Synthesis of Integrated Bio-Refinery

by

Lee Kok Hock

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

January 2010

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
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in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(CHEMICAL ENGINEERING)

Approved by,

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TRONOH, PERAK

January 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

LEE KOK HOCK

ABSTRACT

There is no doubt that the major challenge that industrial processes are facing is in terms of economic aspect. Economic aspect such as market condition or operating cost is forcing the changes in quantities and qualities of desired products. With this, it showed the necessity for industry to reassess the production technologies or to initial the new production paths which can bring more profit for the industry. Hydrocarbon is the essential energy resource for the current world. With the depletion hydrocarbon reserves and the increasing of the hydrocarbon prices, industries start to shift the focus into bio-based resources to replace the dependency of the current economy in the hydrocarbon. Besides that, the productions of the hydrocarbon-based product have followed with several environmental issues. A lot of improvement had been suggested and applied, bio-refinery is one of the emerging core idea. Bio-refinery is defined as a processing facility which converts the biomass into valued product such as liquid transportation fuels. This study covers the technologies that available in bio-refinery and the process flow sheets for each technology. The objectives of this study are to create the available database of biomass process technologies and come out with the most profitable process flow of the bio-refinery. The major issue that led to the less interest of the industry in bio-refinery is in terms of its economic value. With the availability of bio-mass feedstock, bio-refinery will be the major player in the future industry especially in terms of renewable energy. In the bio-refinery, the processes involved are anaerobic digestion, fermentation, gasification and pyrolysis. Different process will have different end products and led to different profits generations. This is the main function of the research to optimize the profit that generated from the integrated bio-refinery using the modeling via GAMS software. From the results, it is justified that, when integration carried for both thermochemical and biochemical processes, it will provided the average profit. For biochemical conversion, it provided much lowest profit compared to the integration process. In the other hand, the thermochemical conversion will result in highest profit than the average profit generated by integration process.

ACKNOWLEDGEMENTS

The author wished to take this opportunity to express his utmost gratitude to the any individual that have taken their time and effort to assist the author in completing this project. Without the cooperation from these individuals, there is no doubt that the author would encounter some complications throughout the course.

First and foremost, the author's utmost gratitude goes to the project supervisor, Dr. Shuhaimi Bin Mahadzir. Without his guidance and patience, the author would not be succeeded to complete the project. Also to the Final Year Research Project Coordinators, Dr. Khalik Mohamad Sabil and Dr. Mohanad El-Harbawi for providing the initial information required to begin the project.

To all individuals that has helped the author in any way but whose name is not mentioned here, the author thank you all.

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CHAPTER 1

INTRODUCTION

Back to the year in 1970's, industries started to show the interest in biomass-for-energy facilities due to the energy crisis and the ecological impact. Recently, the industries have raised more concern in the sustainability of the traditional industries. With the dramatically changes in the price of hydrocarbon product such as crude oil for the past few years, the industries tend to move the focus into the new technologies that can minimize the world dependency on the hydrocarbon as energy resources. Figure 1 below shows the crude oil price from National Energy Board of Canada starting in Jan 2000 until July 2008. Obviously, it shows a continuous rise up of the price of crude oil. Even in the early of 2009, the crude oil price is dramatically dropped, however the price of crude oil for this moment is in raising trend.

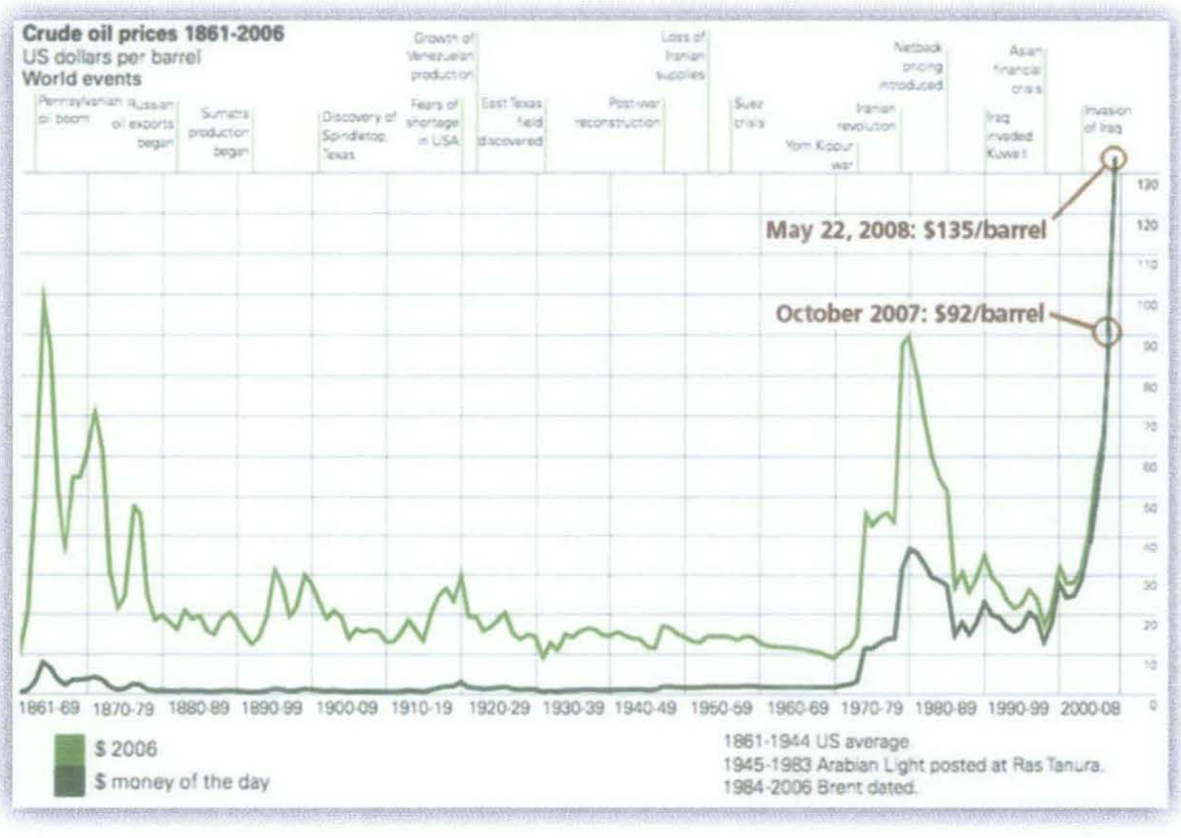

Figure 1: The crude oil prices recorded from year 2000 until 2008 (SIS Solar Ventures, 2009)

Furthermore, the depletion of natural resources and discharge of hazardous wastes in current industry practices is another factor that caused western countries started to pay more attention in the bio-refinery which can be utilize and substitute the hydrocarbon as the fuel for transportation and energy resources for human. In this chapter, the introduction will be presented in following order: background study, problem statement, objectives and scope of study.

1.1. Background Study

Since the last decades, the scientists have raised the concern of the suitability of the current industries that mainly depend on the natural resources which are nonrenewable. The current practice of the industries that created negative impact to the ecology system again is another concern for the scientists for example the green house effect. A bio-refinery can address some of these concerns because it involves the usage of renewable resources, it is a part of a sustainable life cycle, and it normally results in less green house gas emission compared to fossil-based processes (Cormier, 2005).

Back to the year in 1970's, there was an initial surge of interest in biomass-for-energy facilities following the energy crisis and the increase in crude oil prices but many of the original ideas were not commercially pursued because of the increasing of subsequent decline in oil price (Cormier, 2005). However, in this globalization area, due to the high rate of development, the situation had changed while more attention is paid to global warming and the unstableness of the fossil fuels' price. The industries show the interest in finding the alternative energy that can reduce the dependency of the fossil fuels in terms of energy supply, transport fuel and etc.

Thus, the idea of bio-refinery emerged to serve as the option that can improve the current condition. The main concern to the industry is the profit of the concept of bio-refinery. Bio-based economy hardly competes with mineral based economy due to the ten times lower opertaion cost of mineral based economy (Annita Westenbroek, Kenniscentrum Papier en Karton, 2006).

1.2. Problem Statement

Human development has always been associated directly or indirectly with energy use, and because of this the sources of energy were dealt with in the recent past as fully available to human necessity (Demirbas, 2009). In short, the current world situation shows us that the world faced energy crisis, environmental issue and the energy system (distribution of energy resources). The implication of bio-refinery concept has the limitations or difficulties in generating profit to the industry. Current technologies producing bio-based product such as pyrolysis, fermentation and hydrogenation requested high operating cost. Thus, the study about synthesis of bio-refinery has been carried out to enhance the production of bio-based product and generate more possible profit to the industry.

1.3. Objective

The objectives of this project are to build database on the biomass processing technology in order to integrate both thermochemical and biochemical processing of biomass and obtained the optimum profit from the integrated process technologies of bio-refinery.

1.4. Scope of Study

The project requested to build database on the biomass processing technology in order to get the maximum profit from both thermo chemical and biochemical processing of biomass. Few tasks and research have to be carried out for both processes. The production path in thermochemical conversion includes gasification and pyrolysis and biochemical conversion which consists of fermentation and digester have to be determined through study and research.

The study in biomass available as the feedstock is important to show the significant of this project. The biomass will undergo the mentioned processes and being converted into different bio based products. The study in mass balance, operation costs, and the end product price for each process will be the concern in this project to analyst the production of the desired product in order to maximize the profit throughout the processes. In order to do so, GAMS software will be used in this project.

CHAPTER 2

LITERATURE REVIEW

2.1. Biomass

2.1.1. Characteristic of Biomass

Biomass is an interesting concept and a vital part as the feedstock for alternative energy. Biomass is defined as the material derived from living, or recently living organisms and it can equally apply to both animal and vegetable derived material (Cosmos, 2009). Biomass is one of the potential renewable energy for fuel production. Biomass as the feedstock that is renewable, sustainable, efficient, cost effective and safe thus it has huge potential to generate renewable fuel replacing fossil fuel. Varies valued chemical products also can be produced using biomass. The Figure 2 below shows the different in prices for the renewable feedstock and non-renewable feedstock.

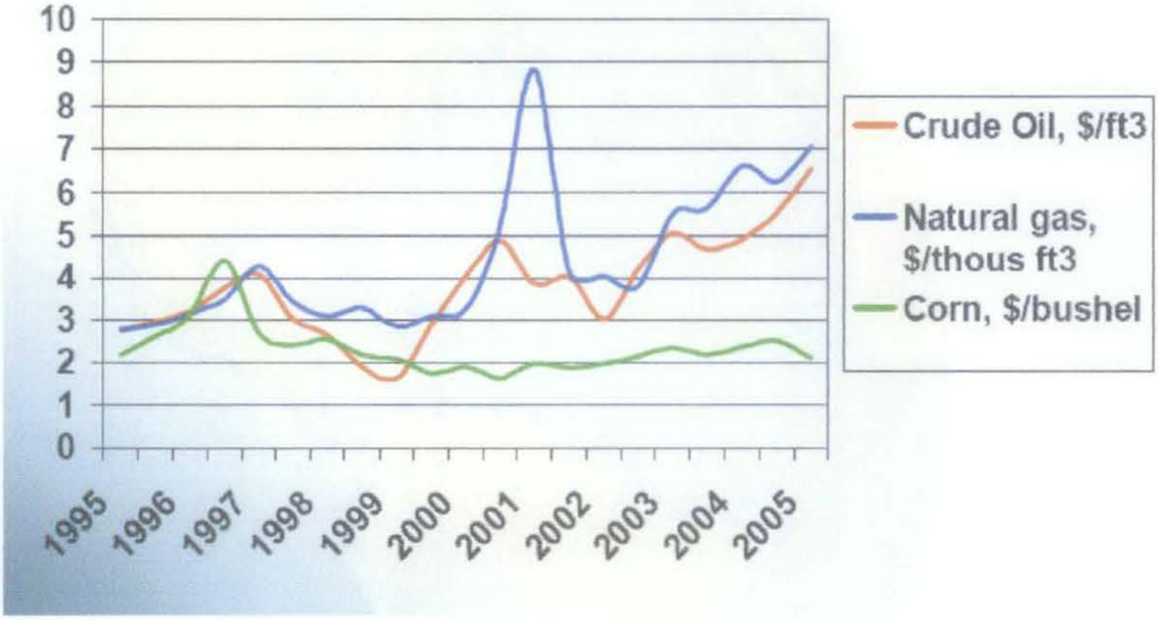

Figure 2: Cost for different feedstocks (Bohlmann, 2009)

From the Figure 2 above, it is obviously to conclude that the low cost in the biomass feedstock price will be the driving force to develop more in the bio-refinery technologies. The most common types of biomass are wood, crops (e.g. rice, maize and wheat) and waste (e.g. food waste, manure) (James H. Clark and Fabien E. I. Deswarte, 2008). These resources are considered as renewable because they can be continually re-grown or regenerated. They take up carbon dioxide from the air while they are growing (through photosynthesis) and then return it to the air at the end of life, thereby creating a 'closed loop' (Deswarte, 2008). The Figure 3 below shows how the cycle of CO_2.

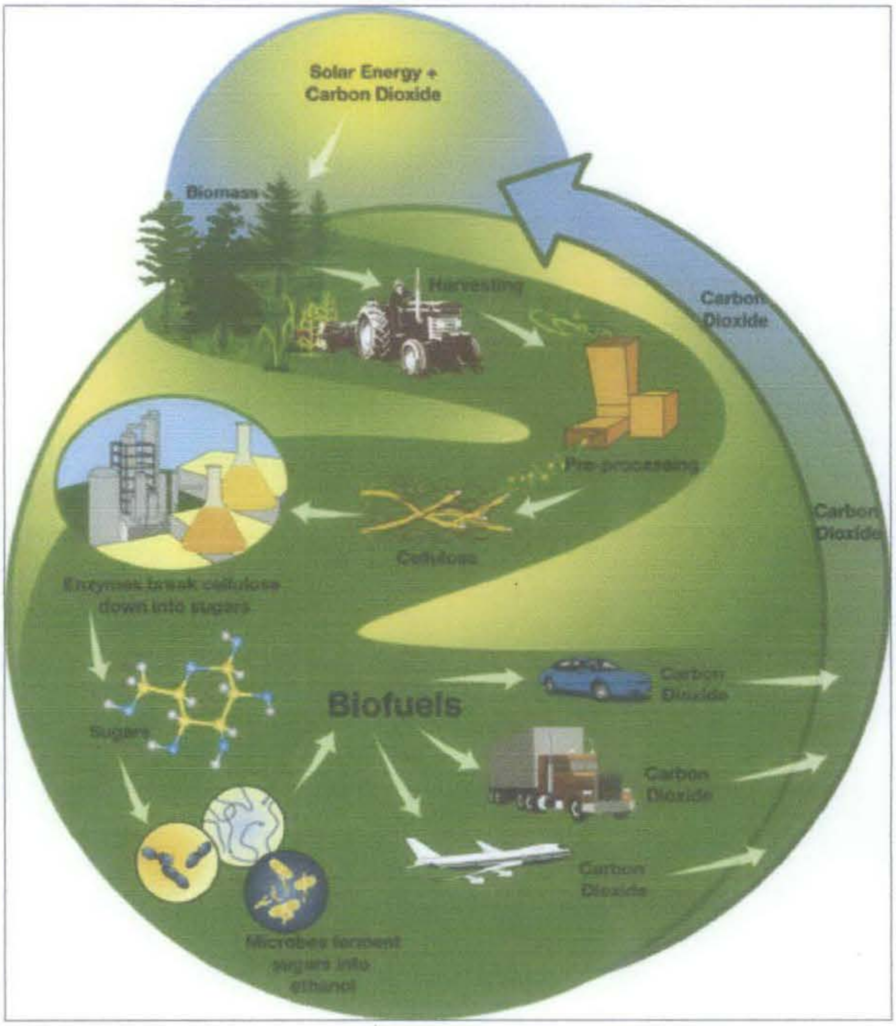

Figure 3: The cycle of CO_2 (Biomass Produce Renewable Energy, 2010)

From the Figure 3 above, it is clearly shown that how the greenhouse effect can be minimized with the application of biomass as the feedstock to produce energy. Biomass can produce energy as hydrocarbon do is mainly because of the properties of biomass that consists of components Carbon, Hydrogen and Oxygen.

In order to use biomass for energy production all the properties of biomass that shown in Table 1 have to be taken into account.

Table 1: Biomass Properties (Fabio Orecchinia and Enrico Boccib, 2007)

Property	Range
Proximate analysis	
Humidity content (moisture)	10 % to 70 %
Calorific Value[a]	2 to 22 MJ/kg
Volatile matter	30% to 80%
Fixed carbon	15% to 30%
Ash	1% to 10 %
Ultimate analysis (by weight)	
Cellulose	30% to 50%
Hemi-cellulose (polysaccharides)	20% to 40%
Lignin	5% to 30%
Carbon	40% to 50%
Oxygen	38% to 43%
Hydrogen	5% to 7%
Alkali metal and inorganic element	1% to 15%
Bulk Volume and Density	1 to 50 m3/t (daf)
Times of cultivation	6 to 24 months
Yield (potential annual production capacity)	1 to 100 (dmt[b]/ha)/yr
Characteristics of cultivation	Depends on climates, water, pesticides and fertilisers demand
Production cost	Negative (for waste) to 1 (DC)-5 (IC) €/GJ
Transport cost	Function of the distance travelled and the energy density (from 0 to 1 MJ/km)
Conditions of the supply enterprises	Depends on local conditions

[a]NCV on daf (dry ash-free) basis.
[b]dmt: dry matter tons.

There are basically two categories of biomass feedstock which are grains and lignocelluloses. The example of grains feestock is corn while the lignocelluloses feedstock is composed of cellulose and hemi-cellulose and they are compose about two-third of a dry biomass (Cormier, 2005).

The following is a typical composition of lignocelluloses (Scurlock, 2003):

- Cellulose, between 40% and 60% of the dry biomass, is formed of glucose-glucose dimer. Hydrolysis is needed to break down the hydrogen bond and the product, glucose, is a six carbon sugar.
- Hemicellulose, between 20% and 40% of dry biomass, consist of short highly brached chains of various sugars, mainly five-carbon and six-carbon as xylose, arabinose, galactose, glucose and mannose. Hemicellulose are easy to break down during the hydrolysis.
- Lignin, between 10% and 25% of dry biomass, counted as a residue during the ethanol process.

2.1.2. Availability of Biomass

The availability of biomass is the key element for bio-refinery. According to the study by the Department of Energy, USA the current quantity of biomass in the entire U.S. is about half of a billion dry tons (U.S. Department of Agriculture 2005). The study by the Department of Energy also predicted there will be over one billion ton of biomass would be available with the some pretreatment or modification of the biomass. It is estimated that biomass will supply 5% of the US nation's power, 20% of its transportation fuels, and 25% of its chemical by 2030 (U.S Department of Agriculture and U.S. Department of Energy 2005).

The Table 2 below shows that the potential availability of biomass in U.S. Nation.

Table 2: Potential availability of biomass under increased crop yields and technology changes (U.S. Department of Agriculture and U.S. Department of Energy 2005)

Type	Quantity (million dry tons)
MSW & other wastes	31
Manures	44
Grains (bio-fuels)	55-95
Other crop residues	37-49
Soybeans	26
Small grain residues	19-32
Wheat straw	42-72
Corn stover	152-230
Perennial crops	156-377

Besides the availability of biomass reserve in the world, the other side of the biomass feasibility is the price at which biomass is available. The biomass feedstock recorded is $0.05/kg (Vanderspurt, 2009). With the low price of the feedstock cost, it attracted more interst from the industry. For the example, as set out in the White paper, EU's goal is to significantly increase the use of biomass, adding further 90 million tonnes oil equivalent (Mtoe) by year 2010. If these targets were achieved, biomass would provide around 50% of the energy derived from renewables. In the longer term, it is anticipated that biomass could contribute 20% of the current EU primary energy demand, with more than 20 million hectares used for fuel crops (European Commission, 2000).

2.2. Bio-refinery

Future refineries will face with feedstock problems in terms of availability and cost. As the price of crude oil is keeping increasing and the supplies diminish, there is a need for alternative sources of energy feedstock. One of the solutions is through the concept of bio-refinery. The term bio-refinery was recently coined to address refineries capable of converting biomass to valuable chemicals or energy (Cormier, 2005). As more renewable sources are used the direct contribution is less waste will be generated in the ecological cycle. Besides as a substitution for fossil resources, bio-refinery may also be able to be considered as integrated use of living organism, microorganism and enzymes. Thus, bio-refinery is one way to mitigate the negative effects of local ecosystem services and at the same time maximising the value of the biomass and minimizing waste. This integrated approach corresponds to the biorefinery concept and is gaining increased attention in many parts of the world (Kamm, B. and M. Kamm, 2004; Halasz, L., G. Povoden, and M. Narodoslawsky, 2005) as illustrated in Figure 3, the biorefinery of the future will be analogous to today's petrorefineries (Realff, M.J. and C. Abbas, 2004; National Renewable Energy Laboratory, www.nrel.gov/biomass/biorefinery.html).

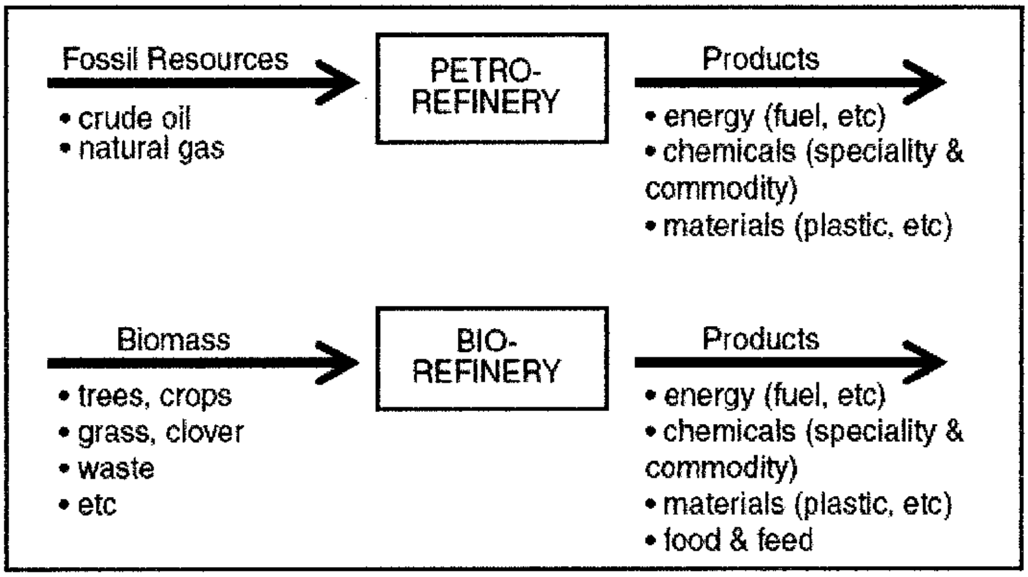

Figure 4: Comparison of petrorefinery vs. biorefinery

There are a several number of technological process options that available to make use of a wide variety of biomass types as a renewable energy source. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it to another form, such as liquid biofuel or combustible biogas. While for some classes of biomass resource there may be a number of usage options, for others there may only one appropriate technology (Conversion Technologies , 2008). Bio-refinery can be based on a number of processing platforms using different ways of processes such as physical, thermal, and biochemical processes. The processing of biomass with its product is summarized in Table 3.

Table 3: Biomass Technology Chart (Biomass Energy Home Page, 2009)

Technology	Conversion Process Type	Major Biomass Feedstock	Energy or Fuel Produced
Direct Combustion	Thermochemical	wood agricultural waste municipal solid waste residential fuels	heat steam electricity
Gasification	Thermochemical	wood agricultural waste municipal solid waste	low or medium-Btu producer gas
Pyrolysis	Thermochemical	wood agricultural waste municipal solid waste	synthetic fuel oil (biocrude) charcoal
Anaerobic Digestion	Biochemical (anaerobic)	animal manure agricultural waste landfills wastewater	medium Btu gas (methane)
Ethanol Production	Biochemical (aerobic)	sugar or starch crops wood waste pulp sludge grass straw	ethanol
Biodiesel Production	Chemical	rapeseed soy beans waste vegetable oil animal fats	biodiesel
Methanol Production	Thermochemical	wood agricultural waste municipal solid waste	methanol

In this project the focus will be in thermal processing and biochemical processing which consists of gasification, pyrolysis, anaerobic digestion and fermentation. The following parts of this chapter will briefly defined the process and discuss the process in terms of processing path and the end products for each process.

There are two main conversion technologies in the bio-refinery process which are thermal conversion and bio-chemical conversion.

2.2.1. Biochemical Conversion

Anaerobic Digestion

Anaerobic Digestion is the process of decompostion of organice matter by a microbial consortium in an oxygen-free environment. It is a process found in many naturally occuring anoxic environment including watercourses, sediments, waterlogged soils and the mammalian gut. It can also be applied to a wide range of feedstock including industrial and municipal waste waters, agricultural, municipal, food industry waste and plant residues (J.Ward, 2007).

There are two basic AD processes, which take place over different temperature ranges (Conversion Technologies: Anaerobic Digestion , 2008):

- Mesophilic digestion takes place between 20°C and 40°C and can take a month or two to complete.
- Thermophilic digestion takes place from 50-65°C and is faster, but the bacteria are more sensitive.

Fermentation

Fermentation is the process used in brewing and wine making for the conversion of sugars to alcohol (ethanol CH_3CH_2OH). The same process, followed by distillation, can be used to obtain pure ethanol (bioethanol) for use as a transport biofuel (Conversion Technologies: Fermentation , 2008).

Conventional fermentation processes for the production of bioethanol make use of the starch and sugar components of typically cereal or sugar (beet or cane) crops. Bio-ethanol can be readily added to conventional petrol in concentrations up to 10%. However most of the European manufacturers' vehicle warranties only cover up to a 5% bioethanol with 95% petrol blend (Conversion Technologies: Fermentation , 2008). Ethanol is the one of the most promising bio-refinery product which is mainly produced by fermentation (95 fermentation, 5% synthetic from ethylene) (CORMIER, 2005). Ethanol could be used as an alcoholic beverage, industrial alcohol, and fuel-related alcohol (Berg C, 2003). Thus, ethanol represents an easy alternative bio-fuels for the future and is seen as the way of reducing dependence on fossil fuels. For instance, according to Dinneen (2005), if a 10%-ethanol and 90%-gasoline fuel blenids used, this will:

- Reduce tailpipe fine particulate matter (PM) emission by 50%
- Reduce secondary PM formation by diluting aromatic content in gasoline
- Reduce carbon monoxide (CO) emission by up tp 30%
- Reduce toxics content by 13% (mass)

The United States has witnesses an increasing level of interest in ethanol production as shown in Figure 5.

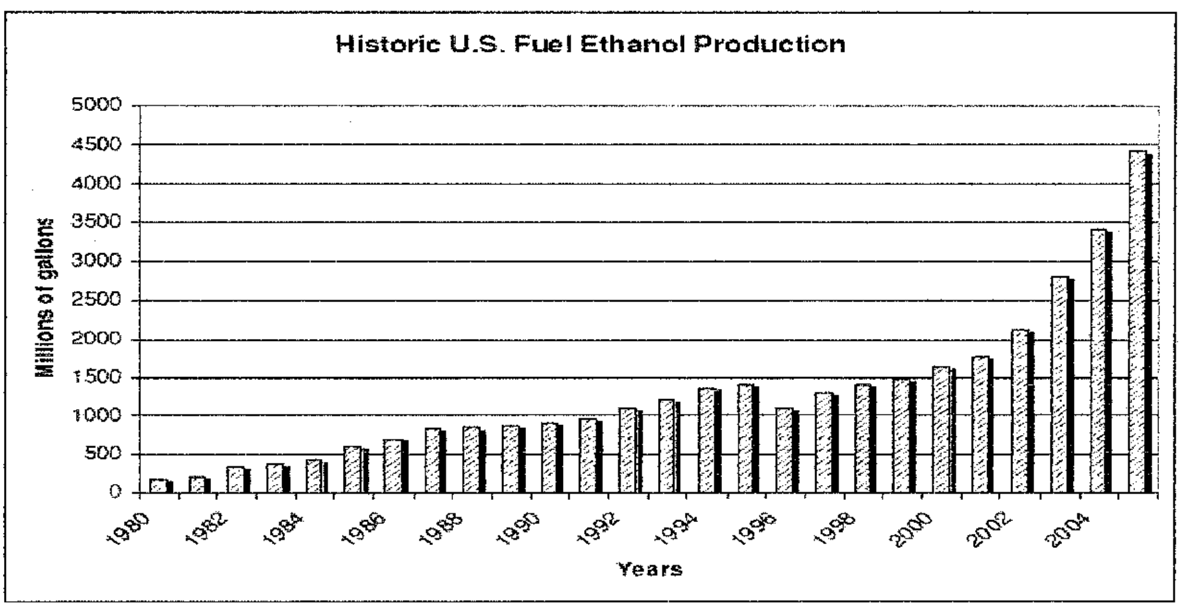

Figure 5: Historic U.S. fuel ethanol production (Dinneen B, 2005)

2.2.2. Thermal Chemical Conversion

Gasification

Gasification is a partial oxidation process whereby a carbon source such as coal, natural gas or biomass, is broken down into carbon monoxide (CO) and hydrogen (H_2), plus carbon dioxide (CO_2) and possibly hydrocarbon molecules such as methane (CH_4) (Conversion Technologies: Gasification , 2008).

Gasification technology can be used for (Conversion Technologies: Gasification , 2008):

- Heating water in central heating, district heating or process heating applications
- Steam for electricity generation or motive force
- As part of systems producing electricity or motive force
- Transport using an internal combustion engine

Pyrolysis

Pyrolysis is the precursor to gasification, and takes place as part of both gasification and combustion. It consists of thermal decomposition in the absence of oxygen. It is essentially based on a long established process, being the basis of charcoal burning (Conversion Technologies: Prolysis, 2008).

Applications for pyrolysis include (Conversion Technologies: Gasification , 2008):

- Biomass energy densification for transport or storage
- Co-firing for heat or power
- Feedstock for gasification

2.3. Production Path of Each Process

As discussed there are four main conversion technologies in converting the biomass feedstock to added value product. The Figure 6 below shows the potential integrated bio-refinery that consists of both conversion technologies.

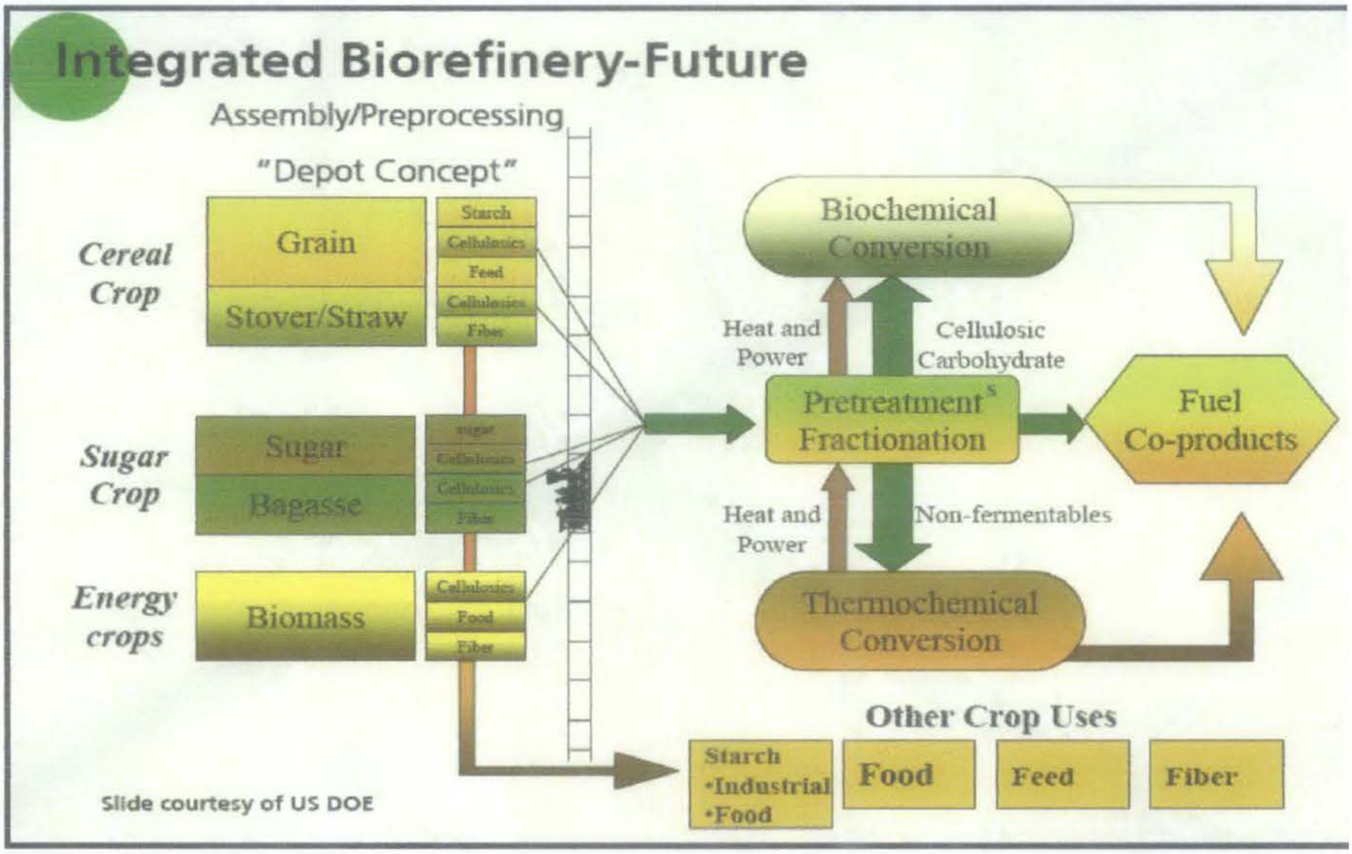

Figure 6: The overall process flow for integrated bio-refinery (http:// www.abengoabiorefinery.com)

The figure above shown the overall process that invloved in intergrated bio-refinery. Basically, the biomass as the feedstock will send to the bio-refinery to be processed into the desired proiduct. After the pretreatment, the biomass inlet will send to two types of conversion called as biochemical conversion and thermochemical concersion. In this section, each production path will be discussed in details.

2.3.1. Anaerobic Digestion

The Figure 7 below shows the basic anaerobic digestion flow chart.

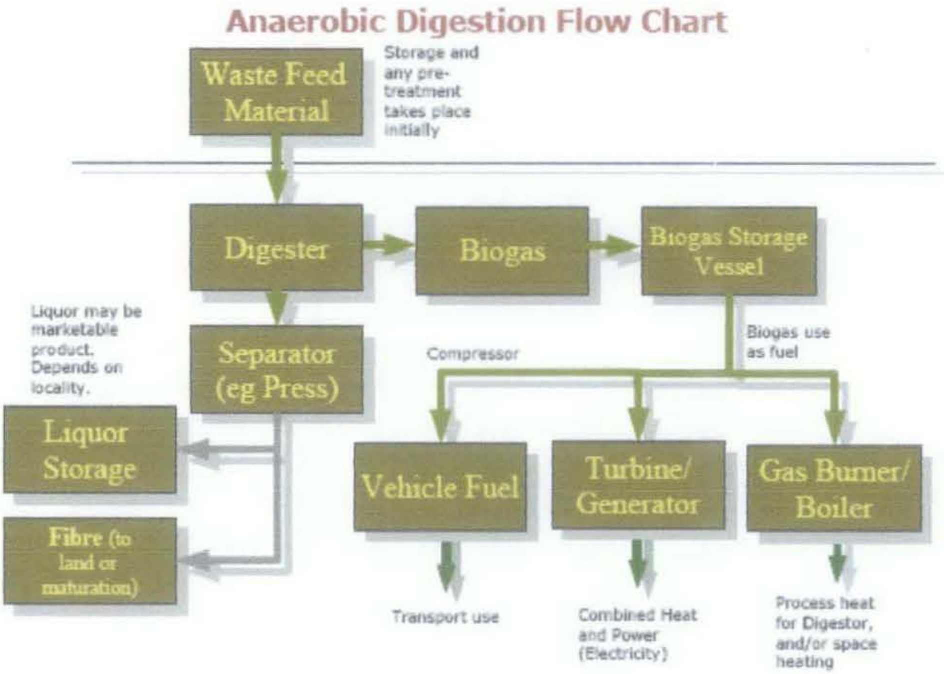

Figure 7: The anaerobic digestion flow chart (Anaerobic Flow Diagram , 2009)

Anaerobic digestion provides a viable alternative to landfill for category 2 wastes which are food industry wastes, domestic wastes, and abattoir wastes. Once produced, biogass is generally composed of 48-65% methane, 36-41% carbon dioxide, up to 17% nitrogen. (J.Ward, 2007).

From the research, the weight percentage and phase of Anaerobic Digestion is shown as table below.

Table 4: Weight percentage and phase of Anaerobic Digestion effluent (Zakaria, 2009)

	Output	**wt%**	**Phase**
Input: **1 kg biomass**	Fuel Gas (Methane)	7.80	Gas
	CO2	24.50	Gas
	Sludge	39.90	Liguid/Solid
	Traces Gas	27.80	Gas

From the table above, the methane consists of 7.8% of the total product and mostly of the product will be in sludge form. This sludge and traces gas may undergo certain recovery process in order to get the valued product. From the Anaerobic Digestion process, the methane can be used as fuel gas to provide energy after combustion in transportation purposes.

2.3.2. Fermentation

The Figure 8 below shows the process flow diagram of fermentation process.

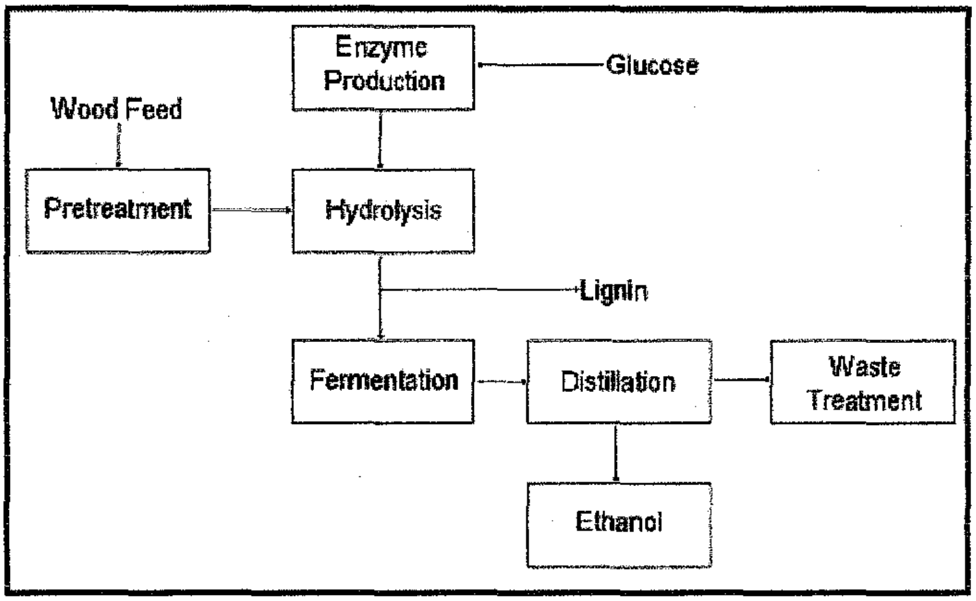

Figure 8: The fermentation process (Environment Canada, 1999)

Fermentation is generally the process that convert the carbohydrate such as sugar into an acid or an alcohol. In other words, fermentation can be refer as the use of yeast to change sugar into alcohol. Fermentation occurs naturally in many different foods given the right condition. The most widely used sugar for ethanol fermentation is blackstrap molasses which contains about 35-40 wt% sucrose, 15-20 wt% invert sugars such as glucose and fructose,a nd 28-35 wt% of non-sugar solid (Zakaria, 2009).

From the research, the weight percentage and phase of Fermentation is shown as Table 5.

Table 5: Weight percentage and phase of Fermentation effluent (Zakaria, 2009)

	Output	**wt%**	**Phase**
Input: 1 kg biomass	Ethanol	5.16	Liquid
	CO_2	5.63	Gas
	Traces Gas	37.72	Gas
	Sludge	51.48	Liguid/Solid

From the table above, the valued product generated by the Fermentation process will be ethanol which consists of 5.16% of the total product. Similar with the Anaerobic Digestion, most of the product will be in sludge form. The necessary recovery process can be carried on to recover some of the useful product.

2.3.3. Gasification

The Figure 9 below shows the process flow diagram for gasification of biomass.

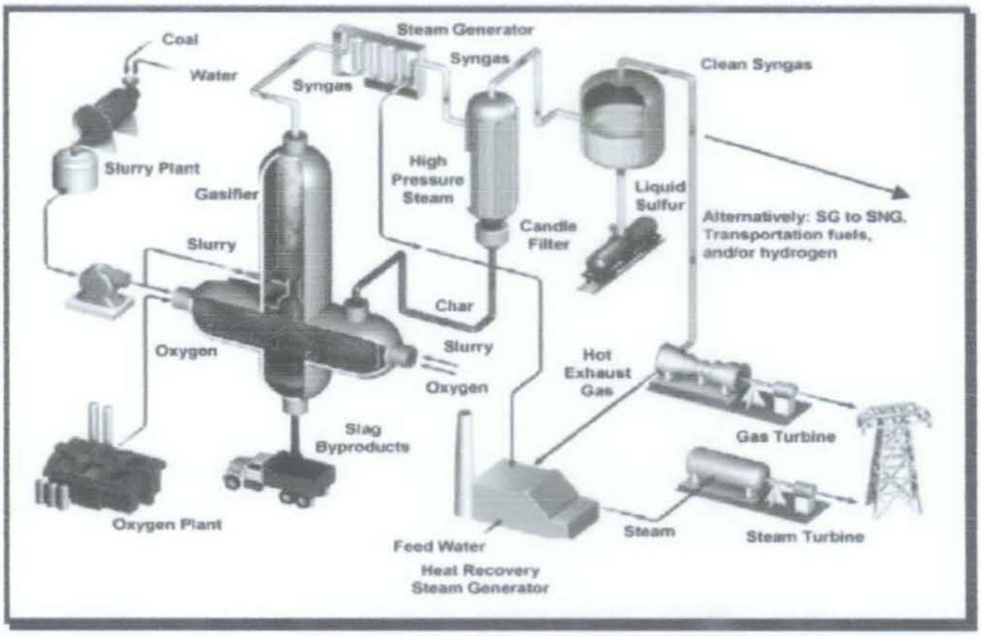

Figure 9: The process for gasification (JPMorgan, 2007)

Gasification of biomass has a long history and has been seen as an attractive alternative to produce power and heat, however, despite many achievements it can only be considered to be commercial for heat applications. Gasification is a process that convert biomass into carbon dioxide and hydrogen by reacting the raw materials at high temperatures with a controlled amount of oxgen. Gasification relies on chemical processes at elevated temperature > 700^0C, which distinguishes it from biological processes such as anaerobic digestion that produce biogas. Currently four types of gasifier are available for commercial use that is counter-current fixed bed, cocurrent fixed bed, fluidized bed and entraiend flow. Among the gasification technology available, probably the most suitable optin for processing biomass would be small scale downdraft gasifier using air as gasifying agent, in order to obtain electricity (Hamzah, 2009).

For Gasification process, the biomass is converted to mixture of gases ad char. The general flow of the process can be shown in the Figure 10 below.

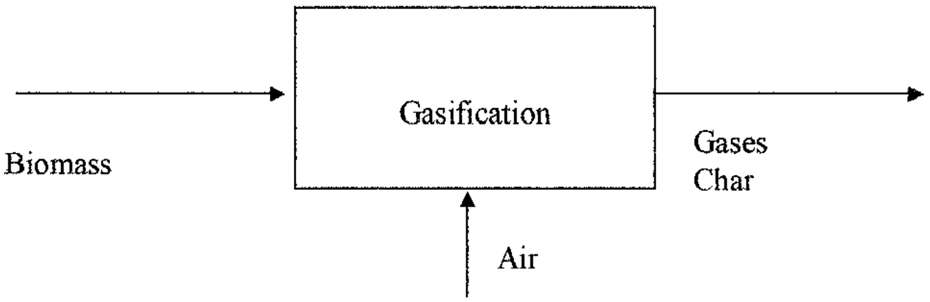

Figure 10: Gasification of biomass

Gasification of biomass generally will yields 80% of gases and 20% of char. The produced gases consists of carbon monoxide, carbon dioxide, hydrogen and methane. Different approach in gasification will yield different percentage among the components of the gases. The weight percentage and phase of gasification is shown by the Table 6 below.

Table 6: Weight percentage and phase of Gasification (Hamzah, 2009)

	Output	**wt%**	**Phase**
Input: 1 kg biomass	Gases	80	Gas
	Char	20	Solid

2.3.4. Pyrolysis

The Figure 11 below shows the process flow diagram for pyrolysis of biomass.

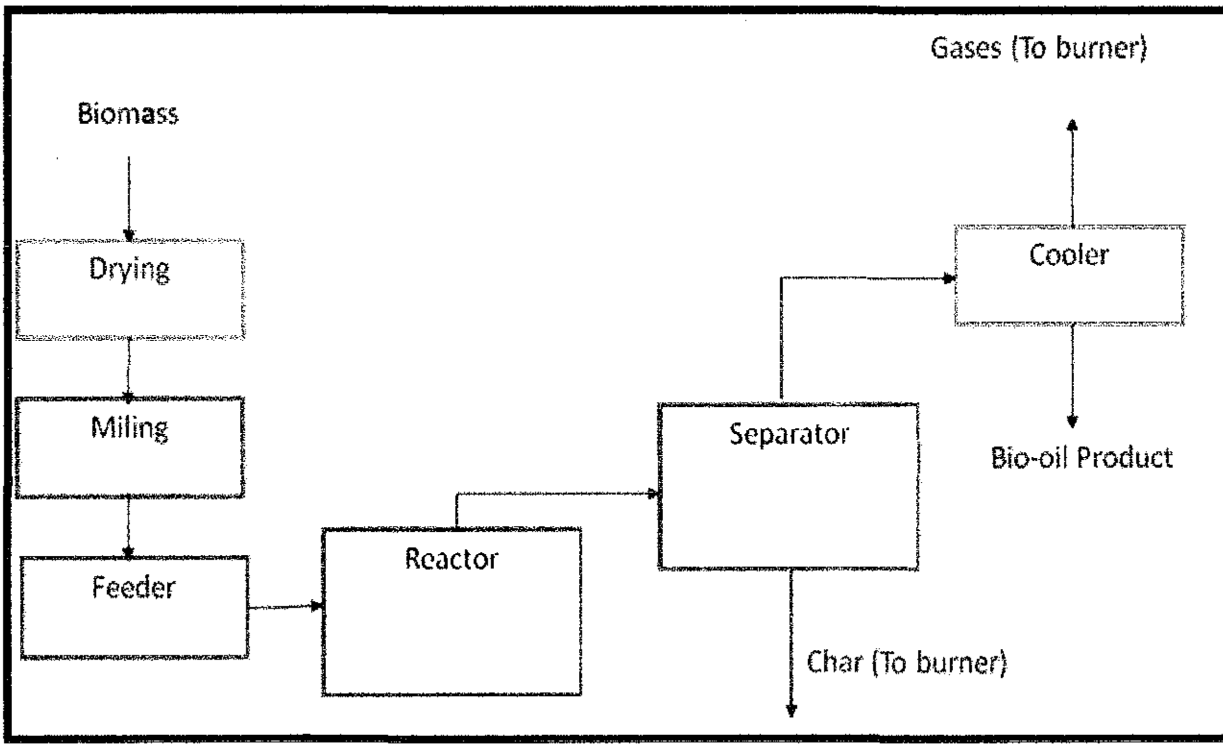

Figure 11: The process of pyrolysis (Hamzah, 2009)

Pyrolysis of the biomass produces there different energy products in different quantities that are bio-oil, bio-gas, and charcoal. Bio-oil can be used to produce direct heat energy to drive electricity generation. Bio-gases can be combusted directly to produce heat or electricity while charcoal can be used as an industrial or domestic fuel (Hamzah, 2009).

For the biomass that undergo Pyrolysis process, the biomass will converted into liquid (bio-oil and water), gases and char. The simple flow for the pyrolysis of biomass is shown as Figure 12 below.

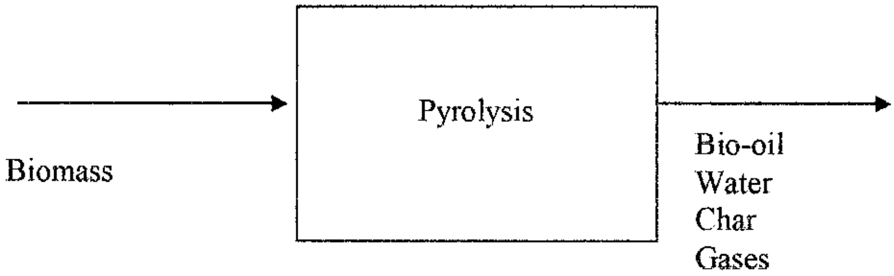

Figure 12: Pyrolysis of Biomass

Generally, for each 1kg of biomass that undergone the pyrolysis process will yields about 70 wt% of liquid, 10 wt% of solids and lastly 20% of gases. The weight percentage and phase of Pyrolysis can be shown in the Table 7 below.

Table 7: Weight percentage and phase of Pyrolysis (Hamzah, 2009)

	Output	**wt%**	**Phase**
Input: 1 kg biomass	Liquid (Bio-oil)	60.0	Liquid
	Water	10.0	Liquid
	Char	10.0	Solid
	Gas	20.0	Gas

CHAPTER 3

OVERALL RESEARCH PROGRESS

As stated in the problem statement, the purpose of this project is to develop a programming to maximize the profit of process synthesis in bio-refinery. So, a completed synthesis process of bio-refinery is requested included the mass balance production for all the processes involved. The project flow for the project is divided into two parts which are FYP 1 and FYP 2.

3.1. FYP 1

For FYP 1, the focus will mainly in research and study for the involved processes and to create a datasheet on each process as shows in Figure 13. While for FYP 2, the focus will mainly in process modeling and synthesis.

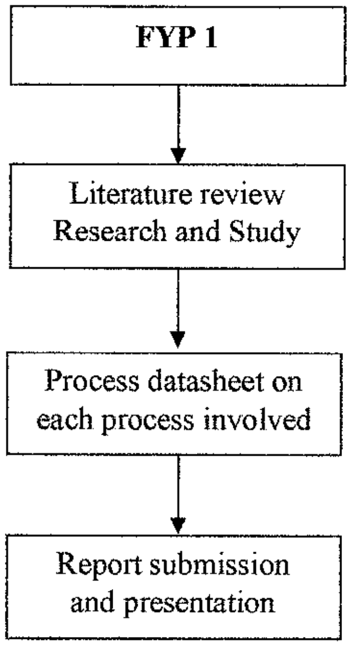

Figure 13: Project flow for FYP 1

As for FYP1, the scopes of works are basically divided into 3 phases which are:

- First Phase: Literature review

  For this phase, there will be more focus in reviewing the literature from various sources such as science direct journal, related book, and web-sites. The expected outcomes from this phase are to have the knowledge in the project involved and find out its significant. Nevertheless, the phase acts as a fundamental for the understanding of the project.

- Second Phase: Process datasheet for each process

  For the second phase, it requests a detail study in the process flwosheet of the conversion technologies especially in terms of material balance. The proposed process synthesis is shown as Figure 14.

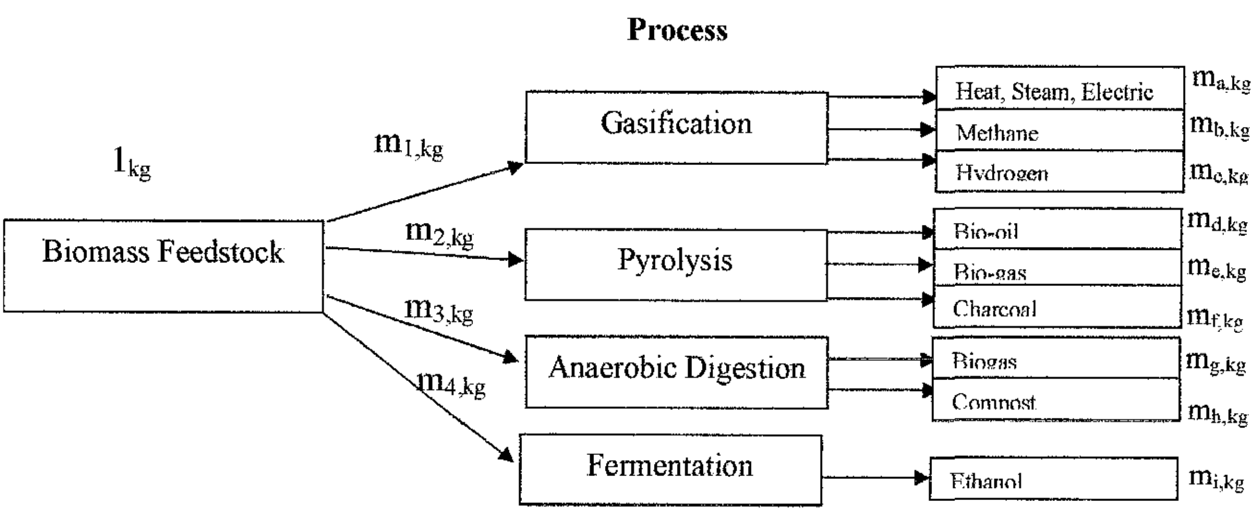

Figure 14: Approach to the synthesis process for bio-refinery

The purpose for the synthesis process in bio-refinery is to determine the optimal flowsheet for bio based product production. Research and analysis of related literature on the mentioned processes are being carried on to create database of process technologies. Data such as material input, material output, energy used and energy produced needed in order to create the most profitable process synthesis. To do this, GAMS will be used in data gathering and data calculation purposes. To have a maximum profit, the lowest cost for operation and material are required since the equation of profit calculation is shown as below:

Profit = (Revenue of product)-[(Cost of Material) + (Process Cost)]

Thus, the profit maximization is subjected to mass balance, energy consumption and process models.

- Third Phase: Interim report submission and presentation

  For the last phase for FYP 1 is the interim report submission and presentation to the internal examiners and the supervisor. The purpose of the report submission is to make sure that the student can explain in terms of writing about the contents of the project as well as its significant. Meanwhile the presentation requested student to explain verbally about the project.

3.2. FYP 2

Meanwhile for the FYP 2 the focus will mainly in programmed the process datasheet on both biochemical and thermochemical processing of biomass in GAMS. Both processing technologies will be integrated and programmed in order to get a maximum profit. Thus, in the FYP 2 the main task will be in GAMS programming.

The basic understanding in GAMS language is essential important to complete this research. So the first step in FYP 2 is getting familiar with GAMS software by practicing the examples that provided. Then, proceed to the real programming for the process datasheet that done in FYP 1.

The project flow chart for FYP 2 as follow:

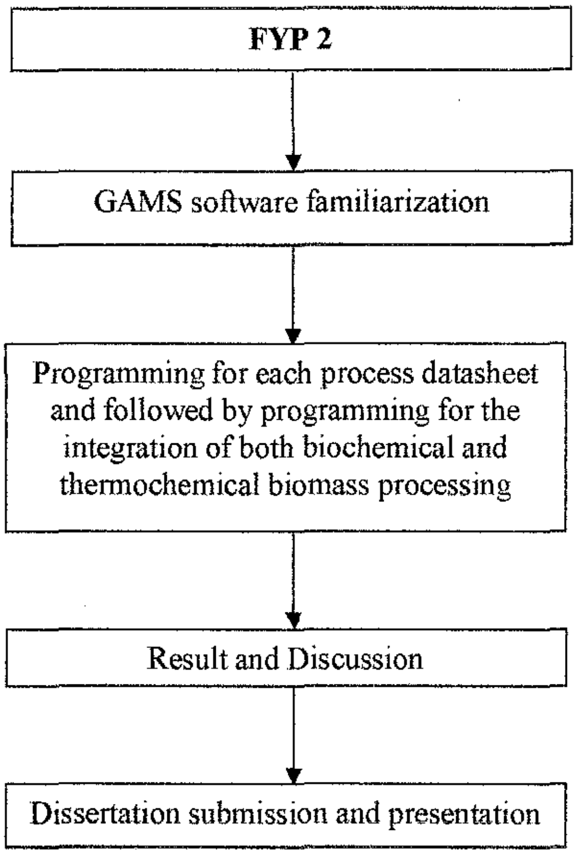

Figure 15: Project flow chart for FYP 2

As for FYP2, the work scopes are basically divided into 4 phases which are:

- First phase: Familiarization of GAMS software.

  This is the first step in FYP 2 which requested to familiar with the GAMS software before proceed to the real programming of the integration bio refinery.

- Second phase: Programming

  All the process datasheets that done in FYP 1 will now be programmed in GAMS to get the potential profit. This followed by programmed the integration of both biochemical and thermochemical biomass processing technologies to get the maximum profit.

- Third phase: Obtaining result and discussion

  The result that gained from the programming will now be analyzed and discussed.

- Forth phase: Dissertation submission and presentation

  The last phase for FYP 2 is the dissertation submission and presentation to the panel examiners and the supervisor.

The important milestones for FYP 1 and FYP 2 can be found in the appendix part attached in this report.

CHAPTER 4

METHODOLOGY

Overall for this project, the overall methods applied can be divided into three main parts. The first part of the methodology is about researching and studying for the literature review. After the literature review part, the project continued by the database creation for each process technologies in the bio-refinery which are Anaerobic Digestion, Fermentation, Gasification and Pyrolysis and programmed each of the process in GAMS to determine the generated profit. The last step of the project is to establish the flowsheet for integrated bio-refinery processes. The same amount of biomass input will be directed to undergo different process technologies to be converted into different end products. The GAMS programming software will be used as the tools to determine the optimal flowsheet for the biomass in order to get the highest profit.

4.1. Research and Study

In this stage, the focus will be in study the relevant documents that related to the synthesis of a conceptual integrated process for the production of renewable fuel. The processes involved are Anaerobic Digestion, Fermentation, Pyrolysis and Gasification. Different technologies that applied in the particular process will be analyzed and average value for the production will be used as the final data.

4.2. Single Process Database and Programming

After the research and study, the next step is to create the database of each process technologies according to the information obtained throughout the research and study. Data such as the input of biomass and the output of the product are the needed in order to calculate the profit for each process.

Taking Anaerobic Digestion as example, with 100 tonne biomass as the input, the output will be roughly 7.8wt% in Methane (fuel gas), 24.5wt% in CO_2, 39.9wt% in sludge and 27.8wt% in traces gas. The 100 tonne of the biomass is allowed to undergo for the Anaerobic Digestion process and the process (from input converted into output) will be programmed to determine the profit.

The profit calculation will be as below:

Profit = (Revenue of product)-[(Cost of Material) + (Process Cost)]

The revenue of product will be the sales of the valued product such as methane (fuel gas) for Anaerobic Digestion. Then the cost of material in this stage actually referred to capital cost that is the price for the machine and cost of raw materials. However in this project, the cost of material is not yet to be taken into consideration. Lastly, the process cost is referred to the electricity consumed in the process. As average, the electricity tariff will be 0.07065 dollars per kwh as stated by Tenaga Nasional Berhad (TNB).

The same procedure will keep repeated for the rest of the processes with the data below:

Table 8: The output product for each process in bio-refinery

<table>
<tr><th rowspan="6">Input:
100 tonne
biomass</th><th colspan="2">Anaerobic Digestion</th><th colspan="2">Fermentation</th><th colspan="2">Gasification</th><th colspan="2">Pyrolysis</th></tr>
<tr><th>Output</th><th>wt%</th><th>Output</th><th>wt%</th><th>Output</th><th>wt%</th><th>Output</th><th>wt%</th></tr>
<tr><td>Methane</td><td>0.078</td><td>Ethanol</td><td>0.0517</td><td rowspan="2">Fuel Gas</td><td rowspan="2">0.8</td><td>Fuel Gas</td><td>0.2</td></tr>
<tr><td>CO2</td><td>0.245</td><td>CO2</td><td>0.0563</td><td>Bio-oil</td><td>0.6</td></tr>
<tr><td>Sludge</td><td>0.399</td><td>Sludge</td><td>0.5148</td><td rowspan="2">Char</td><td rowspan="2">0.2</td><td>Char</td><td>0.1</td></tr>
<tr><td>Traces Gas</td><td>0.278</td><td>Traces Gas</td><td>0.3772</td><td>Water</td><td>0.1</td></tr>
</table>

Each of the process will be programmed with respect to 100 tonne of biomass as the input and directed to different process respectively. The biomass will be converted into different end product according to the wt% as stated in Table 8.

The valued product such as Methane (fuel gas), Ethanol, and Bio-oil will be projected to sales as the price stated below:

Table 9: The selling price for valued product

Output	**Price (\$/tonne)**
Fuel Gas	297
Ethanol	712.5
Bio-oil	300

Fuel gas is mainly consists of Methane and Hydrogen and the price is assumed to be $ 297 with reference to the research paper that recorded the price for methane and hydrogen. For Ethanol, the price is set a bit lower than the ICIS pricing in mid-February 2010. Lastly, the price of Bio-oil is set as $300 per tonne with reference of Unicamp, Brazil in 2004.

Meanwhile to calculate the processing cost, the electricity consumed for each process recorded as Table 10 below.

Table 10: Electric consumption for each process

Process	**Electric Consumed (kwh/ tonne)**
Anaerobic Digestion	9
Fermentation	8.96
Gasification	20
Pyrolysis	18

Based on the information in Table 9 and Table 10, the profit can be calculated for each process. However the constraint is in the programming part, where the material cost is being neglected and the profit gained is a very rough profit.

4.3. Integrated Process Synthesis and Programming

After the programming for each process with the 100 tonne biomass as input, now the programming continued by having 100 tonne of biomass that being directed to undergo each of the process. The programming serves as the purpose to determine the mass that going to each process in order to have the optimum profit.

The overall picture of the program can be shown as the Figure 16 below:

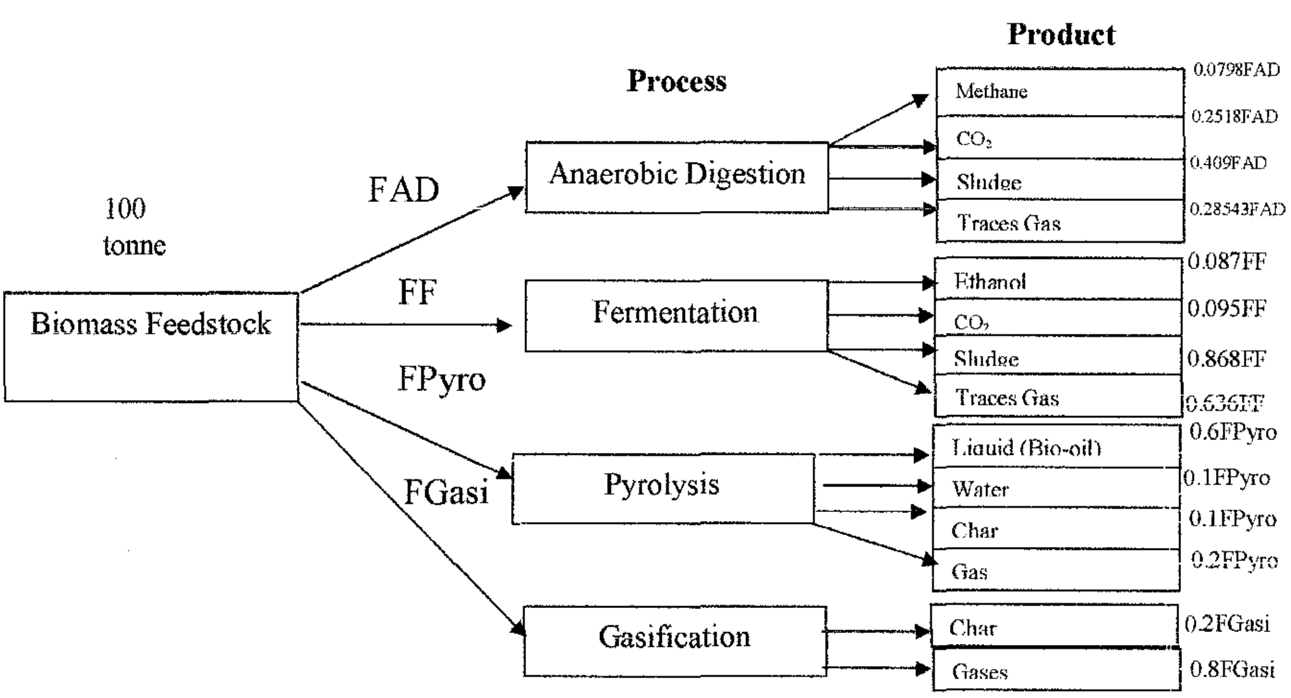

Figure 16: Process datasheet flow for integrated bio-refinery

For the programming, the flow of the biomass going into specific process being labeled as FAD (Anaerobic Digestion), FF (Fermentation), FPyro (Pyrolysis) and FGasi (Gasification) will be set as the free variable and the production figure of each output will set as the constant in the form of table in the programming. With this, biomass that going to the process will convert into the percentage of the product as assigned.

With the conversion from biomass into the product, thus the profit can be calculated by applied the equation as mentioned. However, there are some constraints again for the programming part. The maximum capacity for each reactor to process the biomass is assumed to be 30 tonne per day and minimum 10 tonne per day.

The formulation of Non Linear Programming (NLP) is summarized as below:

1. Objective Function: Maximizing Profit = Revenue – Cost
   - Equation: P =e= z – y;
     - z = revenue =e= FFGAD*FGP + FEF*EP + FFGG*FGP + FFGP*FGP + FBOP*BOP;

where,

FFGAD	= Production of Fuel Gas from Anaerobic Digestion in Tonne
FGP	= Fuel Gas Selling Price $/ Tonne
FEF	= Production of Ethanol from Fermentation in Tonne
EP	= Ethanol Selling Price in $/ Tonne
FFGG	= Production of Fuel Gas from Gasification in Tonne
FBOP	= Production of Bio-Oil from Pyrolysis in Tonne
BOP	= Bio-Oil selling price in $/ Tonne

- y= cost = cAD*x*FAD + cF*x*FF + cGasi*x*FGasi + cPyro*x*FPyro;

where,

cAD	= electric consumed (kwh) per Tonne BM for Anaerobic Digestion
cF	= electric consumed in kwh per Tonne BM for Fermentation
cPyro	= electric consumed in kwh per Tonne BM for Pyrolysis
cGasi	= electric consumed in kwh per Tonne BM for Gasification
FAD	= flowrate of biomass going into Anaerobic Digestion
FF	= flowrate of biomass going into fermenter
FPyro	= flowrate of biomass going into Pyrolysis
FGasi	= flowrate of biomass going into gasification

2. Equality Equations

- FAD =e= CapAD;
- FF =e= CapF;
- FGasi =e= CapGasi;
- FPyro =e= CapPyro;

Where,

CapAD = Capacity for Anaerobic Digestion
CapF = Capacity for Fermenter
CapGasi = Capacity for Gasification
CapPyro = Capactiy for Pyrolysis

The equality equations above serve as the function to ensure that the flowrate to each process will not over the pre-determined capacity.

3. Inequality Equations

- CapAD.lo = 0.10*FBM;
- CapAD.up = 0.30*FBM;
- CapF.lo = 0.10*FBM;
- CapF.up = 0.30*FBM;
- CapGasi.lo = 0.10*FBM;
- CapGasi.up = 0.30*FBM;
- CapPyro.lo = 0.10*FBM;
- CapPyro.up = 0.30*FBM;

The inequality equations are used to set the highest value and lowest value of the capacity for each streams.

CHAPTER 5

RESULTS AND DISCUSSION

The result for each process will be programmed and discussed in the following section.

5.1. Anaerobic Digestion Programming

The programming for Anaerobic Digestion is shown in Appendix B.1. The result from the programming had shown as below:

Table 11: Results for Anaerobic Digestion

Input: 100 tonne biomass	Revenue ($)	Cost ($)	Profit ($)
	2316.60	63.585	2253.015

From the result, it shows that the profit recorded is $ 2253.015. This means that for 100 tonne of biomass that undergoes Anaerobic Digestion process it will generate the mentioned profit. From the result showed above, it can seems that the Anaerobic Digestion did provided a promised profit however the profit seems to be too limited. Furthermore, during the programming, there are a lot of constraints or pre-determined limitation that may bring down the possible profit.

The reason behind this is the low conversion of the biomass into the valued product. Referring to the literature review, there is only 8% of the biomass in converted into the valued product which is fuel gas (methane) and almost 70% will be converted into traces gases and sludge. Thus a recycle stream system or recovery system may be applied in order to increase the production of valued product thus increasing the profit.

5.2. Fermentation Programming

The programming continues for the Fermentation process as shown in Appendix B.2. The result from the programming is shown as below:

Table 12: Result for Fermentation

Input: 100 tonne biomass	Revenue ($)	Cost ($)	Profit ($)
	3683.625	63.302	3620.32

The Fermentation recorded more high profit compared to Anaerobic Digestion mainly because the high selling price of Ethanol compared to Methane (fuel gas). The profit gained from 100 tonne of biomass that undergo Fermentation process is $ 3620.32.

Comparing to the Anaerobic Digestion, the profit that generated by the Fermentation is slightly higher. It can be explained by the literature reviews which stated the selling price of Ethanol is much higher than the methane (fuel gas). Thus even the Fermentation process encounter the same difficulty as Anaerobic Digestion in terms of the conversion of valued product but with the high value of the end product the profit generated will be better.

Same approach is suggested for Fermentation process in order to increase the profit generated which is by applied the recycle stream or introduce recovery system in order to process the sludge and traces gases into valued product. The total conversion of Biomass into Ethanol is approximately 5% only. Thus, improvement in the processing technologies will definitely increase the potential profit in Fermentation process.

5.3. Gasification Programming

The programming result for Gasification is shown as below:

Table 13: Result for Gasification

Input: 100 tonne biomass	Revenue ($)	Cost ($)	Profit ($)
	23760.000	141.300	23618.700

The result for Gasification recorded highest profit compared to both Anaerobic Digestion and Fermentation processes. The reason behind is the high production of Fuel Gas with consists of 80% from the total output. Thus it gives high value in profit figure.

The process of Gasification is different with Anaerobic Digestion and Fermentation which is required a high energy consumption in order to react the biomass in a high temperature. Thus, its efficiency is much more higher compared to both of the biochemical conversion technologies.

Besides the fuel gas that produced, the process also produced char (20% of the production). This char can be recovered and used as the burning materials that provide the heating energy to the process thus reduced the operation costs of the Gasification. The challenge encountered by Gasification is the high operating temperature that required for the process. With the improvement in the process, the profit will be increased.

5.4. Pyrolysis Programming

The programming result for Pyrolysis is shown as Table 14 below.

Table 14: Result for Pyrolysis

Input: 100 tonne biomass	Revenue ($)	Cost ($)	Profit ($)
	23940.00	127.17	23812.8

From the result, it can be concluded that the pyrolysis recorded the highest profit among the four processes in the bio-refinery. Pyrolysis is a process which required high operating costs where the biomass in treated under the inert atmospheric condition with the purpose to avoid the oxidation and gasification of the resultant products.

The reason of high profit generation is due to the high conversion of the biomass into the high valued products which are bio-oil and bio-gas, both of them can be produce direct heat energy to drive electricity generation. Both of the Pyrolysis and Gasification are categorized as thermochemical conversion technologies for biomass conversion. Thus, there is the suggestion in the current industry to integrate both of the processes in order to maximize the profit whereby the biomass will undergo the pyrolysis process where the bio-oil and bio-gases can be produced and further recovered. The remaining sludge or gases can be undergo gasification which operate in high temperature to further produce valued fuel gases thus increased the profit.

5.5. Integrated Bio-Refinery Programming

Through the research and study the result of the process datasheet for integrated bio-refinery processes is produced as Figure 17 below:

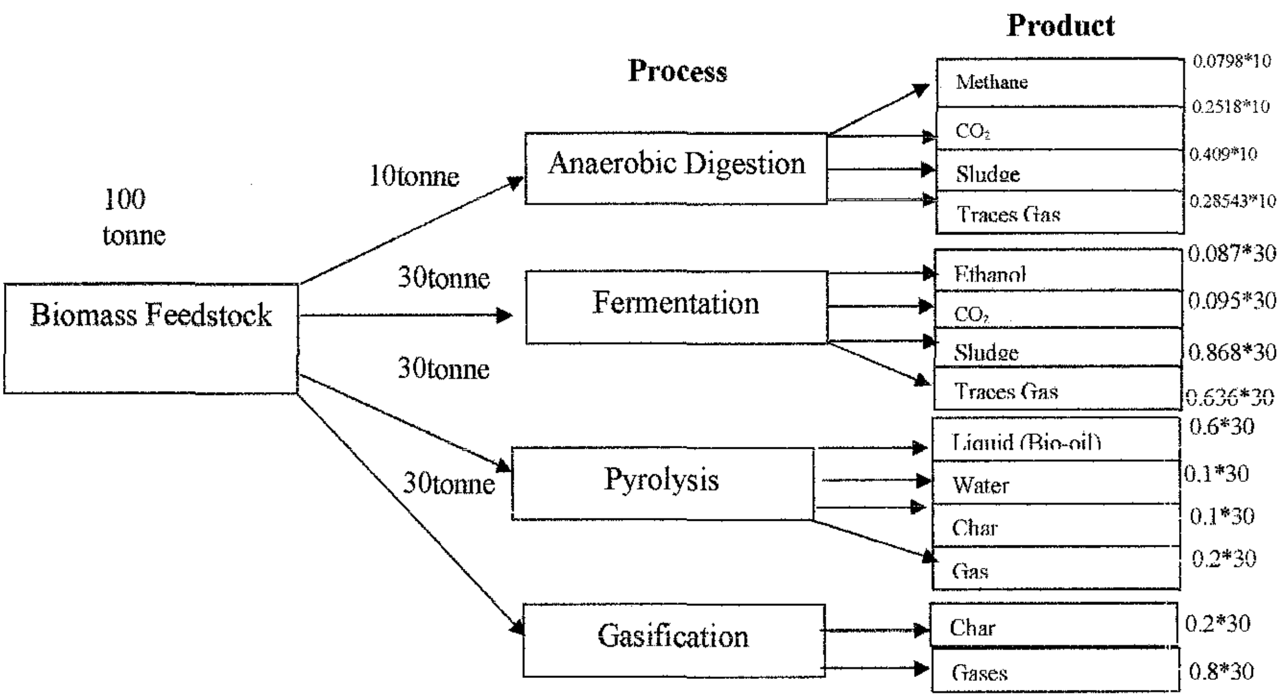

Figure 17: The result of process datasheet for integrated bio-refinery

For each 100 tonne biomass feed, 10 tonne will directed to Anaerobic Digestion, 30 tonne goes to Fermentation, 30 goes to Pyrolysis and another 30 goes to Gasification. Obviously, with the profit optimization purpose, the biomass flow into different processes show that the Anaerobic Digestion process produced less profit thus the amount of biomass inflow to the mentioned process will be the minimum.

It is expected, if the capacity for gasifcation and pyrolysis are increased, there are more of the biomass will be flow into this two processes with the high potential profit generation.

With the result above, further step will be requested in order to determine the overall profit that can be gained from the project. In order to know the result in maximizing the profit, the results will be modeled in GAMS software. In GAMS software, the feedstock that feed into different process will be determined and the profit thus can be calculated.

The profit calculation for the integration bio-refinery is clearly shown as in the Appendix B.5. There are basically three valued product produced from the integration bio-refinery which are Ethanol, Fuel Gas, and Bio-oil.

The result for integrated bio-refinery processes is shown as the Table 15 below:

Table 15: Result for Integrated Bio-Refinery

Input: 100 tonne biomass	**Revenue ($)**	**Cost ($)**	**Profit ($)**
	15646.748	105.890	15540.857

From the result, we can concluded that, the integrated bio-refinery provided a more average profit by involving all the processes and produced variety end products. Both of the total cost and profit that recorded are slight lowest than Gasification and Pyrolysis. By comparing to the profit that given by Anaerobic Digestion and Fermentation, the integrated bio-refinery processes is much more profitable.

The reason behind this is, for Anaerobic Digestion and Fermentation, these processes technologies consider as biochemical conversion and most of the yield will be in sludge form with only a portion (less than 10% of the total weight) consists of valued product. Thus it recorded a very low profit. In the other hand, the Gasification and Pyrolysis processes technologies are categorized as thermochemical conversion which requested high energy consumption by with high amount production of valued product. Thus it can give the high profit.

The processes for Anaerobic Digestion and Fermentation can be further undergone some recovery stages in order to recover the amount of valued product that exist in the form of sludge and traces gas. In short, with the bio-refinery idea, different processes technologies can be combined and produced different end product to meet the different market demand.

In order to maximize the profit generation, there is the suggestion to modify this superstructure of biomass inflow to each process into sequences process. Meaning to say, the biomass will directed to undergo the specific process first and then followed by the other process in order to maximize the profit and minimize the operation cost.

Referring to the study of Anaerobic Digestion and Fermentation, besides the valued product most of the end product will be the sludge and traces gases. Thus the sequence of the biomass flow can be in terms of undergoing the processes of Anaerobic Digestion and Fermentation first, then the by-product (sludge and traces gases) can be directed to go for gasification and pyrolysis process. With the high temperature requirements, the conversion into the valued product can be ensured and thus the potential profit is believed to be higher.

CHAPTER 6

CONCLUSION & RECOMMENDATIONS

Conclusion

From the previous discussion, it can be concluded that the bio-refinery will be a major player in energy industry in the future due to the extra advantages that bio-based industry can bring to the mankind. From the research, obviously the product from the bio-refinery can be used as the renewable alternative energy with a promised profit. For each single process of biomass, it g 0e nerates the profit. When each of the processes being integrated into an integration bio-refinery it provides an optimum profit with varieties end product to meet the market needs. In conclusion, if this project can be done with proper research and development, it can bring substantial profit to the investors.

Recommendations

1. Specific study for each process is requested to have a more knowledge in the current technologies which can minimize the operation costs and lead to more possible profit gained.
2. The study regarding the availability of biomass in the country can be carried out for future planning in bio-refinery.
3. A specific study of an existing bio-refinery in western countries is necessary to justify the profit that can gain from this project.

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APPENDIX A: Milestone for FYP1 & FYP 2

Milestone for the First Semester of 2-Semester Final Year Project (July 2009)

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic	■	■	H1N1 Break					Mid-Sem Break							
2	Preliminary Research Work		■		■											
3	Submission of Preliminary Report				■											
4	Seminar 1 (optional)					■	■	■								
5	Project Work					■	■	■								
6	Submission of Progress Report									■						
7	Seminar 2 (compulsory)										■	■	■	■		
8	Project work continues									■	■	■	■	■		
9	Submission of Interim Report Final Draft														■	
10	Oral Presentation															■

Milestone for the Second Semester of 2-Semester Final Year Project (Jan 2010)

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continue	■	■	■					Mid-Sem Break							
2	Submission of Progress Report 1				■											
3	Project Work Continue				■	■	■	■								
4	Submission of Progress Report 2									■						
5	Seminar (compulsory)										■	■	■			
6	Project work continue									■	■	■	■			
7	Poster Exhibition											■				
8	Submission of Dissertation (soft bound)													■		
9	Oral Presentation														■	
10	Submission of Project Dissertation (Hard															■

APPENDIX B.1: Programming for Anaerobic Digestion

```
Sets
        i process /AD/
        j products /Fuelgas,  CO2, Sludge, Traces_Gas / ;


Table yield (i,j)

         Fuelgas    CO2        Sludge    Traces_Gas
AD       0.078      0.245      0.399     0.278       ;


Scalar FGP selling price for methane in dollars per Tonne/ 297/;
Scalar cAD electric consumed in kwh per Tonne BM for Anaerobic Digestion/ 9/;
Scalar FAD Flowrate of Biomass in Tonne per day to AD / 100/;
Scalar x electric cost dollars per kwh / 0.07065/;

Variables
EC electric cost
y total cost
z revenue
P profit gained ;


Positive variable   FFGAD ;
Equations
        total_cost       define total operation cost
        revenue          define total revenue
        profit           define total profit
        electric_cost     define cost of electric
        ProductFuelGasAD Flowrate methane product from AD
```

```
electric_cost.. EC =e= cAD*x*FAD ;
total_cost.. y =e= EC;

ProductFuelGasAD(i).. FFGAD =e= FAD * yield("AD","Fuelgas");


revenue(i).. z =e= FFGAD*FGP  ;
profit.. P =e= z - y;
model biorefinery_profit /all/;
solve biorefinery_profit using nlp maximizing P;
display  FFGAD.l,
          z.l, y.l, P.l,  EC.l;
```

Figure 18: GAMS programming for Anaerobic Digestion

```
100 VARIABLE FFGAD.L        =       7.800
    VARIABLE z.L            =    2316.600  revenue
    VARIABLE y.L            =      63.585  total cost
    VARIABLE P.L            =    2253.015  profit gained
    VARIABLE EC.L           =      63.585  electric cost
```

Figure 19: Result shown in GAMS for Anaerobic Digestion

APPENDIX B.2: Programming for Fermentation

```
Sets
        i process / F/
        j products / CO2, Sludge, Traces_Gas, Ethanol / ;


Table yield (i,j)

          CO2        Sludge    Traces_Gas  Ethanol

F         0.0563     0.5148    0.3772      0.0517
;

Scalar EP selling price for ethanol in dollars per Tonne/ 712.5/;
Scalar cF electric consumed in kwh per Tonne BM for Fermentation / 8.96/;
Scalar FF Flowrate of Biomass in Tonne per day / 100/;
Scalar x electric cost dollars per kwh / 0.07065/;


Variables
EC electric cost
y total cost
z revenue
P profit gained ;

Positive variable   FEF  ;
```

```
Equations

        total_cost       define total operation cost
        revenue          define total revenue
        profit           define total profit
        electric_cost     define cost of electric
        ProductEthanolF   Flowrate ethanol product from fermenter
;

electric_cost.. EC =e=  cF*x*FF ;
total_cost.. y =e= EC;
ProductEthanolF(i).. FEF =e= FF * yield("F","Ethanol");


revenue(i).. z =e=  FEF*EP   ;
profit.. P =e= z - y;
model biorefinery_profit /all/;
solve biorefinery_profit using nlp maximizing P;
display  FEF.l, z.l, y.l, P.l,  EC.l;
```

Figure 20: GAMS programming for Fermentation

```
104 VARIABLE FEF.L        =      5.170
    VARIABLE z.L          =   3683.625  revenue
    VARIABLE y.L          =     63.302  total cost
    VARIABLE P.L          =   3620.323  profit gained
    VARIABLE EC.L         =     63.302  electric cost
```

Figure 21: Result shown in GAMS for Fermentation

APPENDIX B.3: Programming for Gasification

```
Sets
        i process /Gasi/
        j products /Fuelgas,   Char/ ;


Table yield (i,j)

         Fuelgas      Char
Gasi     0.80         0.20
;


Scalar FGP selling price for methane in dollars per Tonne/ 297/;
Scalar cGasi electric consumed in kwh per Tonne BM for Gasification / 20/;
Scalar FBM Flowrate of Biomass in Tonne per day / 100/;
Scalar x electric cost dollars per kwh / 0.07065/;

Variables
EC electric cost
y total cost
z revenue
P profit gained ;


Positive variable  FFGG;
```

```
Equations

        total_cost       define total operation cost
        revenue          define total revenue
        profit           define total profit
        electric_cost     define cost of electric
       ProductFuelGas_Gasi Flowrate of fuel gas from gasification



electric_cost.. EC =e=  cGasi*x*FBM;
total_cost.. y =e= EC;
ProductFuelGas_Gasi(i).. FFGG =e= FBM * yield ("Gasi","Fuelgas");

revenue(i).. z =e=  FFGG*FGP   ;
profit.. P =e= z - y;
model biorefinery_profit /all/;
solve biorefinery_profit using nlp maximizing P;
display  FFGG.l, z.l, y.l, P.l,  EC.l;
```

Figure 22: GAMS programming for Gasification

```
103 VARIABLE FFGG.L                 =        80.000
    VARIABLE z.L                    =     23760.000  revenue
    VARIABLE y.L                    =       141.300  total cost
    VARIABLE P.L                    =     23618.700  profit gained
    VARIABLE EC.L                   =       141.300  electric cost
```

Figure 23: Result shown in GAMS for Gasification

APPENDIX B.4: Programming for Pyrolysis

```
Sets
        i process / Pyro/
        j products /Fuelgas, Biooil, Char, Water / ;


Table yield (i,j)

         Fuelgas     Biooil  Char  Water
Pyro     0.20        0.60    0.10  0.10
;

Scalar FGP selling price for methane in dollars per Tonne/ 297/;
Scalar BOP selling price for Biooil in dollars per Tonne/ 300/;
Scalar cPyro electric consumed in kwh per Tonne BM for Pyrolysis / 18/;
Scalar FBM Flowrate of Biomass in Tonne per day / 100/;
Scalar x electric cost dollars per kwh / 0.07065/;

Variables
EC electric cost
y total cost
z revenue
P profit gained ;


Positive variable   FFGP, FBOP ;
```

```
Equations

        total_cost        define total operation cost
        revenue           define total revenue
        profit            define total profit
        electric_cost      define cost of electric
        ProductBiooil_Pyro  Flowrate of bio-oil from gasification
        ProductFuelGas_Pyro Flowrate of fuel gas from Pyrolysis;


electric_cost.. EC =e=  cPyro*x*FBM;
total_cost.. y =e= EC;

ProductFuelGas_Pyro(i).. FFGP =e= FBM * yield ("Pyro","Fuelgas");
ProductBiooil_Pyro(i).. FBOP =e= FBM * yield ("Pyro","Biooil");

revenue(i).. z =e=  FFGP*FGP + FBOP*BOP  ;
profit.. P =e= z - y;
model biorefinery_profit /all/;
solve biorefinery_profit using nlp maximizing P;
display  FFGP.l, FBOP.l, z.l, y.l, P.l,  EC.l;
```

Figure 24:GAMS programming forPyrolysis

```
48 VARIABLE FFGP.L                  =       20.000
   VARIABLE FBOP.L                  =       60.000
   VARIABLE z.L                     =    23940.000  revenue
   VARIABLE y.L                     =      127.170  total cost
   VARIABLE P.L                     =    23812.830  profit gained
   VARIABLE EC.L                    =      127.170  electric cost
```

Figure 25: Result shown in GAMS forPyrolysis

APPENDIX B.5: Programming for Integrated Bio-Refinery

```
Sets
i process /AD, F, Pyro, Gasi/
j products /Fuelgas,  CO2, Sludge, Traces_Gas, Ethanol, Biooil, Char, Water / ;


Table yield (i,j)

         Fuelgas     CO2        Sludge     Traces_Gas  Ethanol    Biooil   Char   Water
AD       0.078       0.245      0.399      0.278
F                    0.0563     0.5148     0.3772      0.0517
Pyro     0.20                                                     0.60     0.10   0.10
Gasi     0.80                                                              0.20

;


Scalar FGP selling price for methane in dollars per Tonne/ 297/;
Scalar EP selling price for ethanol in dollars per Tonne/ 712.5/;
Scalar BOP selling price for Biooil in dollars per Tonne/ 300/;
Scalar cAD electric consumed in kwh per Tonne BM for Anaerobic Digestion/ 9/;
Scalar cF electric consumed in kwh per Tonne BM for Fermentation / 8.96/;
Scalar cPyro electric consumed in kwh per Tonne BM for Pyrolysis / 18/;
Scalar cGasi electric consumed in kwh per Tonne BM for Gasification / 20/;
Scalar FBM Flowrate of Biomass in Tonne per day / 100/;
Scalar x electric cost dollars per kwh / 0.07065/;
```

```
Variables
CapAD maximum capacity of AD in Tonne
FAD flowrate of biomass going into AD
CapF  maximum capacity of Fermenter in Tonne
FF flowrate of biomass going into fermenter
CapPyro maximum capacaity of Pyrolysis in Tonne
FPyro flowrate of biomass going into Pyrolysis
CapGasi maximum capacity of Gasification in Tonne
FGasi flowrate of biomass going into gasification
EC electric cost
y total cost
z revenue
P profit gained ;


Positive variable FAD, FF, FPyro, FGasi, FFGG, FFGP, FBOP, FFGAD, FEF, CapF,
CapAD, CapPyro, CapGasi, PFAD, PFF, PFGasi, PFPyro ;
```

```
Equations

        total_cost        define total operation cost
        revenue           define total revenue
        profit            define total profit
        Balance_fraction balance of fraction split into AD and Fer
        BalanceAD         balance of AD
        BalanceF          balance of F
        BalanceGasi       balance of Gasification
        BalancePyro       balance of pyrolysis
        electric_cost      define cost of electric
        ProductFuelGasAD Flowrate methane product from AD
        ProductEthanolF   Flowrate ethanol product from fermenter
        ProductFuelGas_Gasi Flowrate of fuel gas from gasification
        ProductBiooil_Pyro  Flowrate of bio-oil from gasification
        ProductFuelGas_Pyro Flowrate of fuel gas from Pyrolysis
        PerFAD                Percentage of Flow to AD
        PerFF                 Percentage of Flow to F
        PerFGasi              Percentage of Flow to Gasi
        PerFPyro              Percentage of Flow to Pyro
;

Balance_fraction.. CapAD + CapF + CapGasi + CapPyro =e= FBM;
```

```
CapAD.lo = 0.10*FBM;
CapAD.up = 0.30*FBM;
CapF.lo = 0.10*FBM;
CapF.up = 0.30*FBM;
CapGasi.lo = 0.10*FBM;
CapGasi.up = 0.30*FBM;
CapPyro.lo = 0.10*FBM;
CapPyro.up = 0.30*FBM;

BalanceAD.. FAD =e= CapAD;
BalanceF.. FF =e= CapF;
BalanceGasi.. FGasi =e= CapGasi;
BalancePyro.. FPyro =e= CapPyro;

PerFAD.. PFAD =e= FAD / FBM ;
PerFF..  PFF =e= FF / FBM;
PerFGasi.. PFGasi =e= FGasi / FBM;
PerFPyro.. PFPyro =e= FPyro / FBM ;

electric_cost.. EC =e= cAD*x*FAD + cF*x*FF + cGasi*x*FGasi + cPyro*x*FPyro;
total_cost.. y =e= EC;

ProductFuelGasAD(i).. FFGAD =e= FAD * yield("AD","Fuelgas");
ProductEthanolF(i).. FEF =e= FF * yield("F","Ethanol");
ProductFuelGas_Gasi(i).. FFGG =e= FGasi * yield ("Gasi","Fuelgas");
ProductFuelGas_Pyro(i).. FFGP =e= FPyro * yield ("Pyro","Fuelgas");
ProductBiooil_Pyro(i).. FBOP =e= FPyro * yield ("Pyro","Biooil");
```

```
revenue(i).. z =e= FFGAD*FGP + FEF*EP + FFGG*FGP + FFGP*FGP + FBOP*BOP  ;
profit.. P =e= z - y;
model biorefinery_profit /all/;
solve biorefinery_profit using nlp maximizing P;
display FAD.l, FF.l, FGasi.l, FPyro.l, FFGAD.l, FEF.l, FFGG.l, FFGP.l, FBOP.l,
        PFAD.l, PFF.l, PFGasi.l, PFPyro.l, z.l, y.l, P.l,  EC.l;
```

Figure 26: GAMS programming for Integrated Bio-Refinery

```
105 VARIABLE FAD.L           =        10.000  flowrate of biomass g
                                              oing into AD
    VARIABLE FF.L            =        30.000  flowrate of biomass g
                                              oing into fermenter
    VARIABLE FGasi.L         =        30.000  flowrate of biomass g
                                              oing into gasificatio
                                              n
    VARIABLE FPyro.L         =        30.000  flowrate of biomass g
                                              oing into Pyrolysis
    VARIABLE FFGAD.L         =         0.780
    VARIABLE FEF.L           =         1.551
    VARIABLE FFGG.L          =        24.000
    VARIABLE FFGP.L          =         6.000
    VARIABLE FBOP.L          =        18.000
    VARIABLE PFAD.L          =         0.100
    VARIABLE PFF.L           =         0.300
    VARIABLE PFGasi.L        =         0.300
    VARIABLE PFPyro.L        =         0.300
    VARIABLE z.L             =     15646.748  revenue
    VARIABLE y.L             =       105.890  total cost
    VARIABLE P.L             =     15540.857  profit gained
    VARIABLE EC.L            =       105.890  electric cost
```

Figure 27: Result shown in GAMS for Integrated Bio-Refinery