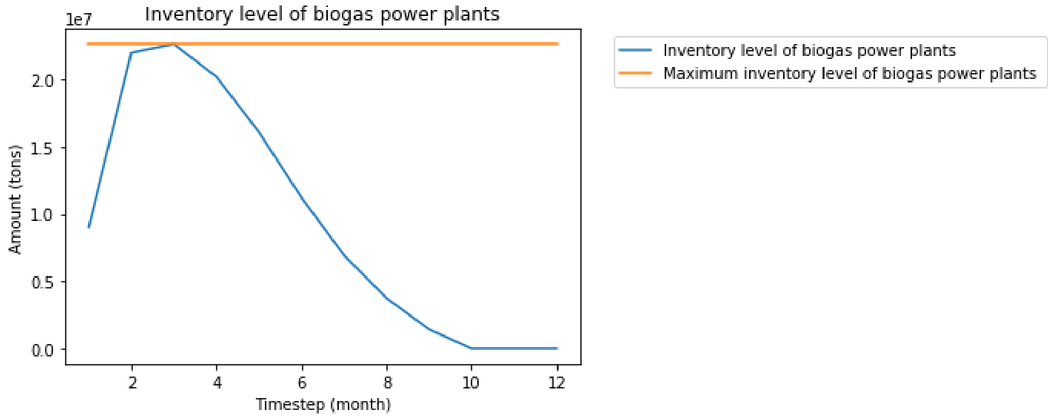
Figure 4.5: Case 2: Energy produced from plants



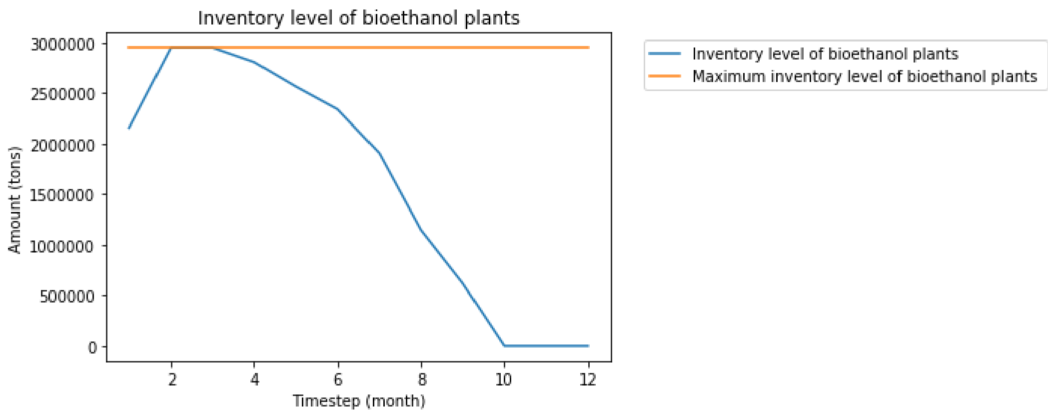
(a) Inventory level of all plants



(b) Inventory level biomass power plants



(c) Inventory level biogas power plants



(d) Inventory level bioethanol plants

Figure 4.6: Case 2: Inventory level of plants

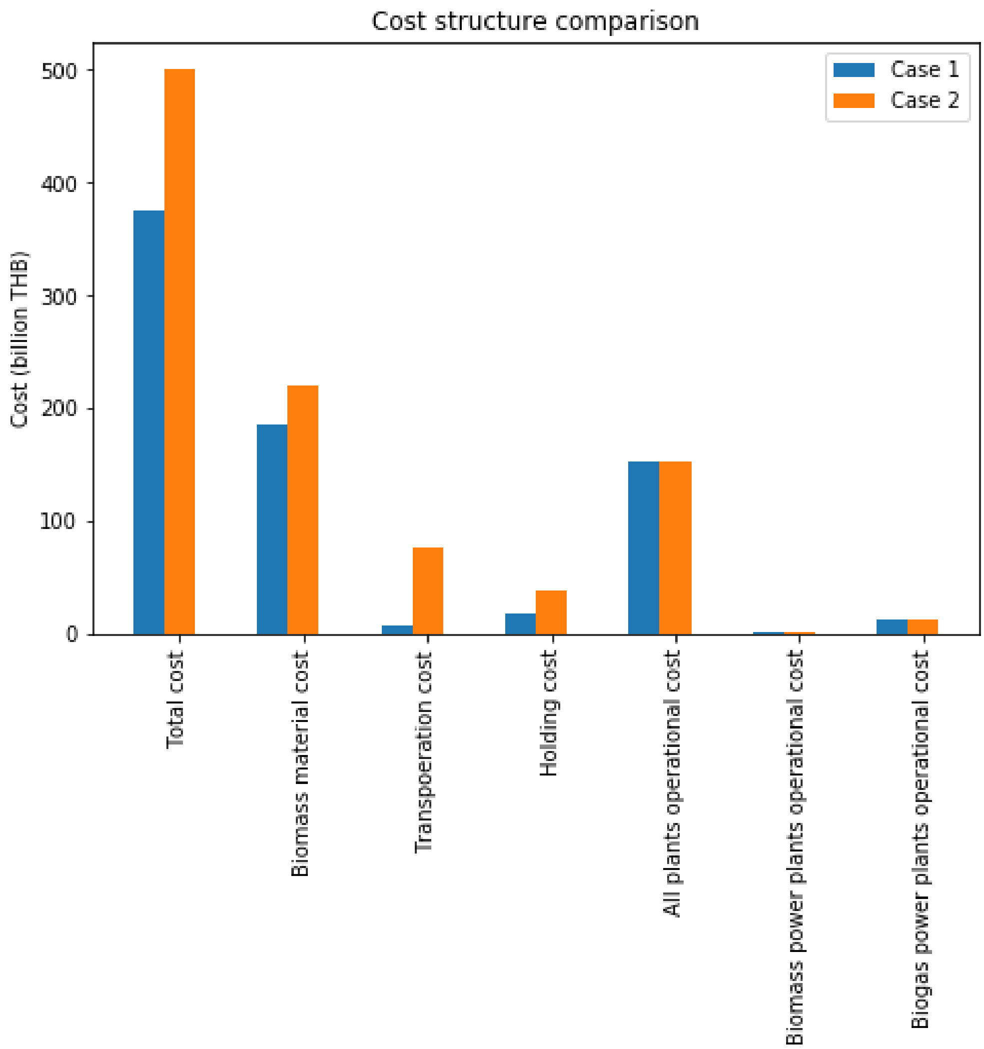


Figure 4.7: Cost structure comparison of case 1 and case 2

However, if we consider each plant individually, case 2 has 100% of all plants operate while there are 75.87% in case 1 which 100% for biomass power plants and bioethanol plants, but just 44.32% of biogas power plants operate. The percentage of operating plants is shown in figure 4.9.

An overall inventory utilization of all plants in case 2 is 30.32% higher than in case 1; where biomass power plants, and bioethanol plants are 91.27% and 19.79% higher; while an overall biogas power plants is 0.41 lower than case 1. In term of variance of inventory level, an overall populational variance of all plants in case 1 is $6.519 \times 10^{13} tons^2$ higher than case 2; where the populational variance of biomass power plants stay the same, but biogas power plants is $3.6 \times 10^{11} tons^2$ higher while bioethanol plants is $6.14 \times 10^{10} tons^2$ lower comparing to case 2. The inventory utilization and variance are shown in figure 4.10 and 4.11 respectively.

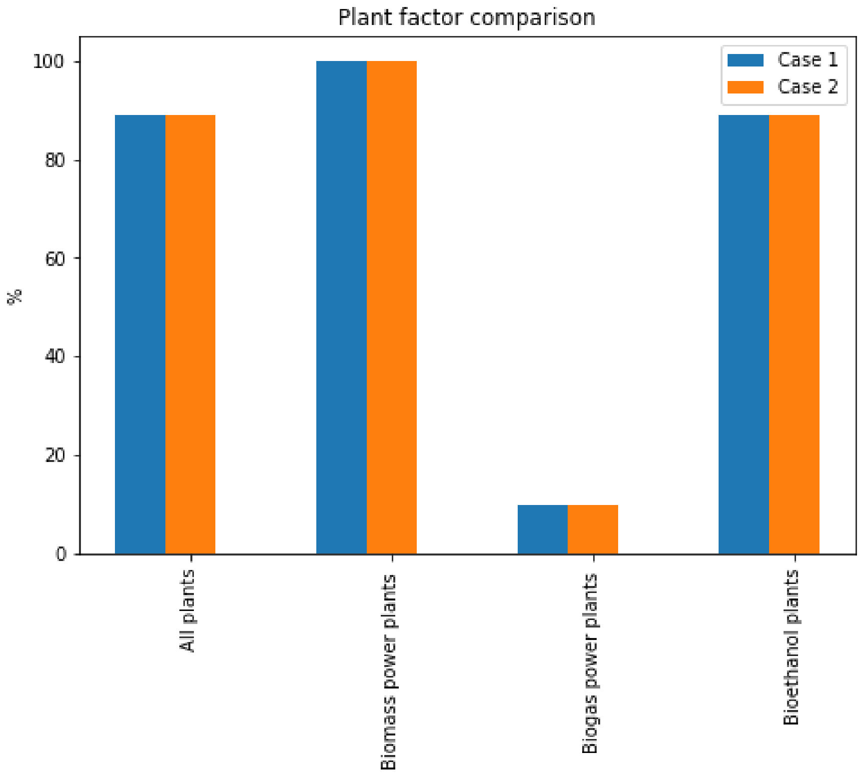


Figure 4.8: Capacity factor comparison of case 1 and case 2

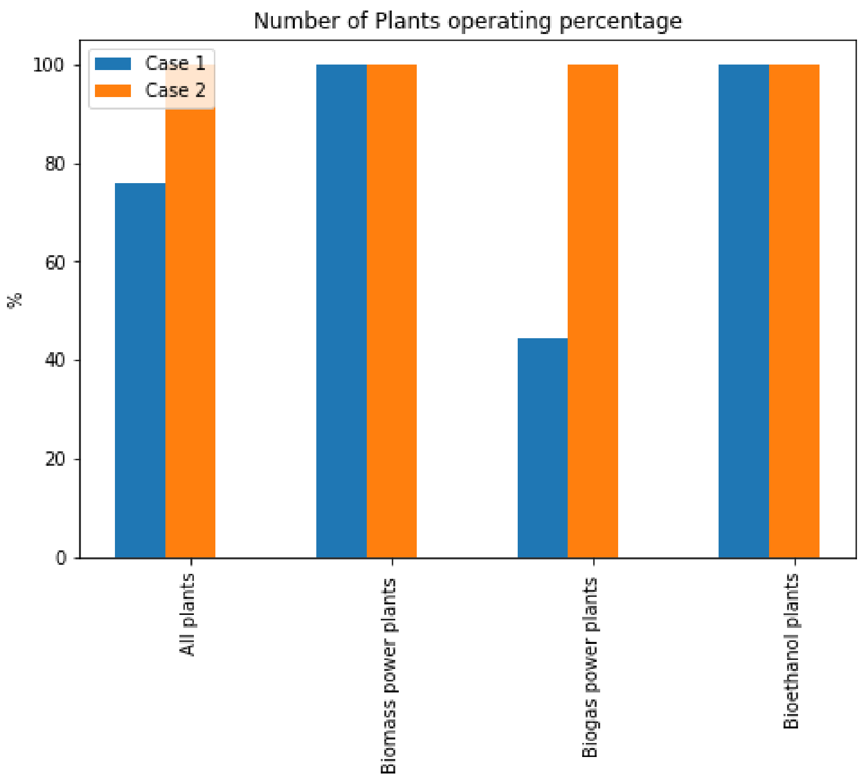


Figure 4.9: Percent of operating plants comparison of case 1 and case 2

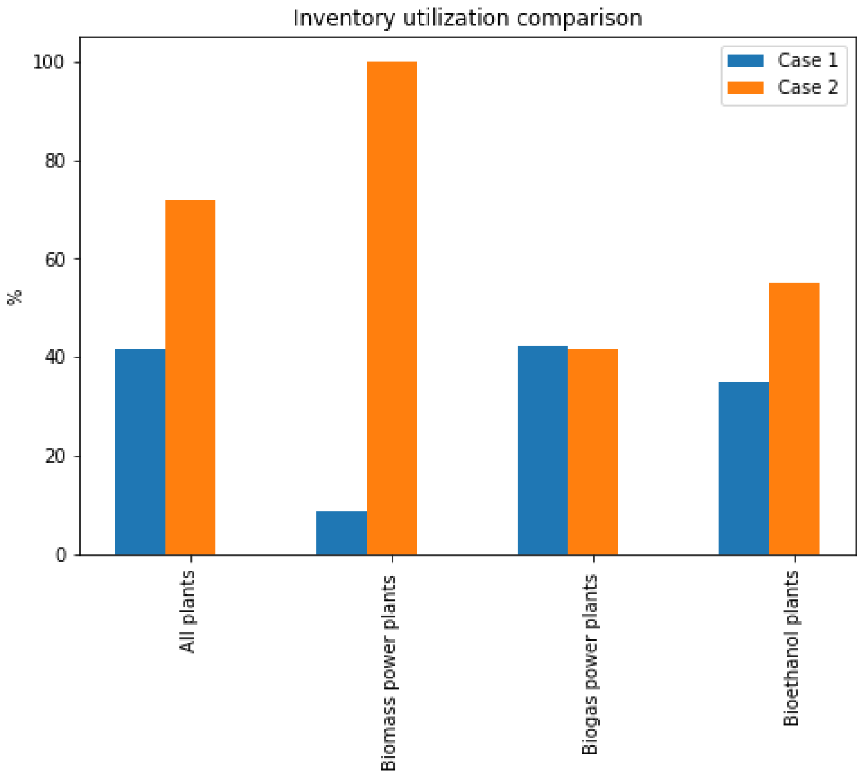


Figure 4.10: Inventory utilization comparison of case 1 and case 2

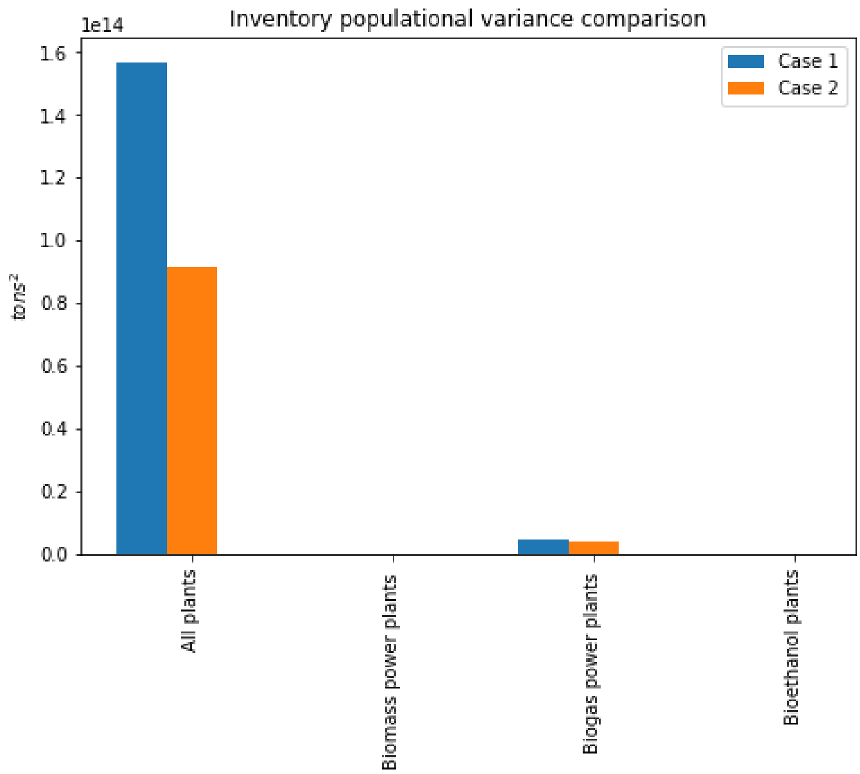


Figure 4.11: Inventory populational variance comparison of case 1 and case 2

Chapter 5

Supply chain improvement

Since one of our objectives is to improve the bioenergy supply chain to make Thailand reach the target consumption in biomass, biogas from energy crops, and bioethanol as determined in AEDP. However, the current maximum bioenergy potential cannot satisfy those target except bioethanol. Considering maximum biomass power plants and biogas power plants, their maximum electricity production capacities are 3,000.47 MW and 403.50 MW respectively. However, since we consider maintenance time at 15%, that means the real maximum production capacity is at 403.50*0.85 = 342.97 MW which is also less than the target. From this information, we need to build more biomass and biogas power plants, and plant more crops (since biomass is derived from crops). Thus, important questions are how many crops Thailand need to plant and where, and how many power plants including how much their capacity Thailand have to install to meet the target. To find these answers, we introduce new power plants index m , and new variables; additional biomass $B_{b,s,t}^{add}$, and new biomass power plants with maximum production capacity $Elc_{pq}^{max,new}$. The new plants have inventory level I_{bmqt}^{new} with their maximum inventory level $I_{mq}^{new,max}$. The amount of biomass delivered from suppliers to new power plants is $X_{bsmqt}^{B,new}$ and the amount of biomass fed into the energy production process is $X_{bmqt}^{P,new}$.

5.1 Additional biomass

First, we have to know how much additional biomass needed. To answer this, we change the objective function to minimize additional biomass as shown in equation 5.1. However, since we have new variables, constraints need to be changed as well. The general idea of constraints is still the same as in section 4.1 but we add new variables constraints.

$$Min\ \Phi = \sum_{b,s,t} B_{b,s,t}^{add} \tag{5.1}$$

In this case, we assume all new biomass power plants use gasification technology and biogas power plants still use the same technology (anaerobic digestion). Biomass available limitation constraint changes to inequality 5.2. Here we add biomass delivered to new power plants $X_{bsmqt}^{B,new}$ to biomass delivered to old plants X_{bspqt}^{B} of which cannot exceed the old and additional biomass suppliers have at each time-step $B^{max}_{bst} + B^{add}_{bst}$.

$$0 \leq \sum_{p,q} X^{B}_{bspqt} + \sum m, q X^{B,new}_{bsmqt} \leq B^{max}_{bst} + B^{add}_{bst} \;\; \forall b, s, t \tag{5.2}$$

Inventory limitation at each old plants stays the same as well as inventory change and biomass fed into the energy production process as equations 3.7, 3.8, and 3.9. However, we have to add additional constraints. For an inventory limitation of new biomass power plants, it follows inequality 5.3, while an inventory limitation of new biogas power plants follows inequality 5.4. An inventory change and biomass fed into the energy production process at the new biomass power plant follow equation 5.5 and inequality 5.6 respectively. And an inventory change and biomass fed into the energy production process at the new biogas power plant follow equation 5.7 and inequality 5.8 respectively.

$$0 \leq \sum_{b} I^{new}_{bmqt} \leq I^{new,max}_{mq} \qquad \forall m, q = 2, t \tag{5.3}$$

$$0 \leq \sum_{b} I^{new}_{bmqt} \leq I^{new,max}_{mq} \qquad \forall m, q = 4, t \tag{5.4}$$

$$\begin{aligned} I^{new}_{b,m,q,t} &= \sum_{s} X^{B,new}_{bsmqt} - X^{P,new}_{bmqt} \qquad \forall b, m, q = 2, t = 0 \\ I^{new}_{b,m,q,t} &= I^{new}_{b,m,q,t-1} + \sum_{s} X^{B,new}_{bsmqt} - X^{P,new}_{bmqt} \qquad \forall b, m, q = 2, t \neq 0 \end{aligned} \tag{5.5}$$

$$\begin{aligned} X^{P,new}_{b,m,q,t} &\leq \sum_{s} X^{B,new}_{bst} \qquad \forall b, m, q = 2, t = 0 \\ X^{P,new}_{b,m,q,t} &\leq I^{new}_{b,m,q,t-1} + \sum_{s} X^{B,new}_{bst} \qquad \forall b, m, q = 2, t \neq 0 \end{aligned} \tag{5.6}$$

$$\begin{aligned} I^{new}_{b,m,q,t} &= \sum_{s} X^{B,new}_{bsmqt} - X^{P,new}_{bmqt} \qquad \forall b, m, q = 4, t = 0 \\ I^{new}_{b,m,q,t} &= I^{new}_{b,m,q,t-1} + \sum_{s} X^{B,new}_{bsmqt} - X^{P,new}_{bmqt} \qquad \forall b, m, q = 2, t \neq 0 \end{aligned} \tag{5.7}$$

$$\begin{aligned} X^{P,new}_{b,m,q,t} &\leq \sum_{s} X^{B,new}_{bst} \qquad \forall b, m, q = 2, t = 0 \\ X^{P,new}_{b,m,q,t} &\leq I^{new}_{b,m,q,t-1} + \sum_{s} X^{B,new}_{bst} \qquad \forall b, m, q = 4, t \neq 0 \end{aligned} \tag{5.8}$$

For energy production constraints, we add a new inequalities as shown in 5.9 and 5.10 additionally to old constraints 3.10, 3.11, and 3.12.

$$f_q^{H-Elc} * \sum_b (X_{b,m,q,t}^{P,new} * f_b^{B-H,B}) \leq Elc_{m,q}^{max,new} * pf_q * 24 * N_t \qquad \forall m, q = 2, t \tag{5.9}$$

$$f_q^{H-Elc} * \sum_b (X_{b,m,q,t}^{P,new} * f_b^{B-H,G}) \leq Elc_{m,q}^{max,new} * pf_q * 24 * N_t \qquad \forall m, q = 4, t \tag{5.10}$$

Total energy produced and energy demand balancing of electricity generated from biomass constraint is changed from equation 3.13 to equation 5.11, and total energy produced and energy demand balancing of electricity generated from biogas constraint is changed from equation 3.14 to equation 5.12. Here, we add electricity produced from new biomass power plant $\sum_b (X_{b,t}^{P,new} * f_b^{B-Elc,B})$ to the energy produced from old biomass power plants $\sum_p (\sum_b (X_{b,p,q=1,2,3,t}^{P} * f_b^{B-Elc,B}))$, and balance them with the demand. Similarly, we add electricity produced from new biogas power plant $\sum_b (X_{b,p,q,t}^{P} * f_b^{B-Elc,G})$ to the energy produced from old biogas power plants $\sum_b (X_{b,m,q,t}^{P,new} * f_b^{B-Elc,G})$. However, the electricity from biogas and bioethanol balancing constraints stay the same as equations 3.13 and 3.15. Moreover, we consider about seasonal harvesting of biomass and local area.

$$\sum_p (\sum_b (X_{b,p,q=1,2,3,t}^{P} * f_b^{B-Elc,B})) + \sum_b (X_{b,m,q=2,t}^{P,new} * f_b^{B-Elc,B}) = D^{Elc,B} * 24 * N_t \qquad \forall t \tag{5.11}$$

$$\sum_p (\sum_b (X_{b,p,q,t}^{P} * f_b^{B-Elc,G})) + \sum_b (X_{b,m,q,t}^{P,new} * f_b^{B-Elc,G}) = D^{Elc,G} * 24 * N_t \qquad \forall q = 4, t \tag{5.12}$$

The optimization took 3,014 seconds to optimize. The result shows that to minimize the additional biomass, Thailand needs to have more molasses by 32.73 million tons which are 4.65 billion tons of sugarcane harvesting equivalently. This means that the country needs to grow more sugarcane by 45.64 billion tons or 5,347% of the current sugarcane amount. However, rather than molasses, harvesting sugarcane also gives sugarcane leaves and trunks, and sugarcane bagasse as well. The sugarcane leaves and trunks is 15.81 billion tons additional, and sugarcane bagasse is 26.04 billion tons additional.

The additional biomass optimal result for each supplier is attached in the file named "additional biomass supplier profile.csv" [27] and the additional biomass after considering growing more crops (which is sugarcane in this case) at each supplier is attached in the file "additional biomass supply from growing additional crops.csv" [27]. Provinces code's description is described in appendix B.

5.2 New power plants location

After we knew additional biomass, now we can find suitable locations for new power plants. Here, we try to answer which province the power plants should locate to minimize the total supply chain cost. We have to know the distance between suppliers and provinces which power plants possibly locate as well. We calculated these distances by using the Python-OSRM package. The calculated distances are attached to the file named "industrial area loc.csv" [27]. The distances are represented as parameter L_{sf} where s is a from-supplier index and f is a to-province index for a mathematical model. Other variables are binary variable Y^{new}_{mf}, which are decision variables whether new power plants m will be located at province f or not.

To find the locations of new power plants, we use the center of gravity method by minimizing the distances between suppliers and new power plants as in equation 5.13

$$Min\,\Omega = \sum_{m,s,f} (L_{s,f} * Y^{new}_{m,f}) \tag{5.13}$$

Constraints we considered consist of a summation of the binary variables Y^{new}_{mf} equal to the number of new power plants which in this case is 2 as shown in equation 5.14; one for biomass power plant, and one for biogas power plant. Another constraint is in Thailand, there is one province that cannot build any type of industry which is Bangkok (code: Province 01) (equation 5.15).

$$\sum_{m,f} Y^{new}_{m,f} = 2 \tag{5.14}$$

$$Y^{new}_{m,f=indexofProvince\ 01} = 0 \qquad \forall m \tag{5.15}$$

The optimization took 0.38 seconds to optimize. The result showed that both power plants should locate at Province 60 which is Saraburi. The total distance from suppliers to Suraburi is 3.38×10^5 km.

5.3 Capacities of new power plants: the case 3

From section 5.1 and 5.2, we already knew the additional biomass and locations of new power plants. Now, the rest questions are how much maximum electricity production capacity the new power plants should have, and how a supply chain will be.

Here constraints are slightly changed from section 5.1. The objective function is to minimize total cost but also slightly changed from section 4.1. The objective function follows equation 5.16; where annual biomass cost, annual transportation cost, annual operational cost, and holding cost follow equations 5.17, 5.18, 5.19, and 5.20 respectively. However, constraints are still the same as in section 5.1 except inequality 5.2 that does not contain $+B^{add}_{b,s,t}$ in the right hand side of the inequality anymore (5.21). But B^{max}_{bst} data set is changed since we already consider an additional biomass as parameters. The new data set of after-biomass-addition monthly supplier profile is attached in the file "after-addition monthly suppliers profile.csv" [27].

$$\begin{aligned} Min\ Z' &= Annual\ biomass\ cost + Annual\ transportation\ cost \\ &+ Annual\ operational\ cost + Annual\ holding\ cost \end{aligned} \tag{5.16}$$

$$Annual\ biomass\ cost\ = \sum_{b,s,p,q,t} (C^B_{bst} \cdot X^B_{bspqt}) + \sum_{b,s,m,q,t} (C^B_{bst} \cdot X^{B,new}_{bsmqt}) \tag{5.17}$$

$$Annual\ transportation\ cost\ = \sum_{b,s,p,q,t} (C^{TV}_b \cdot X^B_{bspqt} \cdot L_{spq}) + \sum_{b,s,m,q,t,f} (C^{TV}_b \cdot X^{B,new}_{bsmqt} \cdot L^{new}_{sf}) \tag{5.18}$$

$$\begin{aligned} Annual\ operational\ cost = &\sum_{p,q=1,2,3,t} (C^{OElc}_{pq} \cdot (f^{H-Elc}_q * \sum_b (X^P_{bpqt} * f^{B-Elc,B}_b)) \\ &+ \sum_{p,q=4,t} (C^{OElc}_{pq} \cdot (f^{H-Elc}_q * \sum_b (X^P_{bpqt} * f^{B-Elc,G}_b)) \\ &+ \sum_{p,q=5,t} (C^{OEth}_{pq} \cdot \sum_b (X^P_{bpqt} * f^{B-Eth}_b)) \\ &+ \sum_{m,q,t} (C^{OElc}_q \cdot (f^{H-Elc}_q * \sum_b (X^{P,new}_{bmqt} * f^{B-Elc,B}_b)) \end{aligned} \tag{5.19}$$

$$Annual\ holding\ cost\ = \sum_{p,q,t} (\sum_b (I_{bpqt} \cdot C^h_b)) + \sum_{m,q,t} (\sum_b (I^{new}_{bmqt} \cdot C^h_b)) \tag{5.20}$$

$$Biomass\ constraint:\quad 0 \leq \sum_{p,q} X^B_{bspqt} + \sum m, q X^{B,new}_{bsmqt} \leq B^{max}_{bst}\ \ \forall b, s, t \tag{5.21}$$

Let's call this case "case 3". The optimization took 3,124 seconds to optimize. The result showed that the total supply chain cost is 1,370.85 billion THB; which consists of 505.50 billion

THB biomass material cost, 300.32 billion THB transportation cost, 174.47 billion THB holding cost, 236.22 billion THB biomass power plants operational cost, 141.16 billion THB biogas power plants operational cost, and 12.76 billion THB bioethanol plants operational cost. The maximum electricity production capacity of the new biomass power plant is 3115.75 MW, while the maximum electricity production capacity of the new biogas power plant is 64.10 MW.

However, the optimal result showed that just some biomasses are used, and a lot of them are not used. Biomasses type 4, 7, 8, 12, 13, and 17 are used while others are not. The most used type is type 4 which is corncobs. The usage of total biomass and biomass by type is shown in figure 5.1.

The capacity of all plants is 5.48×10^{-3} in this case. The capacity factor of biomass power plants is 2.94×10^{-3}. The capacity factor of biogas power plants is 3.22×10^{-2}. And the capacity factor of biomass power plants is 0.89. The energy produced from plants is shown in figure 5.2. However, there are 83.8% (181 out of 216) of biomass power plants operate, while there are 99.46% (185 out of 186) and 100% (27 out of 27) of biogas power plants and bioethanol plants operate respectively.

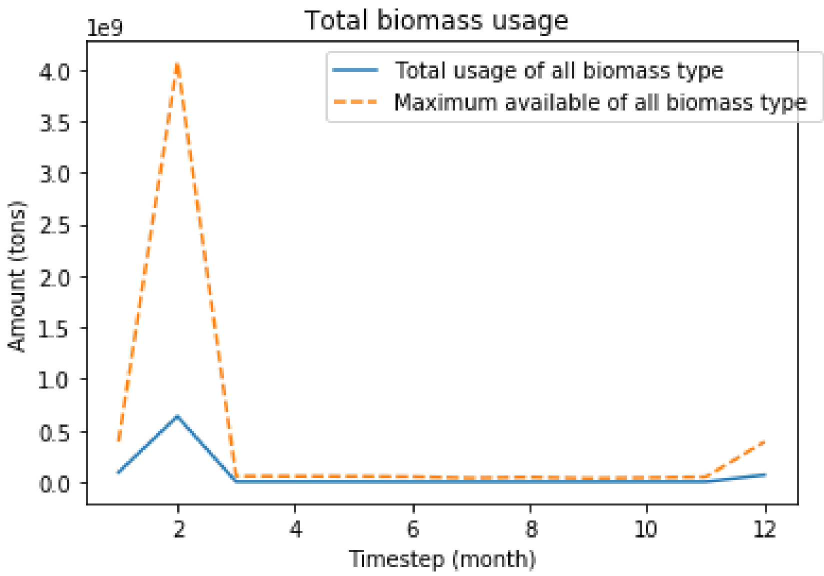
An overall inventory level is high in the early months due to stocking biomass especially type 4. An inventory utilization of all plants is 41.55%, where inventory utilization of biomass power plants, biogas power plants, and bioethanol plants are 10.22%, 41.66%, and 27.51% respectively. A populational variance of the overall inventory level of all plants is $5.60 \times 10^{16}\ tons^2$. Biomass power plants, biogas power plants, and bioethanol plants populational variances are $1.34 \times 10^8 tons^2$, $2.16 \times 10^{14}\ tons^2$, and $7.22 \times 10^{10}\ tons^2$. Here, we can see that biomass power plants' inventory have no bottlenecks. The overall inventory level of all plants, biomass power plants, biogas power plants, and bioethanol plants are shown in figure 5.3.

5.4 Improved supply chain at AEDP target bioenergy: the case 4

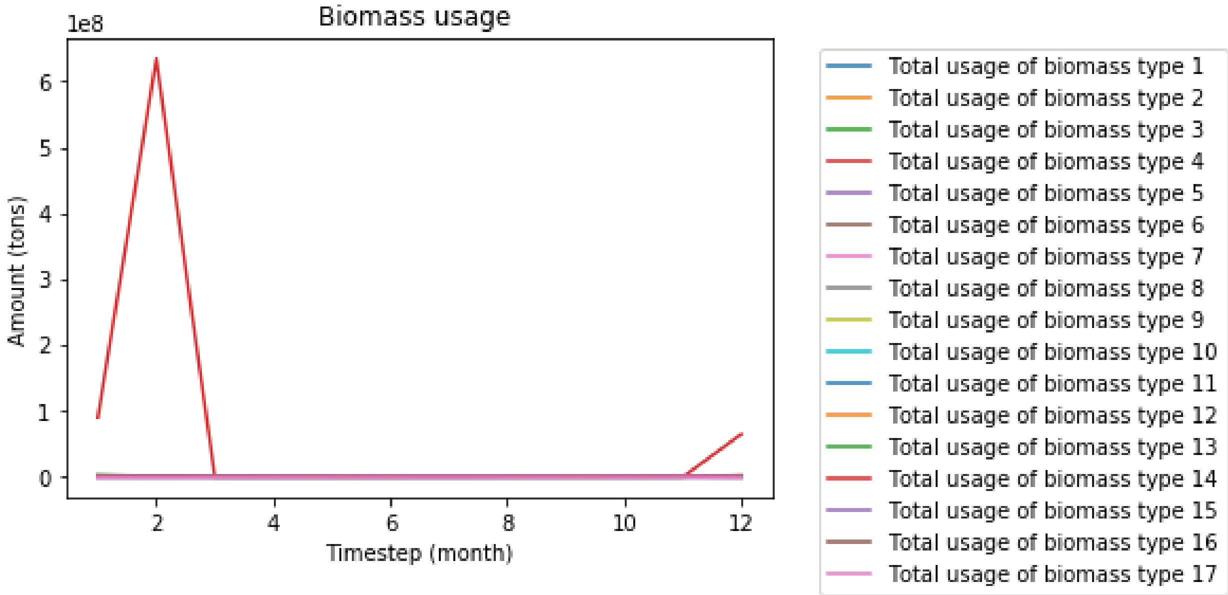
As we already saw the results in section 5.3, not all plants operate which is not quite realistic and the new power plants have too much capacity than necessary, thus we have to improve the supply chain. Here, we improve the supply chain by changing an objective function to minimize maximum inventory level and maximum electricity production capacity of new power plants which as shown in equation 5.22 while constraints stay the same as we discussed in section 5.3.

$$Max\ \Lambda = \sum_{p,q} I_{p,q}^{max} + \sum_{m} I_{m}^{max,new} + \sum_{m} Elc_{m}^{max,new} \tag{5.22}$$

Let's call this case "case 4". The optimization took 3,306 seconds to optimize. The result

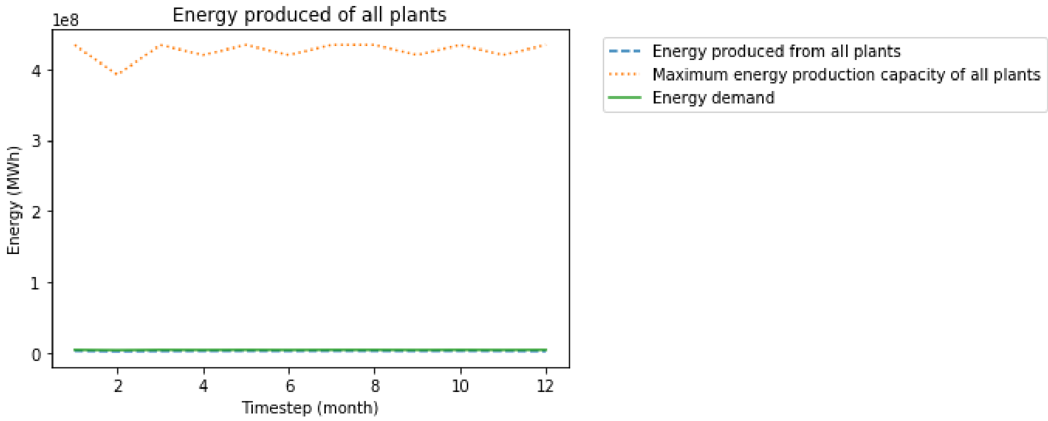


(a) Total biomass usage and its maximum available

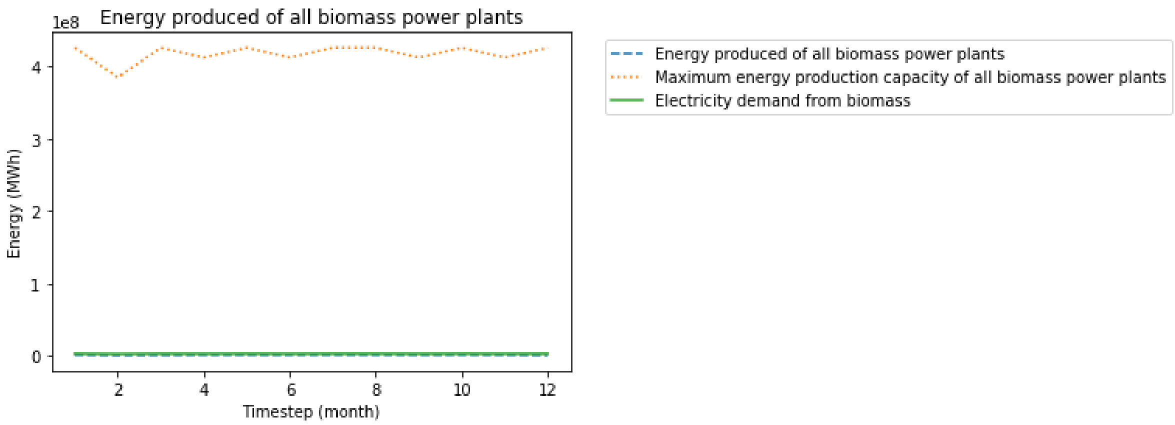


(b) Usage for each type of biomass

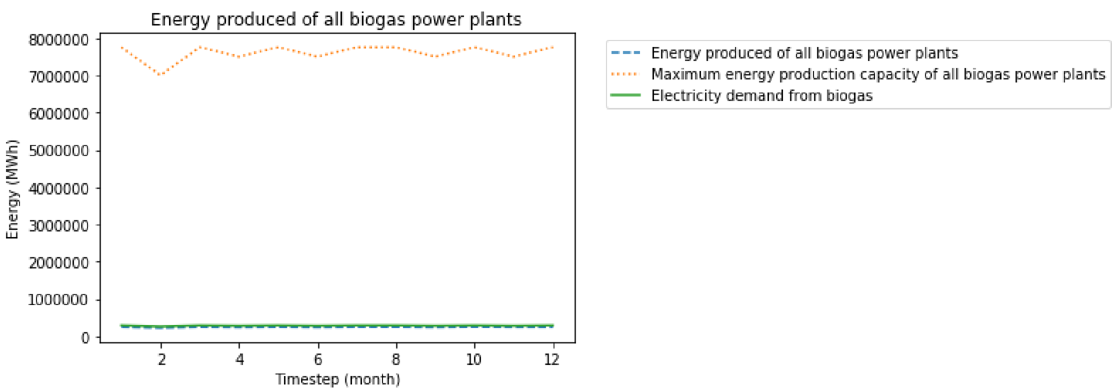
Figure 5.1: Case 3: Biomass usage



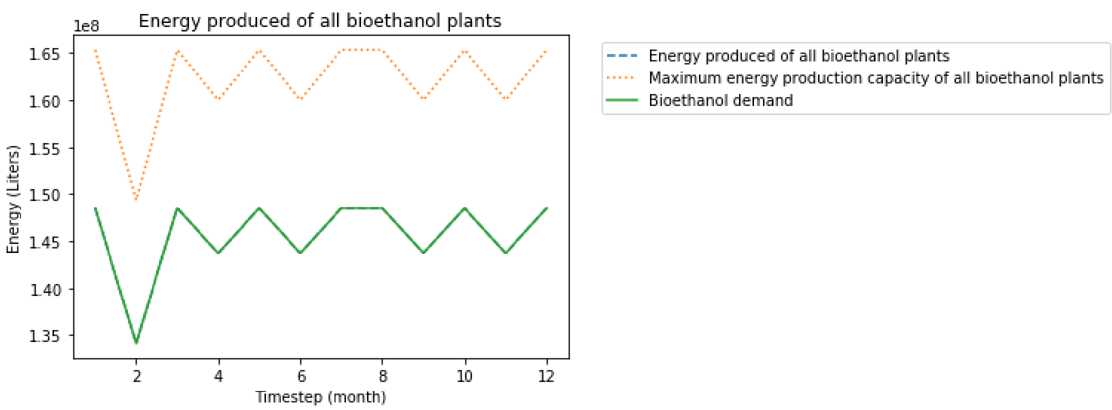
(a) Energy produced from all plants



(b) Energy produced from biomass power plants

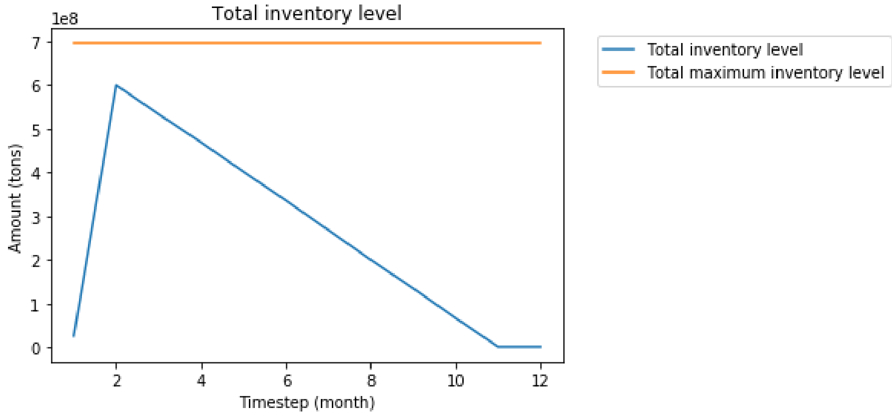


(c) Energy produced from biogas power plants

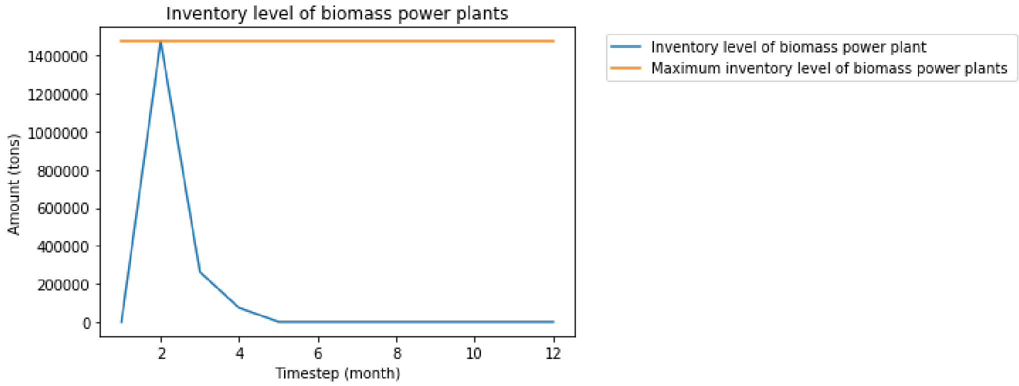


(d) Energy produced from bioethanol plants

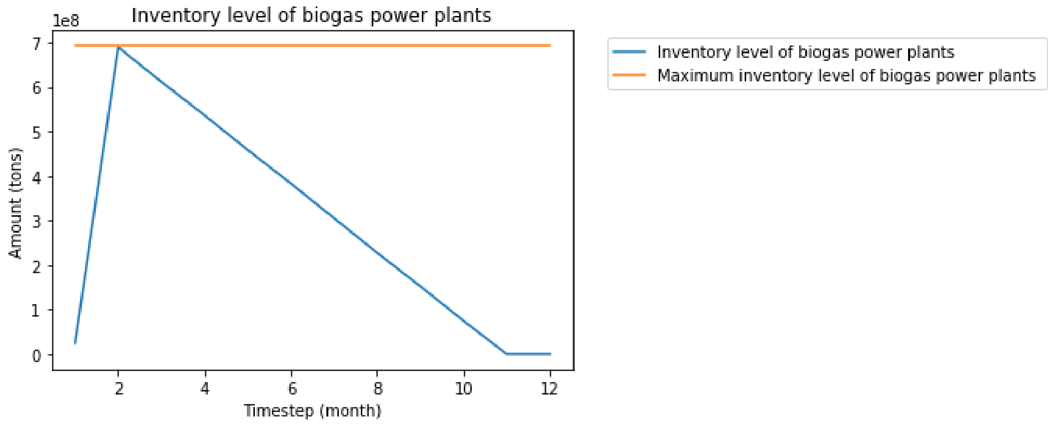
Figure 5.2: Case 3: Energy produced from plants



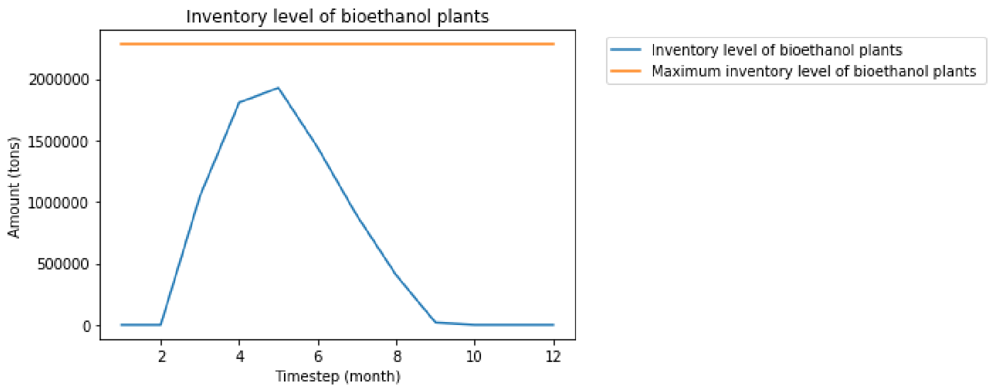
(a) Inventory level of all plants



(b) Inventory level biomass power plants



(c) Inventory level biogas power plants



(d) Inventory level bioethanol plants

Figure 5.3: Case 3: Inventory level of plants

showed that the total cost of this case is 8,155.66 billion THB; which consist of 5,599.22 billion THB of biomass material cost, 274.71 billion THB of transportation cost, 1997.13 billion THB of holding cost, 236.22 billion THB of biomass power plants operational cost, 35.62 billion THB of biogas power plants operational cost, and 12.76 billion THB of bioethanol plants operational cost.

The optimal maximum electricity production of new biomass power plant and biogas power plant are 1634.82 MW and 51.80 MW respectively. All biomass types are used in this case. The most biomass used is molasses. The usage of total biomass and biomass by type are shown in figure 5.4.

The capacity factor of all plants is 1.77×10^{-2} in this case. The capacity factor of biomass power plants is 2.94×10^{-3}. The capacity factor of biogas power plants is 1.30×10^{-2}. And the capacity factor of biomass power plants is 0.89. All plants operate in this case (100%). The energy produced from plants is shown in figure 5.5.

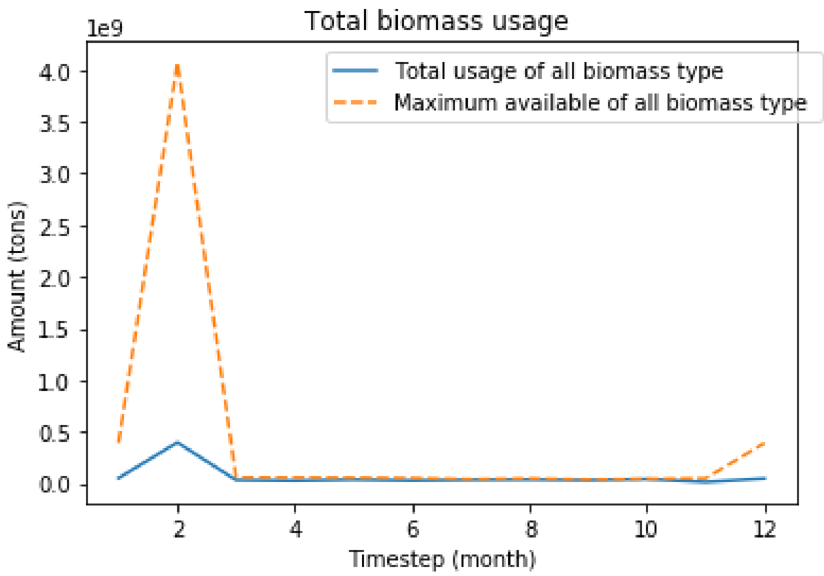
An overall inventory level is high in the early months due to stocking biomass especially type 5, molasses. An inventory utilization of all plants is 74.73%, where inventory utilization of biomass power plants, biogas power plants, and bioethanol plants are 100%, 50.23%, and 43.04% respectively. A populational variance of overall inventory level of all plants is $1.82 \times 10^{16}\ tons^2$. Biomass power plants, biogas power plants, and bioethanol plants populational variances are $0 tons^2$, $9.37 \times 10^{13}\ tons^2$, and $2.64 \times 10^{11}\ tons^2$. Here, we can see that biomass power plants' inventory have no bottlenecks. The overall inventory level of all plants, biomass power plants, biogas power plants, and bioethanol plants are shown in figure 5.6.

5.5 Case 3 and 4 comparison

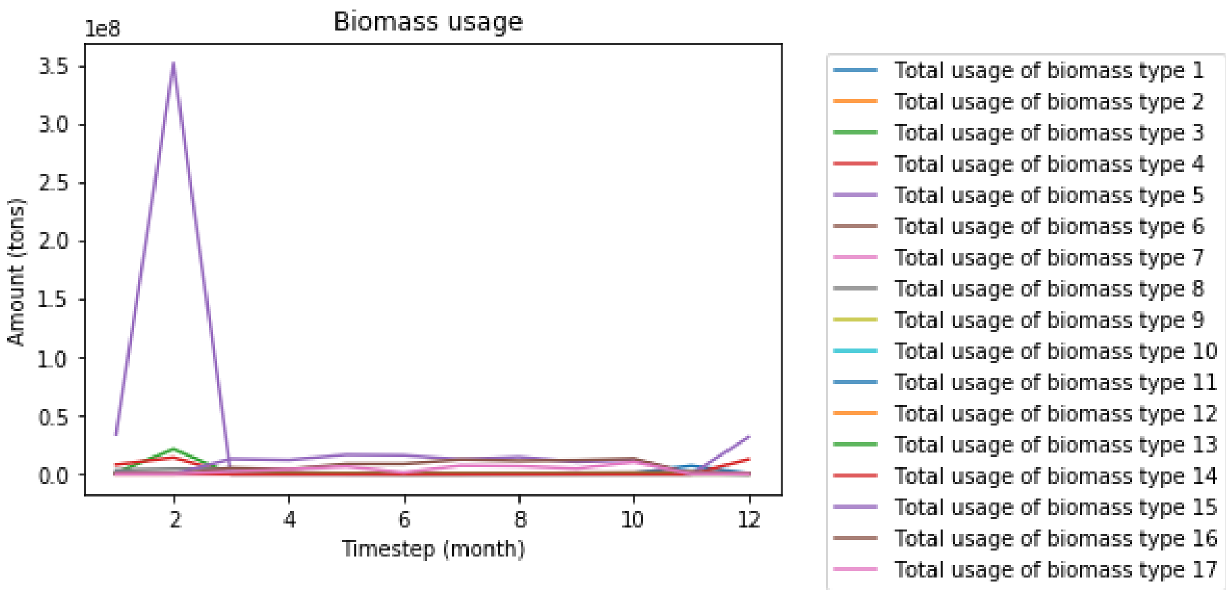
According to the case 3 and case 4 results, case 3 has 6,784.81 billion THB total cost lower than case 4; where biomass material cost and holding cost are 5,093.72 and 1,822.66 billion THB lower than case 4 respectively. However, transportation cost in case 3 is 25.61 billion THB higher than in case 4. Biomass power plants and bioethanol plants' operational costs stay the same, while biogas power plants operational cost in case 3 is 105.54 billion THB higher than case 4. The cost comparison of case 3 and 4 is shown in figure 5.7.

The capacity factor of all plants in case 4 is 8.27×10^{-3} higher than case 3. Biomass power plants and biogas power plants capacity factors of case 4 are also 6.19×10^{-3} and 8.48×10^{-3} higher than case 3 respectively as well, while capacity factor of bioethanol plant remains the same. The capacity factor of bioenergy plants is shown in figure 5.8.

Considering the number of plants operate, case 4 has 100% of all plants operate while there are 91.6% in case 3 which are 83.8%, 99.46%, and 100% of biomass power plants, biogas power plants, and bioethanol plants respectively. The percentage of operating plants is shown in figure

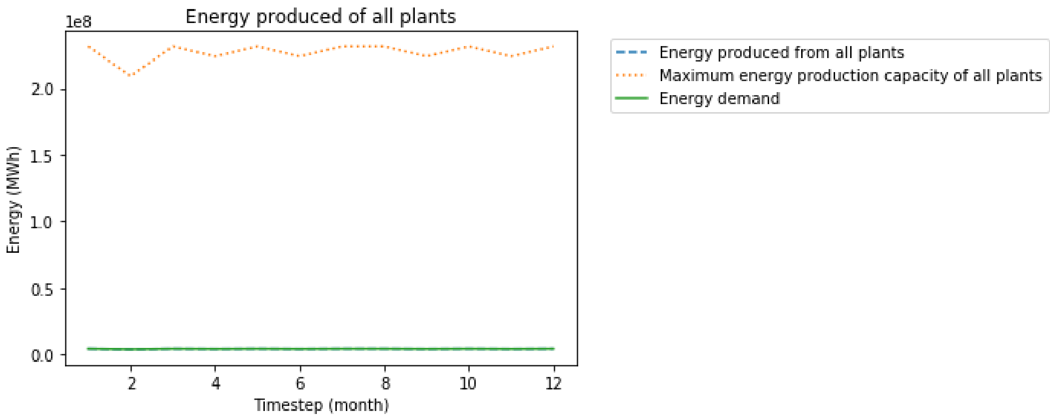


(a) Total biomass usage and its maximum available

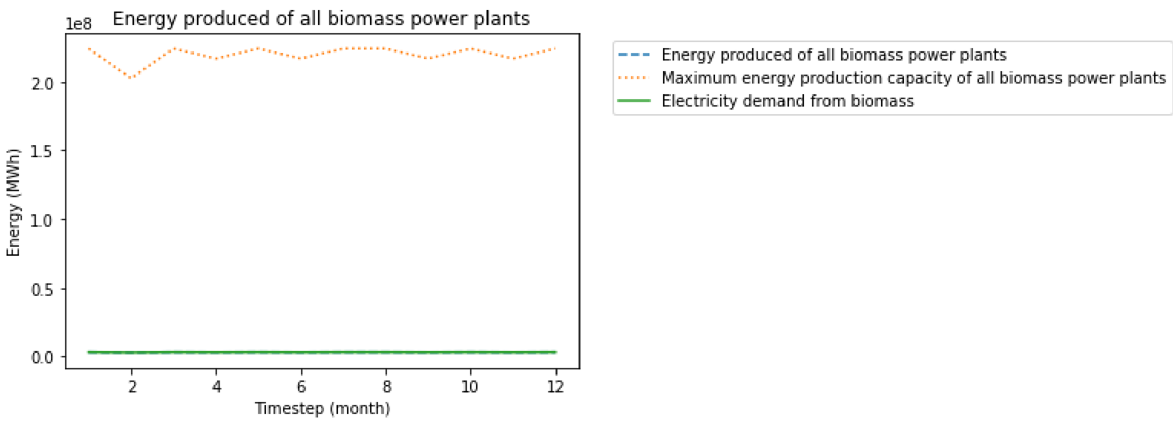


(b) Usage for each type of biomass

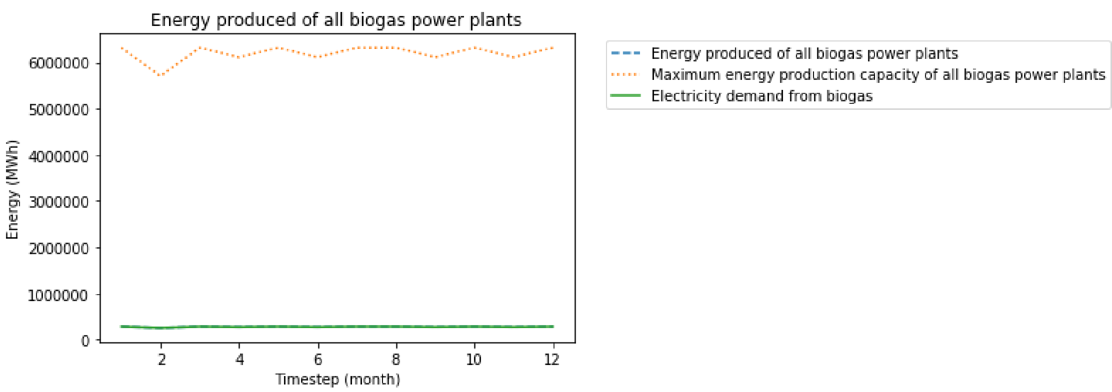
Figure 5.4: Case 4: Biomass usage



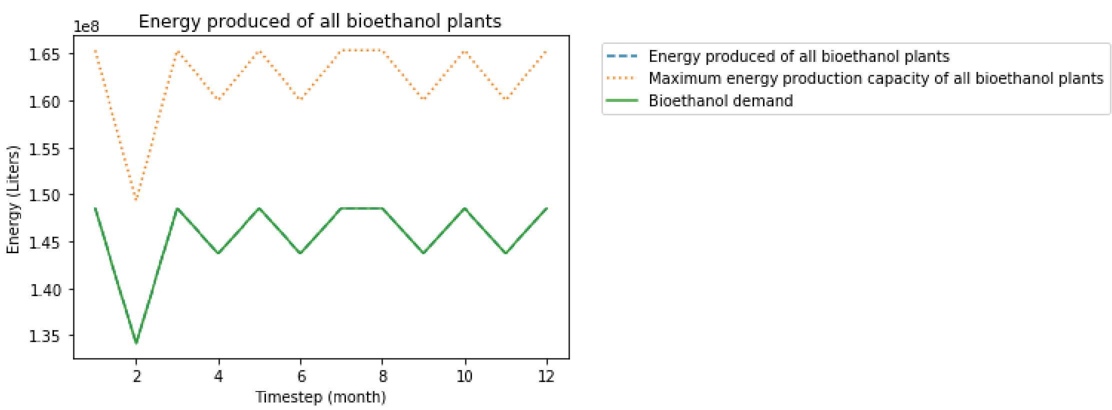
(a) Energy produced from all plants



(b) Energy produced from biomass power plants

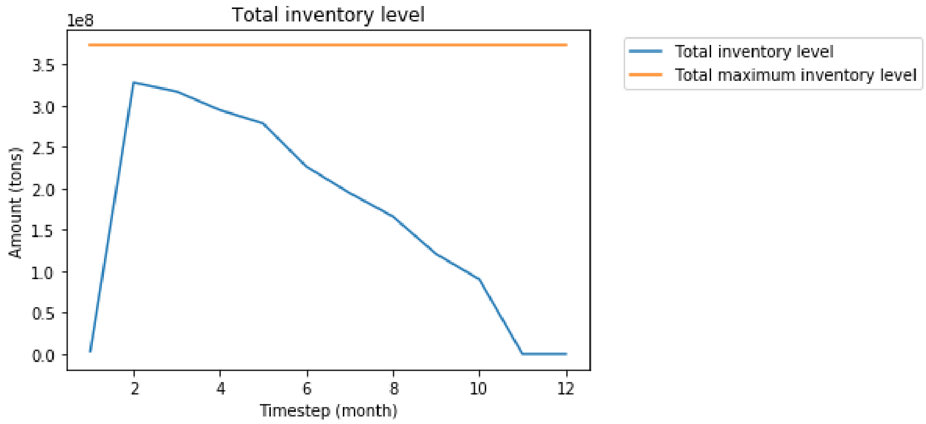


(c) Energy produced from biogas power plants

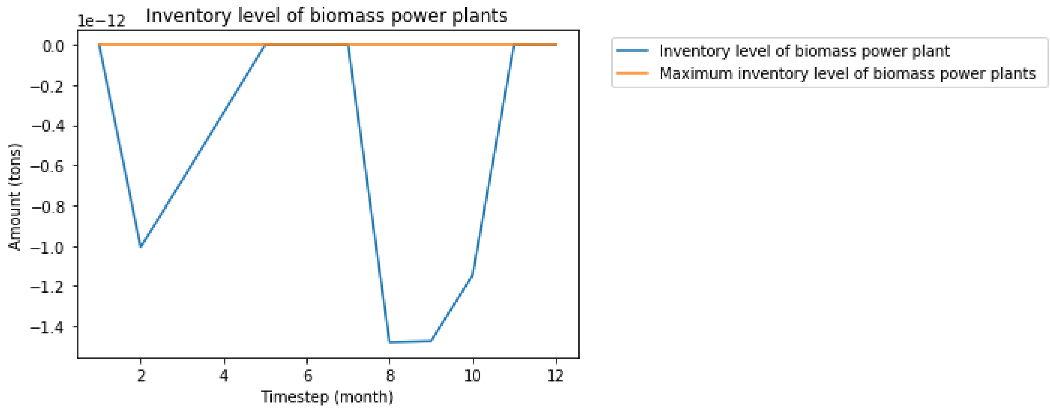


(d) Energy produced from bioethanol plants

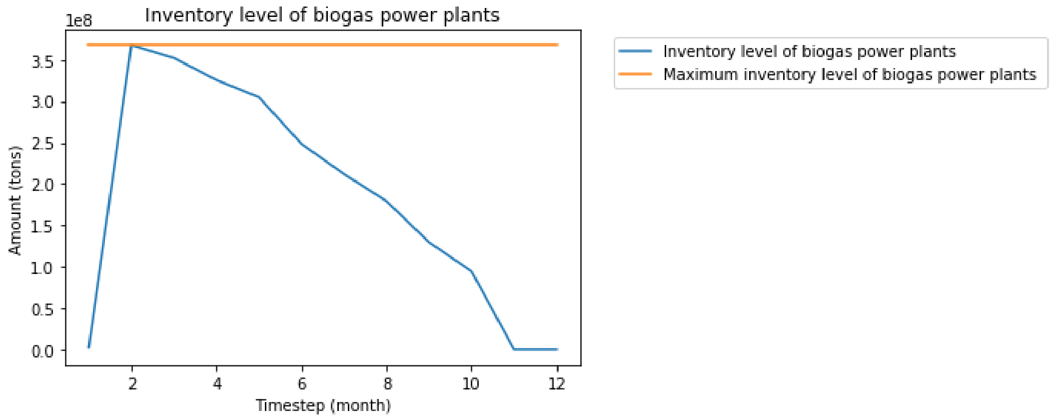
Figure 5.5: Case 4: Energy produced from plants



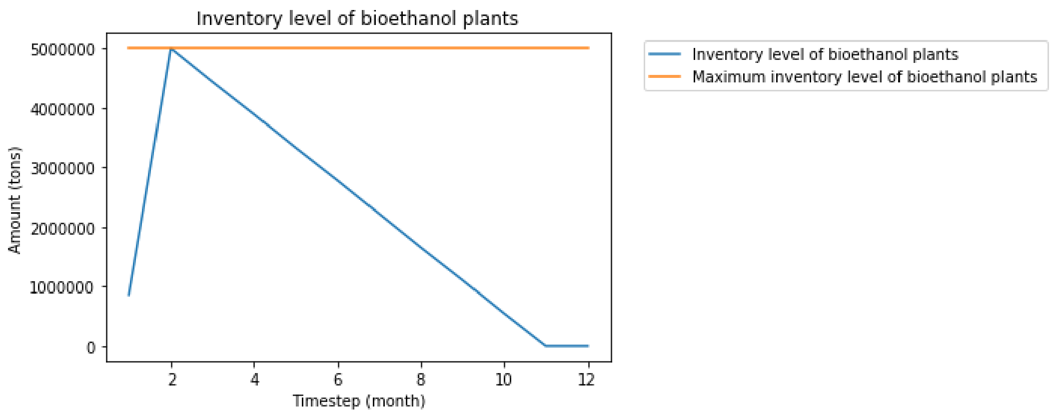
(a) Inventory level of all plants



(b) Inventory level biomass power plants



(c) Inventory level biogas power plants



(d) Inventory level bioethanol plants

Figure 5.6: Case 4: Inventory level of plants

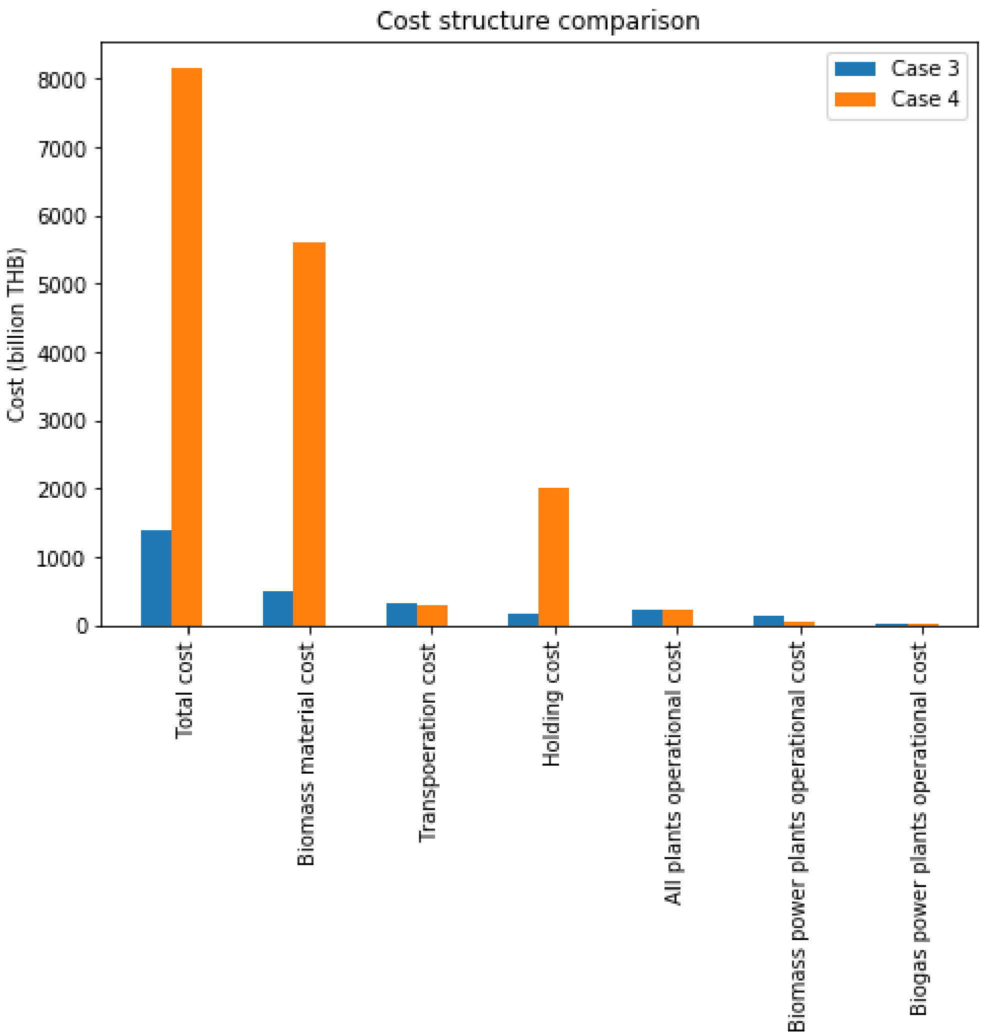


Figure 5.7: Cost structure comparison of case 3 and case 4

5.9.

An overall inventory utilization of all plants in case 4 is 74.31% higher than in case 3; where biomass power plants, biogas power plants, and bioethanol plants are 99.90%, 49.81%, and 42.76% higher respectively. In term of variance of inventory level, overall populational variance of all plants in case 3 is $3.78 \times 10^{16} tons^2$ higher than case 4; where populational variance of biomass power plants and biogas power plants are $1.34 \times 10^{8} tons^2$ and $1.22 \times 10^{14} tons^2$ higher respectively, while bioethanol plants is $1.92 \times 10^{11} tons^2$ lower comparing to case 4. The inventory utilization and variance are shown in figure 5.10 and 5.11 respectively.

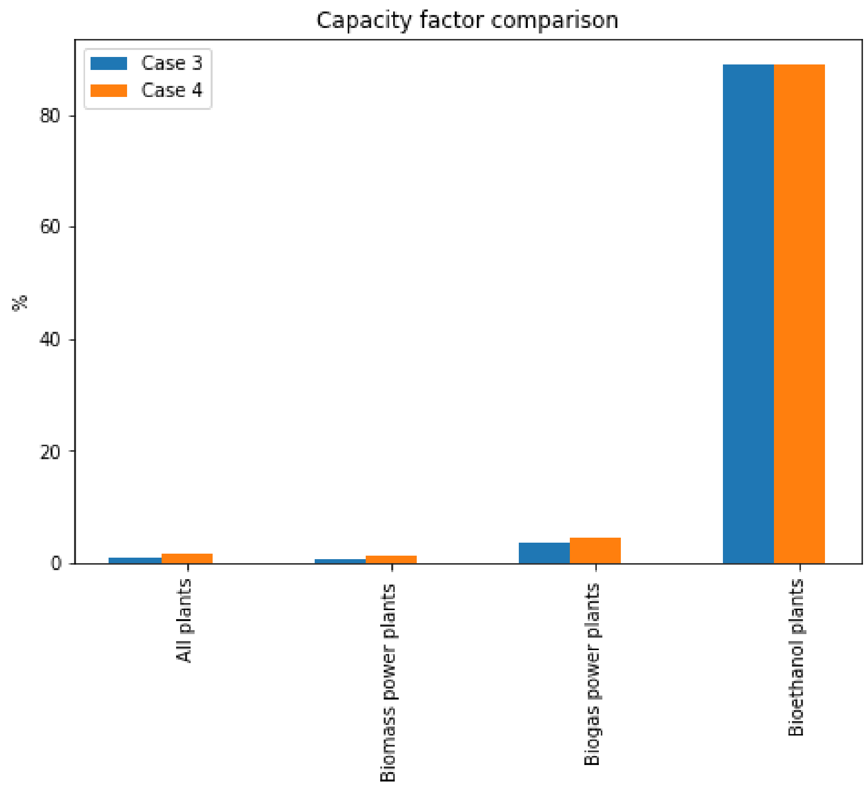


Figure 5.8: Capacity factor comparison of case 3 and case 4

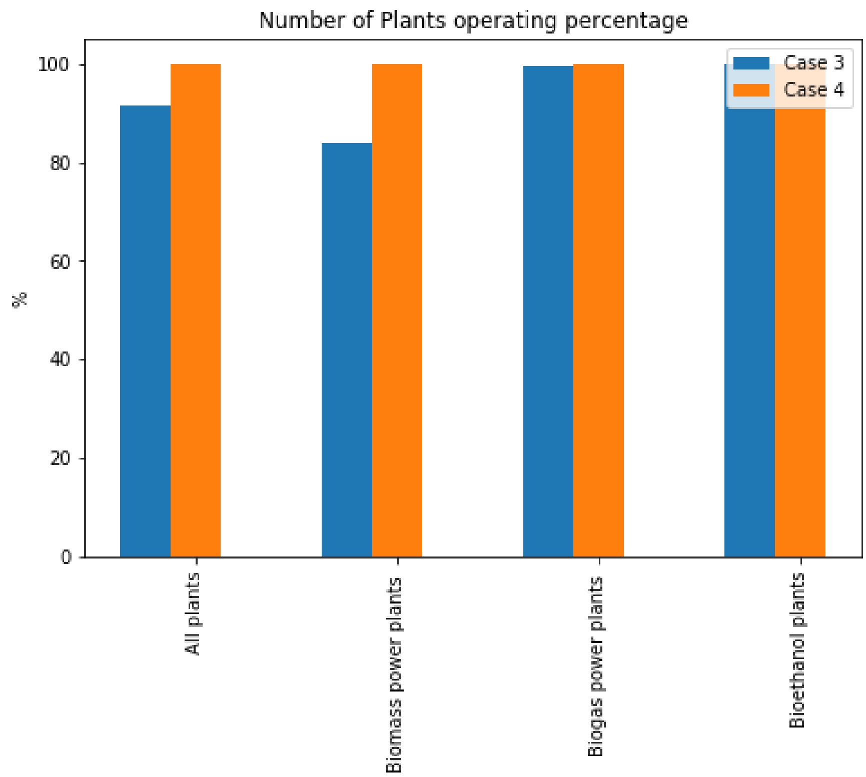


Figure 5.9: Percent of operating plants comparison of case 3 and case 4

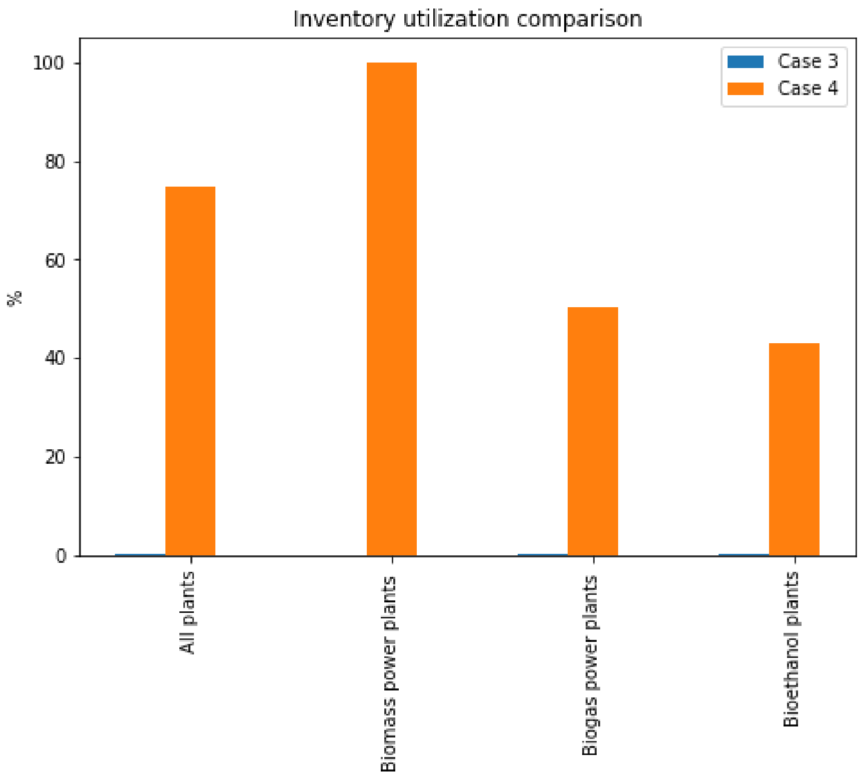


Figure 5.10: Inventory utilization comparison of case 3 and case 4

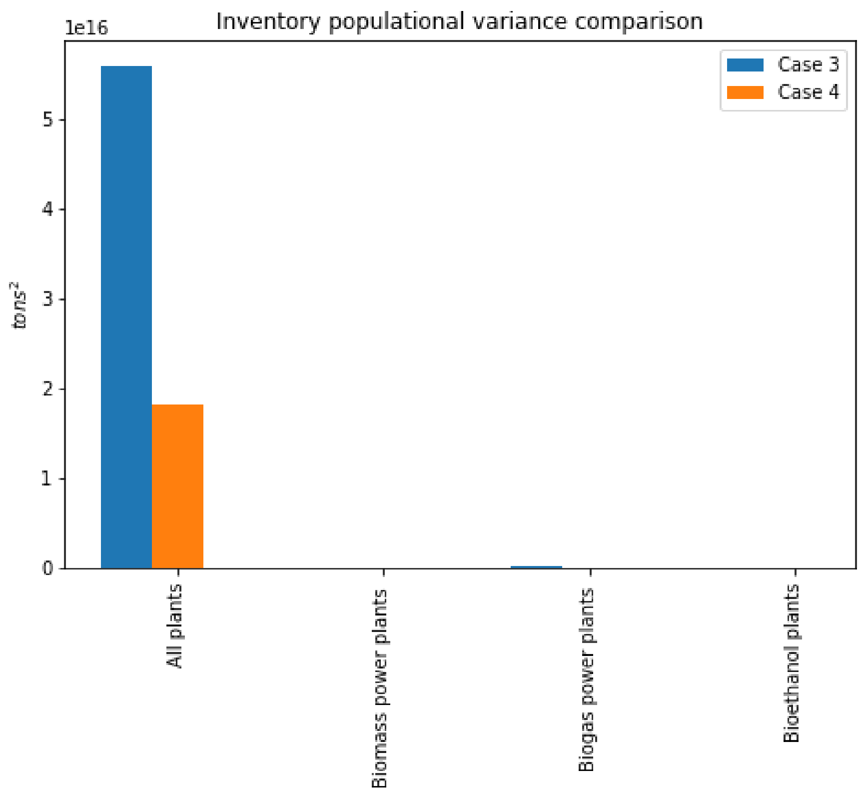


Figure 5.11: Inventory populational variance comparison of case 3 and case 4

Chapter 6
Conclusion and Discussion

6.1 Conclusion

In this thesis, we conducted a bioenergy supply chain simulation and optimization by using the Linear Programming method. Monthly profile of 77-province suppliers, 17 biomasses, 427 bioenergy plants with 5 different energy conversion technologies were considered. The problems were solved by Python programming language version 3.9 with the PuLP package for Linear Programming optimization. The thesis optimized totally different 4 cases. Case 1 was to identify the current amount of bioenergy potential Thailand has with the current amount of biomass and bioenergy plants. Case 2 was to simulate the supply chain at the current bioenergy potential optimized from case 1. Case 3 and 4 were to answer how much additional biomass is needed; and where and how much capacity of new power plants to satisfy AEDP biomass, biogas from energy crops, and bioethanol targets. Where case 3 simulated the supply chain by minimizing the total cost, while case 4 minimized maximum inventory level and new power plants' electricity production capacity.

From the optimized results, case 1 showed that Thailand has a current bioenergy potential to produce bioethanol 4.79 ML/day which can satisfy the AEDP, while electricity generated from biomass and biogas from energy crops are 2,550.4 MW and 35.65 MW respectively. By using this result, the minimized total supply chain cost is 375.22 billion THB while the percentage of plants operate, overall capacity factor, and overall inventory utilization are 75.88%, 0.89, and 41.58% respectively. However, in case 2, by changing the objective function to minimize maximum inventory level, the optimal result showed that the total supply chain cost is 499.99 billion THB while the percentage of plants operate, overall capacity factor, and overall inventory utilization are 100%, 0.89, and 71.90% respectively. We can see that the total cost in case 2 rises by 124.77 THB (33.25%) but the supply chain is utilized more proper.

To see how to improve the supply chain, case 3 and 4 were conducted. The optimal result shows that Thailand should grow 4.65 billion tons more sugarcane which is 5,347% of the current state. By doing the center of gravity method, the new power plants should locate in Saraburi province which is in the central region of Thailand. By minimizing the total supply chain cost, case 3 showed that the new biomass and biogas power plant capacity should be 3,115.75 MW and 64.10 MW respectively. Total supply chain cost is 1,370.85 billion THB while the percentage of plants operate, overall capacity factor, and overall inventory utilization are 91.61%, 9.44×10^{-3}, and 0.41% respectively. However, by changing the objective function to minimize maximum inventory level and electricity production capacity of new power plants, case 4 showed that the new biomass and biogas power plant capacity should be 1,634.82 MW and 51.80 MW respectively. Total supply chain cost is 8,155.66 billion THB while the percentage of plants operate, overall capacity factor, and overall inventory utilization are 100%, 1.77×10^{-2}, and 74.73% respectively. We can see that the new power plants production capacities have drastically lower from case 3 and the supply chain is utilized more proper. Nonetheless, the total supply chain cost is 6,784.81 billion THB (494.9%) higher.

6.2 Discussion and suggestion

As we have seen so far, we can see that there is a trade-off between minimizing the total supply chain cost and utilizing overall facilities in the supply chain and eliminate bottlenecks. To utilize more facilities and reduce bottlenecks, we have to pay more money.

Almost all biomass types give low methane quantity. For example, a ton of rice husk gives 13,520 MJ while it needs 1,489 tons to give the same equivalent heat in a biogas power plant. we suggest that the Ministry of Energy should lower the share of electricity generated from biogas from energy crops, and raise the share of electricity generated from biogas from solid waste or dung instead since it gives about 2-5 times methane content [47] of agricultural residue biomass.

However, this thesis only used Linear Programming. Using a more sophisticated method such as Non-Linear Programming or some supply chain simulation software may give more desirable result. Unfortunately, we already tried to attempt the Non-Linear Programming method but the optimization package we used did not support large data. Finally, another issue is electrical transmission line constraints which we did not consider in this thesis. There are discussions in PDP2015 [35] and PDP2018 [36] that Thailand currently does not have a proper transmission line network to support all alternative energy production. Considering this issue will make the supply chain more systematic and realistic.

Appendix A

Dataset and Source codes

Datasets of 17 biomass types, monthly profile of 77-province suppliers, 427 bioenergy plants data, geographical location, and distance between suppliers and bioenergy plants are attached on the website https://github.com/Pornpawit-Karpkerd/Thesis-Bioenergy-Supply-Chain-Thailand-AEDP.git [27] including python source code in different cases. The following topics will describe how to understand the datasets and the source code files.

A.1 Datasets

A.1.1 Biomass

Biomass information is attached in the file named ”biomass.csv”. This file contains 18 rows x 13 columns. The first column is crops which providing different types of biomass in the second column. The third column is the material cost of biomass in the unit of THB per ton of biomass. The fourth column is the heat capacity of biomass in the unit of Mega Joules per ton of feeding biomass. This data is used to calculate the energy produced from biomass power plants. The sixth column is the equivalent heat capacity of methane yielded from biomass in the unit of Mega Joules per ton of feeding biomass. This data is used to calculate the energy produced from biogas power plants. The eighth column is bioethanol yielding from biomass ratio in the unit of liter per ton of feeding biomass. This data is used to calculate bioethanol produced from bioethanol plants. And the ninth column is transportation cost for each biomass type in the unit of THB per kilometer per ton of carrying biomass. This data is used to calculate transportation cost. The rest columns are not used in the mathematical model. They are just supplements to calculate the used data.

A.1.2 Suppliers profile

Monthly suppliers profile is attached in the file named ”monthly suppliers profile.csv”. This file contains 1,310 rows x 14 columns. The first column is the name of the suppliers who supply different biomass types in the second column. Supplier code name description is described in Appendix B. Column 3 to 14 are monthly data from January to December respectively. The unit of biomass available is a metric ton (1 ton = 1,000 kilograms)

A.1.3 Bioenergy plants information

215 Biomass power plants, 185 biogas power plants, and 27 bioethanol plants information are attached in the file named ”plants profile.csv”. The first column is the code name of plants; F-BMtE is for biomass power plants, F-BGtE is for biogas power plants, and F-BEth is for bioethanol plants. The fifth column is the energy conversion coefficient from heat to electricity for biomass and biogas power plants. The sixth column is the operational cost of biomass and biogas power plants in the unit of THB per Megawatt hour of energy produced. The seventh column is the maximum electricity production capacity for biomass and biogas power plants. The eighth column is the operational cost of bioethanol plants in the unit of THB per liter of bioethanol produced. The ninth column is the maximum bioethanol production capacity of bioethanol plants in the unit of liters per day. And the last column is the maximum operation time of bioenergy plants (since each plant has to take preventive maintenance).

A.1.4 Distance between suppliers and plants

The geographical location (latitude and longitude system) of suppliers and plants are attached in the files ”provinces loc csv.csv” and ”plants loc.csv” respectively. The distances between them are calculated by using the Python-OSRM package. The distance result is attached in the file ”distance.csv”, while the distance among suppliers (provinces) is attached in the file ”industrial area loc.csv”. The distance among provinces is used for case 3 and 4 in Chapter 5.

A.1.5 Additional biomass result from case 3

The additional biomass optimal result is attached in the file named ”additional biomass supply.csv”. However, the result showed that only molasses are additionally needed. Yet, since molasses is derived from sugarcane. Hence, we also have to consider all biomass derived from sugarcane as well. The additional all biomass from sugarcane is attached in the file named ”additional biomass supply from growing additional crops.csv”. And all biomass available from suppliers after adding new additional biomass (this data is used for case 4) is attached in the file named ”after-addition monthly suppliers profile.csv”.

A.2 Source codes

All Python source codes are in .ipynb format.

A.2.1 Thailand's current bioenergy potential

The source code for Thailand's current bioenergy potential discussed in section 4.1 is attached in the file "Case1.1-BestEnergyOutput.ipynb".

A.2.2 Bioenergy supply chain at the current bioenergy potential: the case 1

This topic is also discussed in section 4.1. The related source code is in the file
"Case1.2-SupplyChainWhenUseBestEnergyOutput.ipynb".

A.2.3 Improved bioenergy supply chain at the current bioenergy potential: the case 2

This topic is discussed in section 4.2. The source code is in the file
"Case2-ImprovedSCwhenUseBestEnergyOutput.ipynb".

A.2.4 Additional biomass

This topic is discussed in section 5.1. The source code is in the file
"Case3.1-ImprovedSCforAEDP-additionalBiomass.ipynb".

A.2.5 New power plants location

This topic is discussed in section 5.2. The source code is in the file
"Case3.2-ImprovedSCforAEDP-NewPlantsLoc.ipynb".

A.2.6 Supply chain at AEDP target: the case 3

This topic is discussed in section 5.3. The source code is in the file
"Case3.3-ImprovedSCforAEDP-MinCost.ipynb".

A.2.7 Improved supply chain at AEDP target: the case 4

This topic is discussed in section 5.4. The source code is in the file
"Case4-ImprovedSCforAEDP-Min-maxI.ipynb".

Appendix B

Supplier code description

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Here is a description of 77 provincial supplier codes name.

Code	Supplier	Code	Supplier	Code	Supplier
01	Bangkok	02	Amnat Charoen	03	Ang Thong
04	Bueng Kan	05	Buriram	06	Chachoengsao
07	Chai Nat	08	Chaiyaphum	09	Chanthaburi
10	Chiang Mai	11	Chiang Rai	12	Chonburi
13	Chumphon	14	Kalasin	15	Kamphaeng Phet
16	Kanchanaburi	17	Khon Kaen	18	Krabi
19	Lampang	20	Lamphun	21	Loei
22	Lopburi	23	Mae Hong Son	24	Maha Sarakham
25	Mukdahan	26	Nakhon Nayok	27	Nakhon Pathom
28	Nakhon Phanom	29	Nakhon Ratchasima	30	Nakhon Sawan
31	Nakhon Si Thammarat	32	Nan	33	Narathiwat
34	Nong Bua Lamphu	35	Nong Khai	36	Nonthaburi
37	Pathum Thani	38	Pattani	39	Phang Nga
40	Phatthalung	41	Phayao	42	Phetchabun
43	Phetchaburi	44	Phichit	45	Phitsanulok
46	Phra Nakhon Si Ayutthaya	47	Phrae	48	Phuket
49	Prachinburi	50	Prachuap Khiri Khan	51	Ranong
52	Ratchaburi	53	Rayong	54	Roi Et
55	Sa Kaeo	56	Sakon Nakhon	57	Samut Prakan
58	Samut Sakhon	59	Samut Songkhram	60	Saraburi
61	Satun	62	Sing Buri	63	Sisaket
64	Songkhla	65	Sukhothai	66	Suphan Buri
67	Surat Thani	68	Surin	69	Tak
70	Trang	71	Trat	72	Ubon Ratchathani
73	Udon Thani	74	Uthai Thani	75	Uttaradit
76	Yala	77	Yasothon		

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