Modelling of Power Generation from Biomass Resources

by

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the requirements for the
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(Chemical Engineering)

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CERTIFICATE OF APPROVAL

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Approved by,

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TRONOH, PERAK

SEPTEMBER 2012

CERTIFICATE 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.

…………………………………………………

(NURUL HAMIZAH BINTI ROHAIZAB)

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NURUL HAMIZAH ROHAIZAB

ABSTRACT

Electricity demand rises rapidly every year as a result of industrialization and population growth. Fossil fuel – crude oil, natural gas and coal, and hydro are the main sources to generate electricity in Malaysia. However, Malaysia's government in 8^{th} Malaysia Plan 2001 has encouraged the development of renewable energy as the fifth fuel in electricity generation. Biomass is seen as one of the potential source of electricity generation considering that Malaysia has abundant biomass availability throughout the year. However, until now the utilization of biomass waste to generate electricity is still very low and not competitive yet with fossil fuel production. These problems lead to the study of modelling of power generation from biomass resources. The objective of this study is to determine the optimal feasible route of power generation from biomass resources. Potential biomass resources and possible technologies to convert biomass into electricity will be discussed and integrated into the superstructure model. Then, the linear programming (LP) model for the superstructure is developed and implemented in MATLAB to obtain the maximum power generation. The result obtained from the MATLAB shows that the maximum feasible route of power generation is the route that used pyrolysis process producing upgraded bio-oil with help of gas turbine to generate electricity. The result also shows that electricity generated from biomass is able to achieve targeted amount of energy demand in Malaysia by the year 2015. Therefore, it is concluded that biomass has the great potential to be source of electricity replacing fossil fuel in the future.

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CHAPTER 1: INTRODUCTION

1.1 Background of Study

1.1.1 Global Energy Outlook

There has been an enormous increase in the demand for energy since the middle of the last century as a result of industrial development and population growth [1]. By the year 2035, the global energy demand forecasted to increase by 53% from 505 quadrillion British Thermal Units (Btu) in 2008 to 619 quadrillion Btu in 2020 and 770 quadrillion Btu in 2035, assuming business as usual and no changes in the current laws and policy governing energy consumption [21]. United State Energy Information Administration (US EIA) reports that there are four broad sectors that have high energy demand which are transportation (28%), residential (23%), commercial (19%) and industrial (31%) [32].

Statistic from British Petroleum (BP) shows that energy consumption today is highly dependent on fossil fuels [47]. Fossil fuels are hydrocarbon, primarily coal, fuel oil and natural gas formed from remains of dead plants and animals by exposure to heat and pressure in the earth's crust over hundreds of millions of years. Fossil fuels are of great importance because it can be burned to produce significant amount of energy per unit weight. World Resource Institute (WRI) [23] also reports that, currently 80% of global energy consumption comes from fossil fuels and analysis conducted by International Energy Outlook (IEO) shows that fossil fuels will remain as dominant source of energy until the year 2035[21]. Figure 1-1 shows world energy consumption by fuel from 1990-2035.

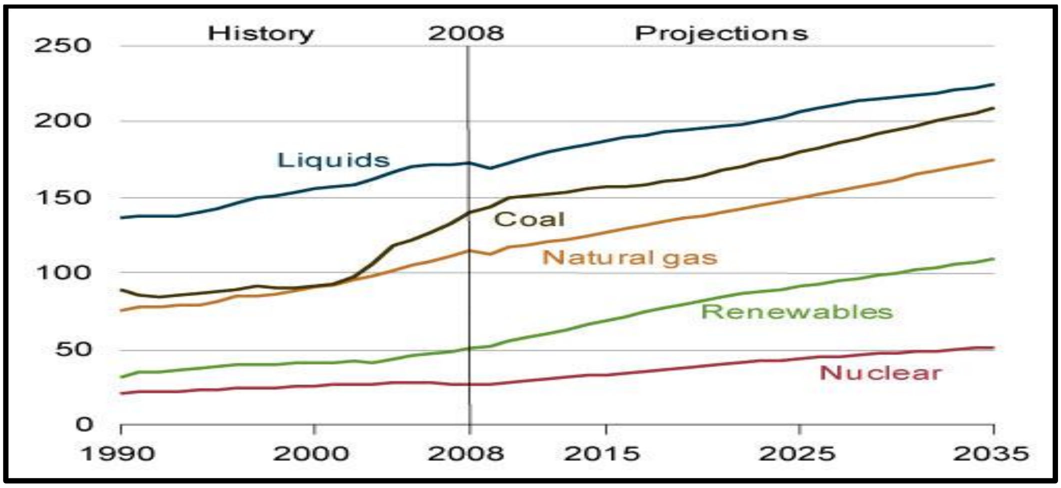


Figure 1-1: World energy consumption by fuel from 1990-2035 [21]

1.1.2 Alternative Source of Energy

Even though fossil fuel is a good source of energy, heavy reliance on it can cause negative impacts to the environment as well as industrial. Fossil fuel is a primary contributor of carbon dioxide emission to the environment reported by US Energy Administration. Carbon dioxide is a main greenhouse gas (GHG) that is responsible for climate change and global warming. Besides, fossil fuel is a non-renewable source of energy which means that it is impossible to recover the supply in a short period of time. The California Energy Commission estimates that the current known reserves of fossil fuels like oil will be depleted within 70 years, as of 2002. Apart from that, the price of fossil fuel is high and in the future there is a possibility of near future gap between demand and supply of oil. During this time, researchers projected that the world oil prices will increase rapidly from current values [21].

These concerns have stimulated the development and utilisation of alternative energy in order to keep the environment clean and to reduce the use of depletable conventional energy source. Among all renewable energies, biomass has been considered as a possible source of energy to meet these challenges. Biomass has a great potential today and in the future, since it is renewable, in contrast to the nature of the fossil fuels. The energy obtained from biomass does not add “new” carbon dioxide, major GHG, to the atmosphere due to its near-carbon neutrality [1, 2]. Besides, there is ample availability of biomass in the world makes the sources unlimited and sustainable throughout the years [18]. It is also biodegradable and non-toxic. It has low emission profiles and thus is environmentally friendly.

1.1.3 Scenario in Malaysia

1.1.3.1 Power Generation in Malaysia

As a developing country, Malaysia's consumption of energy especially in electricity rises rapidly every year and projected to grow further at an average annual rate of 4.7 per cent. Figure 1-2 shows the trend of electricity generation in Malaysia. This consumption growth is mainly driven by industrialisation.

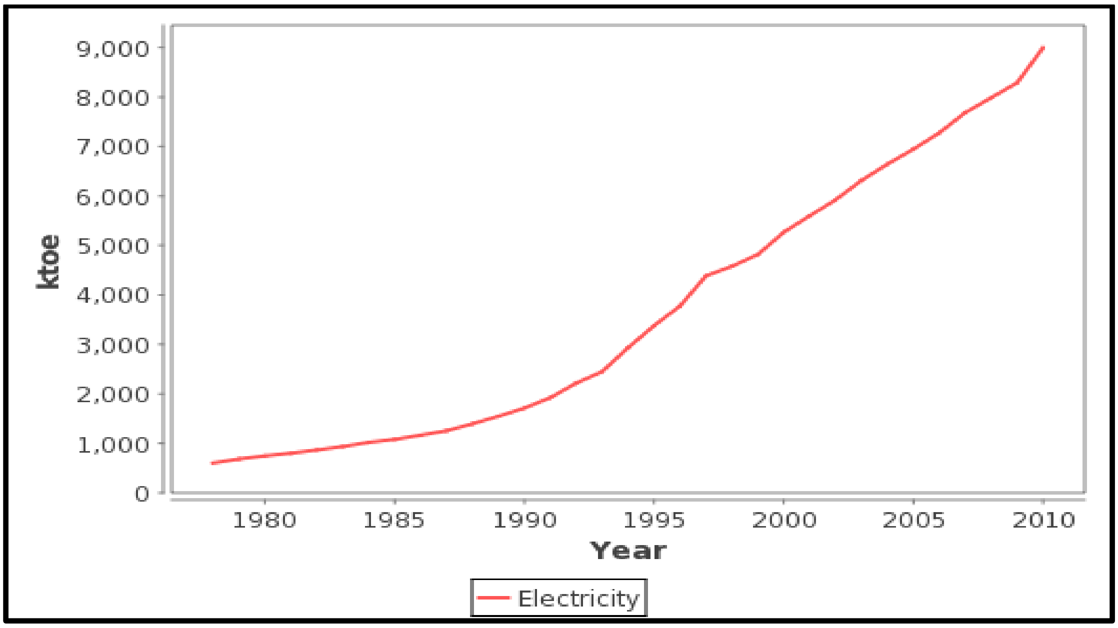


Figure 1-2: Electricity Generation in Malaysia [31]

Recently in 2011, the maximum demand for electricity was 14,000MW in Peninsular Malaysia, 700MW in Sabah and 900MW in Sarawak [25]. The demand for electricity in Malaysia has a strong relationship with GDP (Gross Domestic Product) growth due to the rollout of project under the rolling 5-year Malaysia Plans and the on-going Economic Transformation Programme (ETP). High GDP means high economic growth, high production and high energy. Based on year 2000 rate, for every 1 USD increase in GDP, electricity consumption would increase by 13 Wh [26].

There are a lot of electricity power stations in Malaysia which thermal power plant based on natural gas, crude oil and coal contributes about 86 percent while hydropower plants account for 13 percent to the electricity generation capacity [25]. Study by Yusuf [27] reported that, among the biggest gas-fired power stations are the Sultan Salahuddin Abdul Azis Power Station in Selangor which generates 2420 MW, Lumut Power station in Perak which generates 1303 MW, Sultan Ismail Power station in Terengganu which generates 1139 MW and Tuanku Jaafar Power station in Negeri Sembilan where it generates 1500 MW. One of the oil-fired power stations that generate electricity is the biggest station, named the Gelugor Power station in Penang which generates 398 MW. Tenaga Nasional Berhad (TNB) is the largest electricity utility company in the country with generation capacity of 10,481MW. Other major utility companies are Sarawak Electricity Supply Company (SESCO) and Sabah Electricity Limited (SESB).

Based on the awareness of increasing greenhouse gas (GHG) emission to the environment and some issues on fossil fuel as non-renewable source of energy, Malaysian’s government under the Third Outline Perspective Plan (OPP3) period (2001-2010) and 8th Malaysia Plan (8MP) period (2001-2005) was launched Small Renewable Energy Power Programme (SREP) in 2001 in order to introduce renewable energy as the fifth source for electricity generation [51]. Among the various sources of renewable energy, biomass seems to be the most promising option for Malaysia [26]. Under SREP Project, a few biomass power plants had been proposed to be built in Malaysia. Japanese company “Chubu Electric Power” announced in 2006, plans to build two biomass power plants in Sabah, Bumobipower Sdn. Bhd proposed to build biomass power plant in Perak and recently in March 2008, TNB signed an agreement with Federal Land Development Authority (FELDA) and Japan's J-Power to develop a biomass power plant in Jengka, Pahang [51]. The generation capacity of this plant is 10 MW and would be connected to the grid [51].

By 2015, renewable energy is expected to contribute 1.27 GW to total energy supply in Malaysia [52]. This is not surprising considering that Malaysia has abundant biomass availability throughout the year. Research done by Muis [6] shows that Malaysia has abundant of agriculture residue from rice mills, wood industries, palm oil mills, bagasse and Palm Oil Mill Effluent (POME) which each of these has the potential to generate electricity in order to meet energy demand in the future. Currently, Malaysia produces more than 70 million tonnes of biomass annually and climatic condition in Malaysia is favourable for the biomass production throughout the year [48].

1.1.3.2 Biomass Potential in Malaysia

Being a major agricultural commodity producer in the region, Malaysia is well positioned amongst the ASEAN countries to promote the use of biomass as a renewable energy source in the national energy mix. The term "biomass" refers to all organic matter available on a renewable basis, including dedicated energy crops and trees, agricultural food and feed crops, agricultural crop wastes and residues, wood wastes and residues, aquatic plants, animal wastes, municipal wastes, and other waste materials.

Hassan [48] states that there are five sectors contribute to biomass energy in Malaysia which is municipal waste (9.5%), sugarcane (0.5%), rice industry (0.7%), wood industry (3.7%) and oil palm industry (85.5%). Figure 1-3 shows the biomass potential in Malaysia.

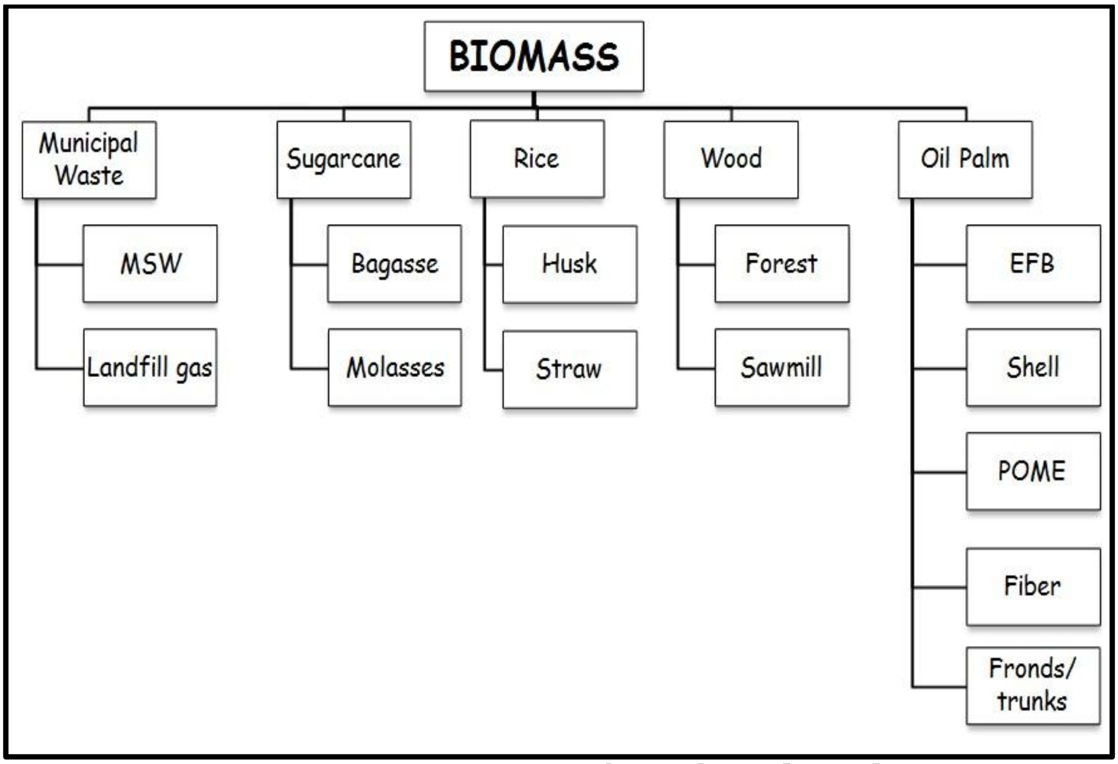


Figure 1-3: Biomass Potential in Malaysia [48, 50]

Biomass production from each sectors and its energy potential are summarized in the Table 1-1 [19].

Table 1-1: Potential Biomass resources in Malaysia in 1999 [19]

Sector	Quantity (kton/year)	Potential annual generation (Gwh)	Potential capacity (MW)
Rice mills	424	263	30
Wood industries	2177	598	68
Palm oil	17980	3197	365
Bagasse	300	218	25
POME	31500	1587	177
Total	72962	5863	665

Oil palm industry contributes towards the largest biomass production in Malaysia with 85.5% out of more than 70 million tonnes per year. This is not surprising considering that 15% of the total land area of Malaysia is covered by this single crop alone. There are 417 palm oil mills in Malaysia, of which 246 are in Peninsular Malaysia and 117 in Sabah [26]. Sumathi et al (2008) reports that, currently Malaysia produces about 47% of world's supply of palm oil which makes Malaysia is the world's largest producer and exporter of palm oil. The type of biomass produced from oil palm industry in Malaysia includes empty fruit bunch (EFB), fiber, shell, wet shell, palm kernel, fronds and trunks [1, 2]. Table 2-2 summarize the type and quantity of oil palm biomass generated per year (based on 2005 data) to present a depiction of energy potential of oil palm biomass.

Table 1-2: Oil palm biomass collected in Malaysia in 2005 and their energy potential [1, 2]

Biomass component	Quantity available (million tones)	Calorific value (kj/kg)	Potential energy generation potential (Mtoe)
Empty fruit brunches	17.00	18 838	7.65
Shell	5.92	20 108	2.84
Fiber	9.60	19 068	4.37
Palm kernel	2.11	18 900	0.95
Fronds and trunks	21.10	-	-
Total	55.73	76 914	15.81

Municipal Solid Waste (MSW) more commonly known as trash or garbage consists of everyday items we use and then throw away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries. This comes from our homes, schools, hospitals, and businesses. Research done by Tarmudi [49] shows that, in Malaysia particularly in Peninsular Malaysia, MSW generation has increased from 5.91 million tonnes per year (16,200 tonnes per day) in 2001 to 6.97 million tonnes per year (19,100 tonnes per day) in 2005 or an average of 0.8 kg/capita/day. The average components of MSW are quite similar with the largest categories consisting of food waste (45%), plastic (24%) followed by paper (7%), iron (6%) and lastly 3% for glass and others.

Sugarcane, paddy residues and wood waste residues are also potential biomass for power generation. Based on the Biomass Resource Inventory Report obtain from

BioGen Project by Malaysia Energy Center (PTM), the potential capacity of power generation from sugarcane, paddy residue and wood waste residue are as per following.

Table 1-3: Power generation from paddy residue [50]

Type of industry	Production year 2000 (Thousand tonnes)	Residue	Residue product ration (%)	Residue Generated (Thousand tonnes)	Potential Energy (PJ)	Potential power (MW)
Rice	2140	Rice husk	22	471	7.536	72.07
		Paddy straw	40	856	8.769	83.86
Total	2140			1327	16.305	155.93

Table 1-4: Power generation from sugarcane residue [50]

Type of industry	Production (Thousand tonnes)	Residue	Residue product ration (%)	Residue Generated (Thousand tonnes)	Energy use factor	Amount for energy use (Thousand tonnes)	Amount of surplus (Thousand tonnes)
Sugar	1111	Bagasse	32	356	1	356	0
		Molasse	Not available				

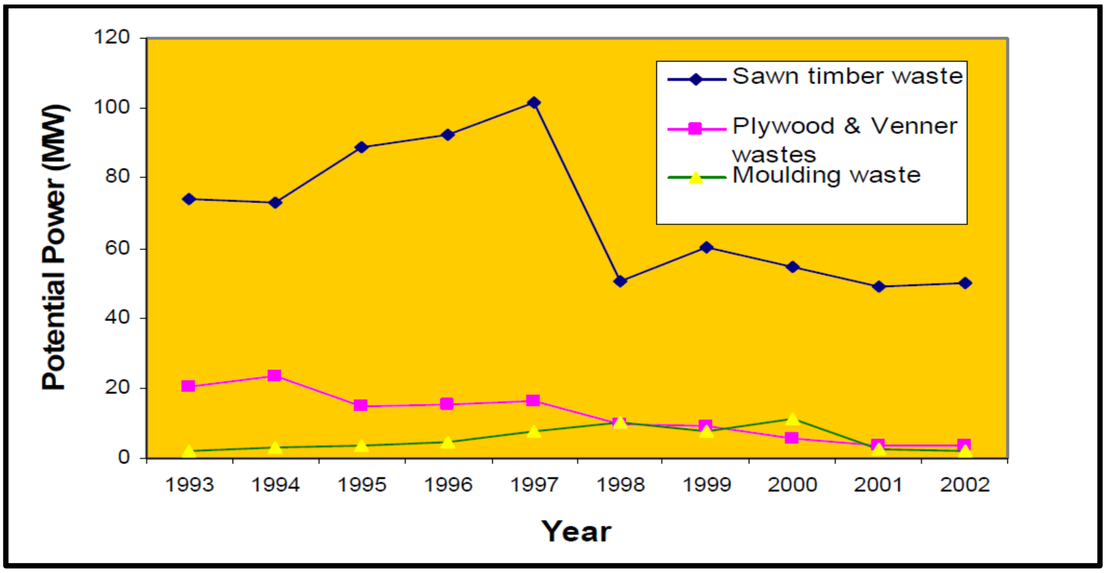


Figure 1-4: Power generation from wood residue [50]

1.2 Problem Statement

In recent years due to the increasing of energy demand and to have clean environment, Malaysia has given much attention to the biomass as a potential source of renewable energy mainly in power generation. Many studies on the biomass conversion for energy technology had been conducted by various researchers and some of the technology had been proven and implemented in Malaysia in small scale. However, utilisation of biomass wastes as a replacement of fossil fuel to generate electricity still very low in Malaysia even though Malaysia is well-known for its agricultural sector and has a significant amount of biomass waste. Only about 4% of primary energy produced in Malaysia is from renewable sources [52]. Biomass also is seen as not competitive yet with the fossil fuel in term of power generation.

Those problem mentioned has brought to the study on the modelling of power generation from biomass resources. Possible routes for biomass conversion to electricity from various biomass resources available in Malaysia are studied and feasible route for maximum power generation is determined.

1.3 Objectives

The specific objectives of this project are:

a) To identify feasible routes of power generation via biomass resources in Malaysia
b) To develop a superstructure model that incorporates the feasible routes of power generation from biomass resources in Malaysia
c) To perform parametric study in order to predict for the route having the maximum electricity production in Malaysia.

1.4 Scope of Study

The scope of study in this project involves developing a superstructure consisting of linear mathematical models to represent the production routes of power generation from biomass resources. The data on the feasible production routes are extracted from literature review of previous works. The linear programming (LP) superstructure model is then developed in MATLAB. Upon parametric studies, the simulation for each route is conducted in order to solve for the maximum power production from biomass resources in Malaysia.

1.5 Relevancy of Project

The most important applicability of a mathematical modelling in real life situation is its flexibility for use to solve industry-relevant sized problems. This project is targeted to find out which production route using biomass resources is worth investing by attaining the most feasible route for process design before applying the decision into real life situations. Besides, it is also potential to fulfil increasing demand of electricity in Malaysia using abundant agricultural waste.

CHAPTER 2: LITERATURE REVIEW

2.1 Technology to Convert Biomass into Electricity

Biomass is one potential source of renewable energy and can be converted into electricity using a number of different routes. Evans et al [3] presented that there are three primary technology categories used for the combustion based conversion of biomass into electricity which are direct combustion, pyrolysis and gasification. These three processes are classified as thermo-chemical process. Lim et al [4] however reported that generally biomass can be converted to electricity using thermo-chemical process and bio-chemical process. Each category has undergone significant development and therefore has many different methods available.

In direct combustion, biomass is burned in a boiler producing pressurized steam, which is expanded through a turbine to produce electricity [5]. Wibulwas et al [17] evaluated the economic feasibility of installing steam power plants in a rice mill by comparing a gasifier internal combustion engine system and a boiler-turbine system. The result suggests that both systems are economically feasible to meet energy demand. Direct combustion is the oldest and simplest, but most inefficient technology. Gasification and pyrolysis have higher efficiency, but require significantly more process control and investment [3].

Pyrolysis is a decomposition process of biomass at high temperature in the absence of air to produce gases, liquids and carbon-rich solid residues [4]. Combustion of these gases occurs in a gas turbine, typically combined cycle [12]. Bridgwater et al [15] presented the comparison of pyrolysis, gasification and direct combustion for electricity generation from wood chip feedstock and concluded that fast pyrolysis system has great potential to generate electricity at a profit in the long term, at lower cost than any other biomass to electricity system at small scale.

During a gasification process, biomass is directly converted to synthesis gas (syngas) in a gasifier under a controlled amount of air. Syngas can be used in internal combustion engine to produce heat or cogeneration system to produce heat and electricity [4]. Electricity capacities range from tens of Kilowatts (KW) to several Megawatts (MW) [5]. Abe et al [16] discussed the potential of rural electricity generation via biomass gasification system. The result suggests that even though agricultural residue such as rice husks may contain high energy potential, however, to supply a biomass gasification system in the long term may require tree farming in order to provide sufficient amount of resources.

There are several kinds of bio-chemical conversion, two of which can potentially produce electricity are biogas fermentation and microbial fuel cell. Biogas fermentation series of processes where microorganisms break down biodegradable materials (usually in the absence of oxygen), thus it is often attributed as anaerobic digestion. The break-down of these biodegradable materials (such as biomass) will produce bio-gas which contain mainly of methane (CH_4) and carbon dioxide (CO_2). These CH_4 and CO_2 after desulphurization and deodorization, can later be used in the combustion system or fed to the fuel cell system to generate electricity [33].

Microbial fuel cell is a device that converts chemical energy directly into electrical energy by the catalytic reaction of microorganisms. In the microbial fuel cell, biomass is oxidized at the anode part producing CO_2, proton (H^+) and electron. Electrons will go through external circuit to the cathode part producing current, and protons go through the exchange membrane. At the cathode part, oxygen reduction reaction occurs just like in the typical chemical fuel cell [29]. Appropriate kinds of microorganisms used in microbial fuel cell are very crucial since they determine the actual mechanism of the oxidation reactions as well as mechanism of electron transfer in the anode part of the fuel cell, which will influence how effectively electrical energy can be obtains from this system.

2.2 Power Generation from Biomass Resources

To complete this superstructure modelling, the simulation data will be extracted from various literature sources. For instance, Ayoub et al [14] developed a design and evaluation methodology for biomass utilization network (B-Nets) planning in local areas. The biomass utilization superstructure (BUSS) relates the biomass resources to their product, available process and possible future processes of utilization in static manner.

Wianwiwat et al [7] prepared a model of Thailand economy used to stimulate a number of potential policies to achieve the Thai government's biomass-generated electricity targets contained in its 15 year renewable energy development plan. The study of this model provides the amount of biomass-based electricity production information from various type of biomass.

Martinez et al [8] also formulated mixed-integer linear programming problems to select the generation plants connected to the Argentinen electricity network. The plant selection will be based on the reduction in life cycle GHG emission and operating cost. Methodology to run this model gives useful information in modelling power generation from biomass resources.

Another previous work is on optimization by Muis et al [6] in which mixed-integer optimization has been developed to optimize fuel mix and meet carbon dioxide target. The model was developed and implemented in General Algebraic Modelling System (GAMS) for the fleet of electricity generation in Peninsular Malaysia.

2.3 Research Gap

However, the literature review reveals that there is limited study on modelling of power generation from biomass resources in Malaysia. This project is different from others as it considering simultaneous different production routes for electricity generation via different technologies. Apart from that, this study focuses on maximum electricity production from biomass available in Malaysia.

CHAPTER 3: METHODOLOGY

3.1 Research Work

The project scope include three key phases namely data gathering, superstructure development and model development and implementation. Figure 3-1 shows the flowchart of the project scope involved.

Phase 1: Data Gathering

Phase 1 focused on gathering the necessary information required in this project. The information needed include:

a) The existing power plant
b) Current electricity demand
c) Biomass availability : types, annual production, potential power generation
d) Feasible technology to convert biomass into electricity

Phase 2: Superstructure Development

The superstructure model will represent all the possible routes for power generation which consist of potential biomass resources and feasible technology to convert biomass into electricity. The project starts with critical literature review on the potential biomass-based electricity in Malaysia. Upon thorough research, it is narrowed down to five main biomass contributor to electricity generation which are palm oil industry, municipal waste, wood industry, rice industry and bagasse. Then, literature review gives guidance on the feasible technologies to generate electricity from biomass resources. This includes thermo-chemical technologies which are direct combustion, pyrolysis and gasification process and also bio-chemical technologies which is anaerobic digestion.

The superstructure network in this study is a single-input-multi-output material flow network, where a single input biomass resource flows through processing stages to generate electricity for each route. The integration of the information obtain into a superstructure development resulted for easier understanding of the whole system.

Phase 3: Model Development and Implementation

The model employed in this study is based on the superstructure development. The objective of this model development is to find the maximum power generation from potential biomass resources in Malaysia. During the model development, a few condition need to be implemented. Then, the maximum electricity generation route will be obtained through simulation of the model using simulation software which is MATLAB.

MATLAB is a programming environment for algorithm development, data analysis, visualization, and numerical computation. The most use of MATLAB involves typing MATLAB code into the Command Window (as an interactive mathematical shell), or executing text files containing MATLAB code and functions. During the simulation, the Linear Programming (LP) superstructure model will be used to find for the maximum solution (maximum power generation). The correlation between the simulation and the data obtained through literature review will be observed and discussed.

3.2 Project Activities

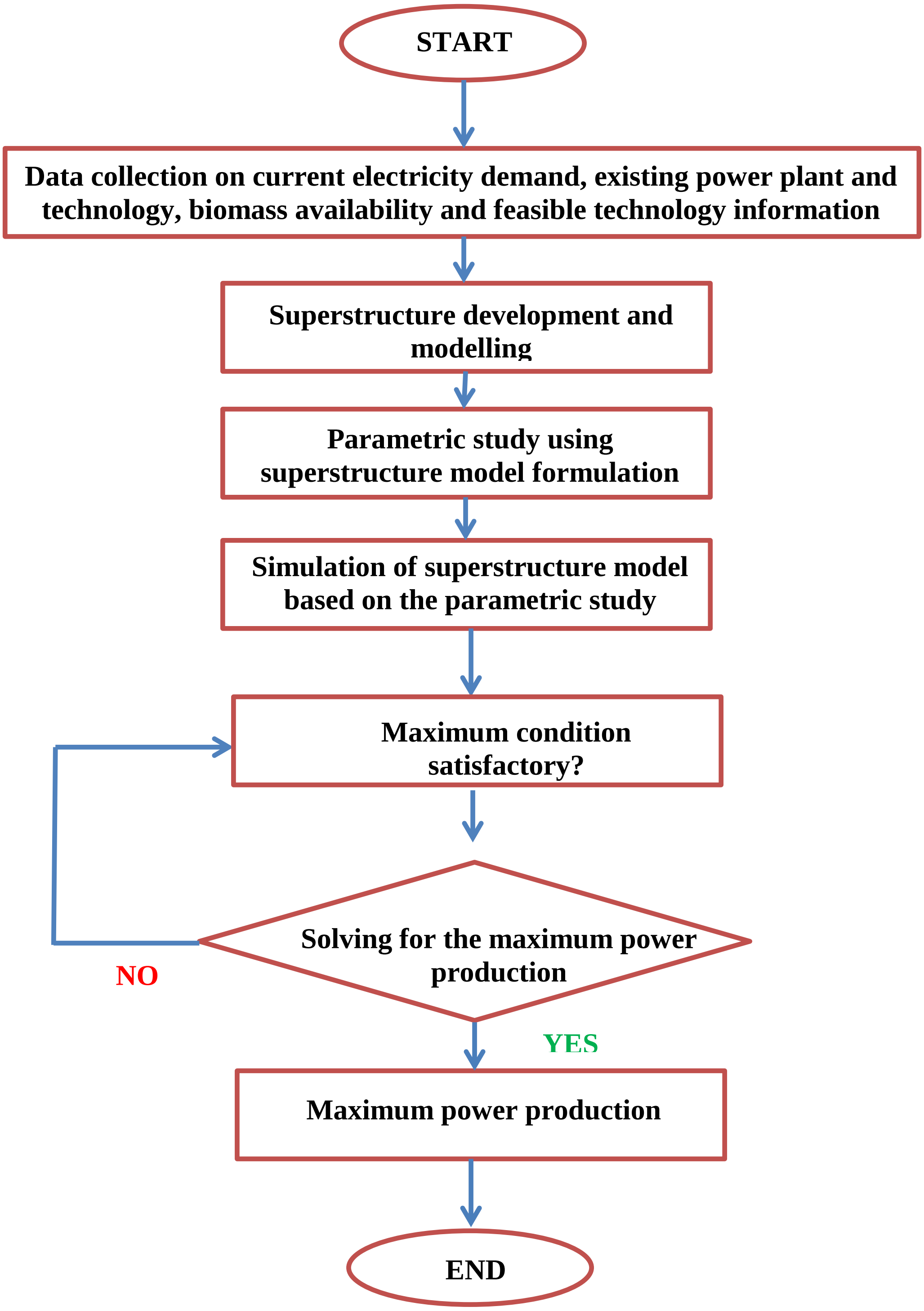


Figure 3-1: Flowchart of Project Activities.

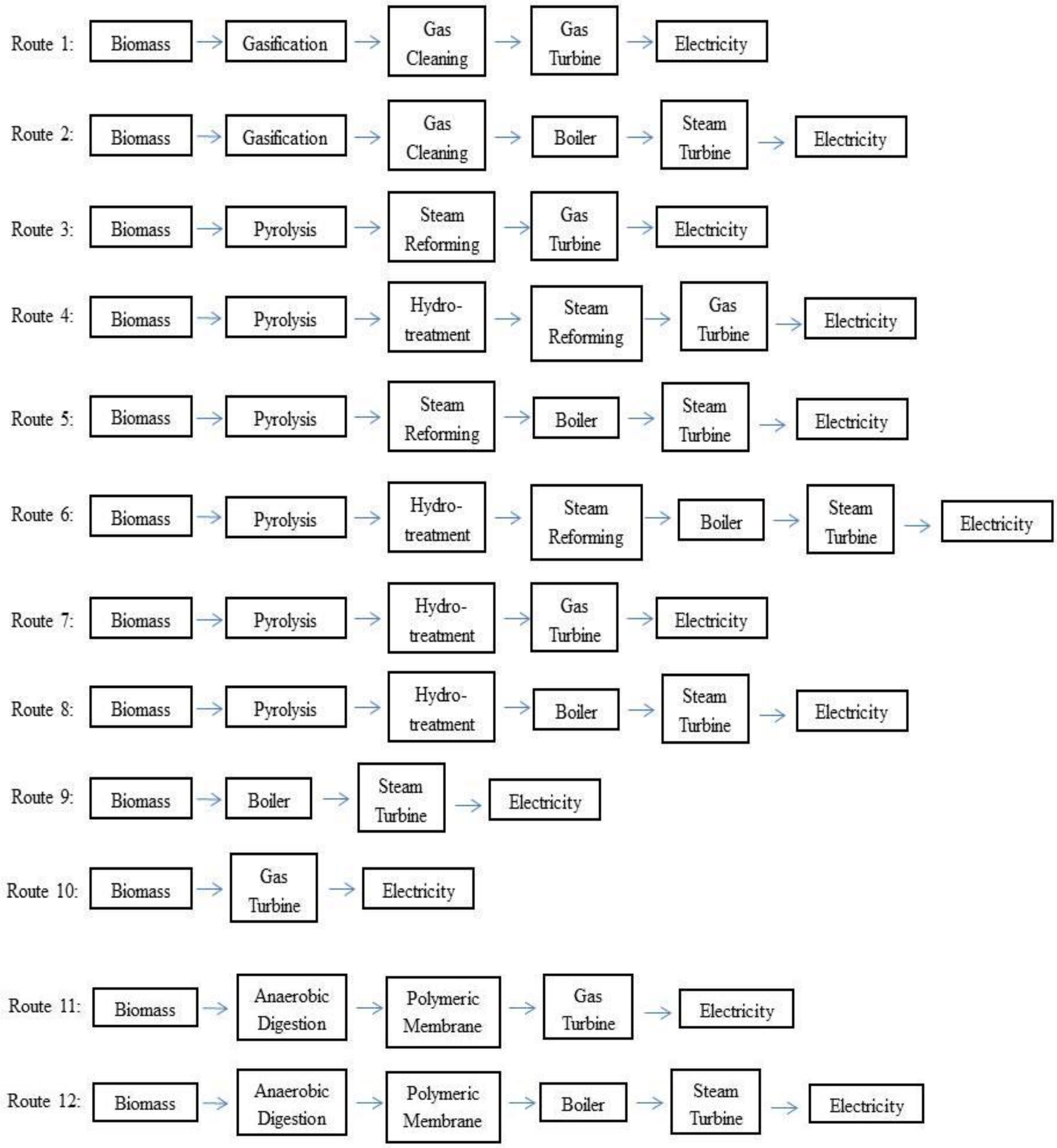
3.3 Gantt Chart

NO	DETAILS/WEEK	1	2	3	4	5	6	7		8	9	10	11	12	13	14
SEMESTER MAY 2012																
NO	**DETAILS/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**MID SEMESTER**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Selection of project topic	■	■													
2	Preliminary research work		■	■	■	■										
3	Submission of extended proposal						■									
4	Proposal defence									■	■					
5	Project work continue															
	5.1 Data collection											■	■	■		
	5.2 Superstructure development & modelling											■	■	■		
6	Submission of interim draft report														■	
7	Submission of interim report															■
SEMESTER SEPTEMBER 2012																
NO	**DETAILS/WEEK**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**MID SEMESTER**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Literature review	■	■	■	■	■	■	■		■	■	■	■	■		
2	Project work continue															
	2.1 Parametric study using superstructure model	■	■	■	■	■	■	■								
	2.2 Simulation of superstructure model based on the parametric study						■	■		■	■	■				
	2.3 Solving for maximum power production											■	■	■		
	2.4 Maximum condition satisfactory												■	■		
	2.5 Maximum power production												■	■		
3	Reporting															
	3.1 Progress report							■		■						
	3.2 Technical paper													■	■	■
	3.3 Disertation													■	■	■
4	Oral presentation															
	4.1 Pre-SEDEX												■			
	4.2 Viva														■	■

CHAPTER 4: RESULT AND DISCUSSION

4.1 Superstructure Development

Superstructure represents all possible routes to convert biomass into electricity. Generally, prepared biomass will undergo chemical processes which are gasification, pyrolysis, direct combustion and anaerobic digestion to form biofuel, gases (hydrogen, biogas and bio-methane) and char. The product from the chemical processes known as fuel then will be burned in steam turbine and gas turbine to produce electricity. There are 12 possible routes assumed to occur in this project and all the possible routes can be summarized in Figure 4-1.



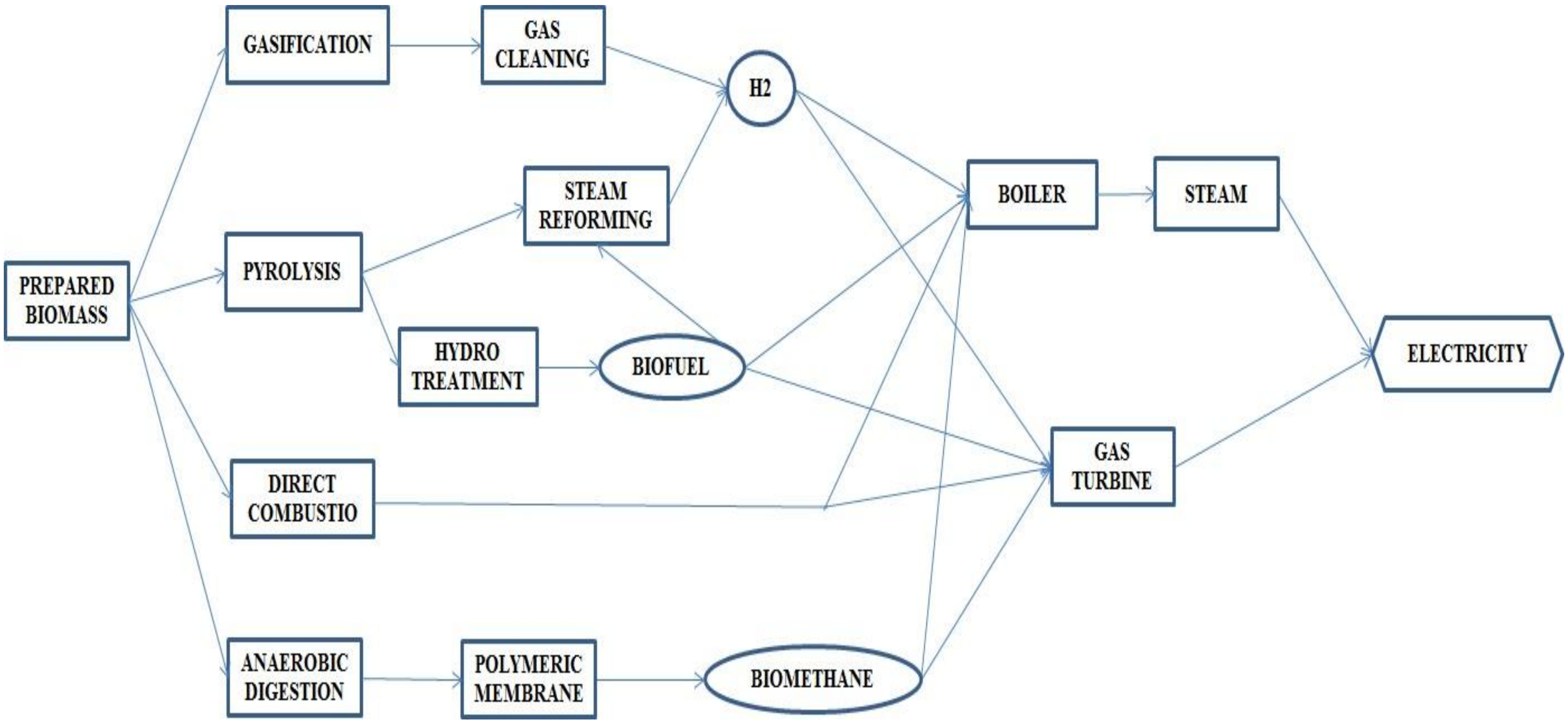


Figure 4-1: Superstructure Development on Modelling of Power Generation from Biomass Resources

4.2 Process Model Formulation

4.2.1 Mass Balances

Mass balances or material balances are the application of the law of the conservation of mass: "Matter is neither created nor destroyed". Mass balance is calculated by the equation 1

$$\sum_i m_i = \sum_o m_o \tag{1}$$

Where m_i is inlet mass and m_o is outlet mass.

The output mass flow rate for selected product in each processes involved in this project is calculated as equation 2 and 3,

$$m_o = m_i \times (\frac{output\ flowrate}{input\ flowrate}) \tag{2}$$

Or

$$m_o = m_i \times (product\ percentage\ yield) \tag{3}$$

4.4.2 Gasification

The conversion of biomass to hydrogen takes place in single pass fluidized bed gasifier through steam gasification process integrated with CO2 capture. There are few assumptions were considered in flow sheet development modeling for gasification process are as follows.

- The gasifier operates under steady state conditions and atmospheric pressure.
- The reactions proceed adiabatically and at constant volume.
- There is no tar formation in this process.

Figure 4-2 shows the mass balance of flow sheet on gasification. The operating conditions for mass balance are 950 K temperature, 3.0 steam/biomass ratio and 1.0 sorbent/biomass ratio [34].

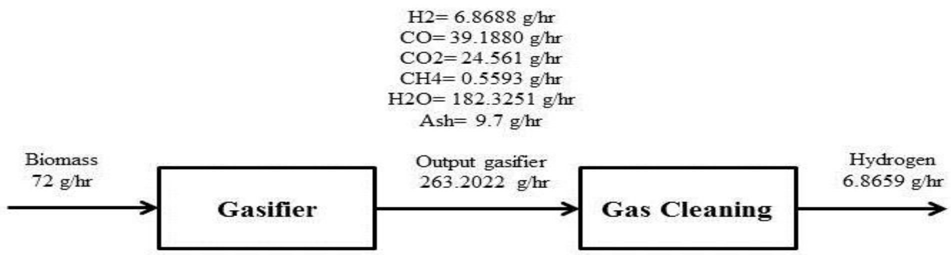


Figure 4-2: Mass Balance of Flow Sheet on Gasification

4.2.3 Pyrolysis

The pyrolysis of biomass was carried out in a fluidized bed unit to produce high liquid yield (70%).The liquid product was separated into two phases: water phase and oil phase. The oil phase was upgraded into liquid fuel by hydrotreatment using sulfided Co–Mo–P in an autoclave with tetralin as solvent [35].

Apart from upgraded into liquid fuel, pyrolysis oil also can be steam-reformed to generate hydrogen gas by a thermocatalytic process using commercial, nickel-based catalysts. The hydrogen yield is as high as 85% of the stoichiometric value [36]. The overall steam-reforming reaction of bio-oil (or any oxygenate with a chemical formula of $C_nH_mO_k$), is given by equation 4,

$$C_nH_mO_k + (2n - k)H_2O = nCO_2 + (2n + m/2 - k)H_2 \quad (4)$$

The stoichiometric yield of hydrogen is $2 + m/2n - k/n$ moles per mole of carbon in the feed [36]. The mass balance flow sheet on pyrolysis to produce bio-oil and hydrogen gas is shown in Figure 4-3.

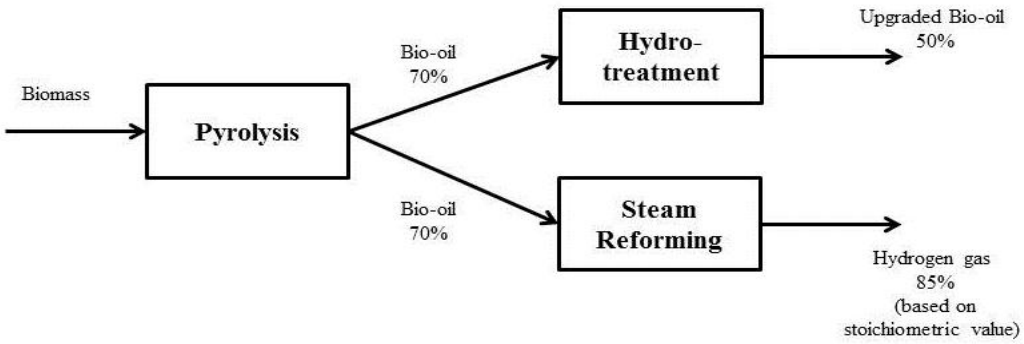


Figure 4-3: Mass Balance of Flow Sheet on Pyrolysis.

4.2.4 Anaerobic digestion

Anaerobic digestion produces biogas which is comprised of around 60% methane (CH_4), 40% carbon dioxide ($C0_2$). Polymeric membrane was used to separate carbon dioxide from the biogas in order to obtain bio-methane used as fuel in steam turbine and gas turbine later [38]. Figure 4-4 shows mass balance flow sheet for anaerobic digestion process.

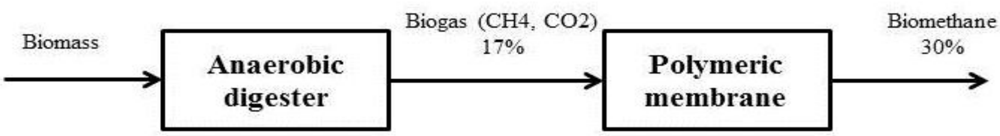


Figure 4-4: Mass Balance of Flow Sheet on Anaerobic Digestion

Based on the mass balance of flow sheets for each processes, the overall mass balance calculation to find mass flow rate of hydrogen gas, bio-methane and bio-fuel are summarized in Table 4-1.

Table 4-1: Overall mass balance calculation

No	Process	Mass Balance Calculation	Reference
1	Gasification	$output\ gasifier = biomass \times 3.656$ $hydrogen\ yield = output\ gasifier \times 0.0261$	[34]
2	Pyrolysis	$output\ pyrolysis = biomass \times 0.7$ $hydrogen\ yield = output\ pyrolysis \times 0.85 \times 0.063$ $upgraded\ bio - oil = output\ pyrolysis \times 0.5$	[35] [36]
3	Anaerobic digestion	$output\ digester = biomass \times 0.17$ $biomethane\ yield = output\ digester \times 0.3$	[38]

4.3 Power Production Model Formulation

4.3.1 Gas turbine

The gas turbine cycle consists of a compressor, a combustion chamber and turbine. Air enters the compressor at *TI, PI,* which are at atmospheric condition. Using the relation for ideal gases for air, the ideal outlet temperature *T2* is obtained by equation 5,

$$\frac{T2}{T1} = \left(\frac{P2}{P1}\right)^{\frac{k-1}{k}} \tag{5}$$

Where PI and P2 are pressures of air entering and leaving the compressor respectively, T1 and T2 are temperature of entering and leaving the compressor respectively and k is the specific heat ratio of air. The temperature of the air leaving the compressor, T_{02} having an isentropic efficiency n_c, can be calculated as equation 6,

$$T_{02} = \frac{T2 - T1}{n_c} + T1 \tag{6}$$

In the present analysis, the turbine inlet temperature is a predetermined parameter, hence, the mass of fuel needed to reach a certain desired turbine inlet temperature is obtained by applying the first law of thermodynamics to the combustion chamber. The first law of thermodynamics for an insulated chamber can be written as equation 7,

Heat supplied by fuel = heat gain by burning gases

$$M_f \times LHV = M_g \times Cp_g \times (T3 - T_{02}) \tag{7}$$

where M_f is mass flow rate of fuel, LHV is lower heating value, *T3* is turbine inlet temperature, M_g is mass flow rate of gases and Cp_g is specific heat at constant pressure for flue gases.

The compression work, W_c of the working air can be estimated for an adiabatic compressor as equation 8,

$$W_c = M_a \times Cp_a \times (T_{02} - T1) \tag{8}$$

Where M_a is mass flow rate of air and Cp_a is the specific heat at constant pressure of inlet air.

Using the relation for ideal gases for exhaust, the ideal outlet temperature of turbine is obtained by equation 9,

$$\frac{T3}{T4} = (e)^{\frac{m-1}{m}} \tag{9}$$

Where e is expansion ratio and m is the specific heat ratio of exhaust gases.

The temperature of the exhaust leaving the turbine having an isentropic efficiency n_t can be calculated as equation 10,

$$T_{04} = T3 - n_t\,(T3 - T4) \tag{10}$$

The power produced by the turbine can be estimated using the first law of thermodynamics for an adiabatic turbine as equation 11,

$$W_t = M_g \times Cp_g \times (T3 - T_{04}) \tag{11}$$

Hence, the net power W_n obtained from the gas turbine is calculated as equation 12,

$$W_n = W_t - W_c \tag{12}$$

4.3.2 Boiler-Steam Turbine

A **boiler** is an enclosed vessel that provides a means for combustion heat to be transferred into water until it becomes heated water or steam. The steam under pressure is then usable in rotating the blade in steam turbine to produce electricity.

The mass flowrate of steam produce, Q from combustion in boiler is calculated as equation 13,

$$Q = \frac{n_b \times M_f \times LHV}{h_g - h_f} \tag{13}$$

Where n_b is boiler efficiency, M_f is mass flow rate of fuel, LHV is lower heating value of fuel, h_g is enthalpy of saturated steam in kcal/kg of steam and h_f is enthalpy of feed water in kcal/kg of water.

The **steam turbine** is then converts the energy of steam into power. Power production, W generated by steam turbine is calculated as equation 14,

$$W = (h_1 - h_3) \times Q \tag{14}$$

Where h_1 is enthalpy of the inlet steam and h_3 is enthalpy of the outlet steam.

However, the enthalpy of outlet steam, h_3 is calculated based on the efficiency of steam turbine, n_s and isentropic enthalpy of outlet steam, h_2 which is obtained from pressure – enthalpy diagram. The calculation is as equation 15,

$$h_3 = h_1 - n_s(h_1 - h_2) \tag{15}$$

The gas turbine cycle calculation and of boiler-steam turbine calculation are calculated using a set of assumption reported in Table 4-2. The data are used for all the routes considered, apart from LHV which varied according to the type of fuel used.

Table 4-2: Main assumption for reference gas turbine and boiler-steam turbine cycle calculation

Equipment	Parameters	Reference
Gas turbine	Ambient condition: 15°C, 1.0132 bar, 60% RH Inlet/outlet pressure losses: 1/3 kPa Air/exhaust gas flow: 631.9/644 kg/s Pressure ratio:17, Expansion ratio: 0.061 Inlet temperature: 1339°C Hydrogen gas LHV: 121000 kJ/kg Efficiency: 86%	[40] [41] [42] [43] [46]
Compressor	Inlet air temperature: 15°C Efficiency: 90%	
Boiler	Type: Fire tube Steam pressure: : 10 kg/cm^2 (g) Steam temperature: 180 ^{0}C Feed water temperature : 85 ^{0}C Enthalpy of saturated steam at 10 kg/cm^2 pressure : 665 kcal/kg Enthalpy of feed water : 85 kcal/kg Efficiency: 81% Hydrogen gas LHV: 121000 kJ/kg	[45] [46]
Steam Turbine	Type: Condensing turbine Inlet temperature: 485 ^{0}C Inlet pressure: 63.7 bar Outlet pressure: 4 bar Efficiency: 80% From pressure – enthalpy diagram *Enthalpy of inlet steam: 3400 kJ/kg* *Isentropic enthalpy of outlet steam: 2600 kJ/kg*	[44] [46]
Constant	k=1.401 m=1.332 Cpg= 1.15 Cpa= 1.005	[42]

4.4 Maximization of Power Production Formulation

Linear programming has been used in this model to find the maximum power production from biomass resources based on the developed superstructure model. Mathematically, the linear programming model can be written as:

Objective function:

$$\text{Max f(i)} = \sum c_t x_i$$

Subjected to:

$$\sum x_i = 1$$

$$0 \le x_i \le 1$$

$$c_t \ge 0$$

Where x_i is the decision variables represent the fraction of input biomass for each route while $c_t x_i$ is linear objective function represent the amount of electricity production for each route.

$\sum x_i = 1$, $0 \le x_i \le 1$, $c_t \ge 0$ represent a set of equality and inequality constraint, where t and i Ɛ {1,…n}. In this project, n is equal to 12.

4.5 Power Generation from Biomass Resources

Based on the superstructure, there are 12 possible routes to produce electricity from biomass resources. All the possible routes undergo simulation in MATLAB in order to find the amount of electricity produced in kW/hr for the same amount of biomass used (kg/hr). The simulated result of the study is transformed into plotted graph as shown in the figure 4-5, holding the other variables constant.

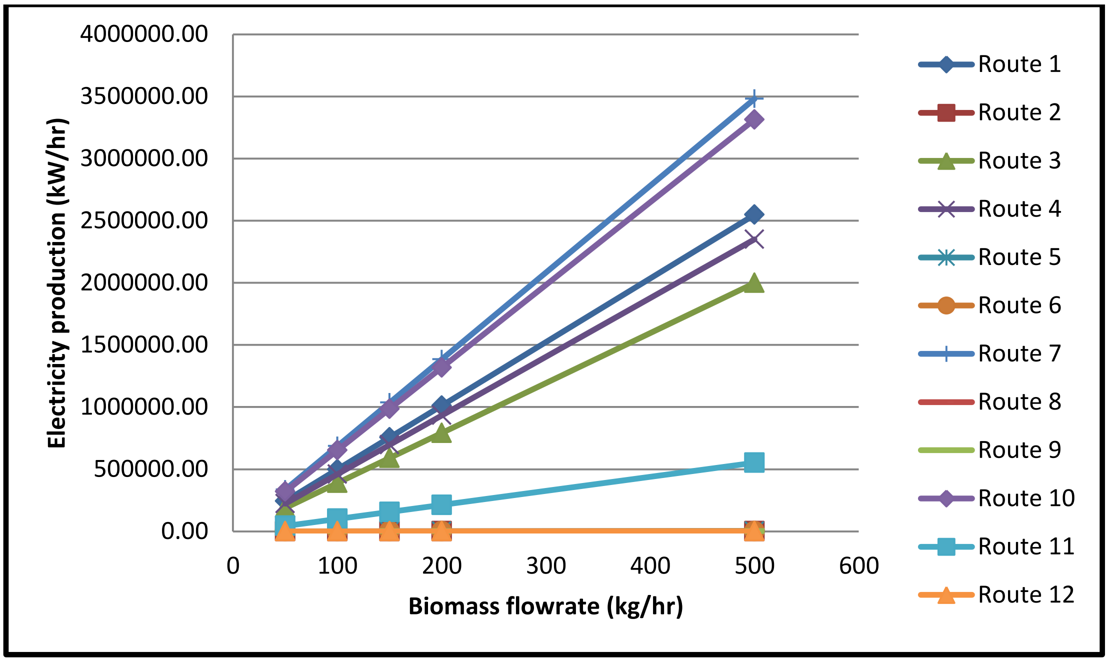


Figure 4-5: Graph of Electricity Production versus Biomass Flow Rate

From figure 4-5, electricity production increased with increasing biomass flow rate for all routes. The highest amount of electricity production is obtained from route 7 which is 3480000 kW/hr for 500 kg/hr of biomass flow rate. Route 7 represents pyrolysis process followed by hydro-treatment process producing upgraded bio-oil. Bio-oil is then used as a fuel in gas turbine generating electricity.

Based on the result, it is concluded that pyrolysis process generated higher electricity than any other process. Comparing the amount of electricity generated using gas turbine and boiler-steam turbine, gas turbine producing much higher electricity production. In general, this result is in accordance by the study conducted by Bridgwater AV, Toft AJ and Brammer JG on a techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. The study concluded that fast pyrolysis has a great potential to generate electricity than any other process at small scale.

4.6 Maximization of Power Production

The maximization of power production formulation is considered as linear programming model by taking fraction of input biomass for each route as decision variable. After running the linear programming model in MATLAB, the result obtained is as shown in Table 4-3.

Table 4-3: The Amount of Power Production and Fraction for each Route.

Biomass Flowrate (kg/h)	62500	625000
Maximum Power Generation (kW/h)	4.36476e+008	4.36628e+009
Fraction for each route		
Route 1	0.0000	0.0000
Route 2	0.0000	0.0000
Route 3	0.0001	0.0000
Route 4	0.0000	0.0000
Route 5	0.0000	0.0000
Route 6	0.0000	0.0000
Route 7	0.9996	1.000
Route 8	0.0000	0.0000
Route 9	0.0000	0.0000
Route 10	0.0000	0.0000
Route 11	0.0002	0.0000
Route 12	0.0000	0.0000

In order to generate maximum power production, input biomass need to select which routes that can give the maximum yield based on the fraction values. The result obtained shows that only one route is seen as dominant route which is route 7. It is also shows that linear programming model does not incorporate the trade-off hence the solution is linear as shown in figure 4-6.

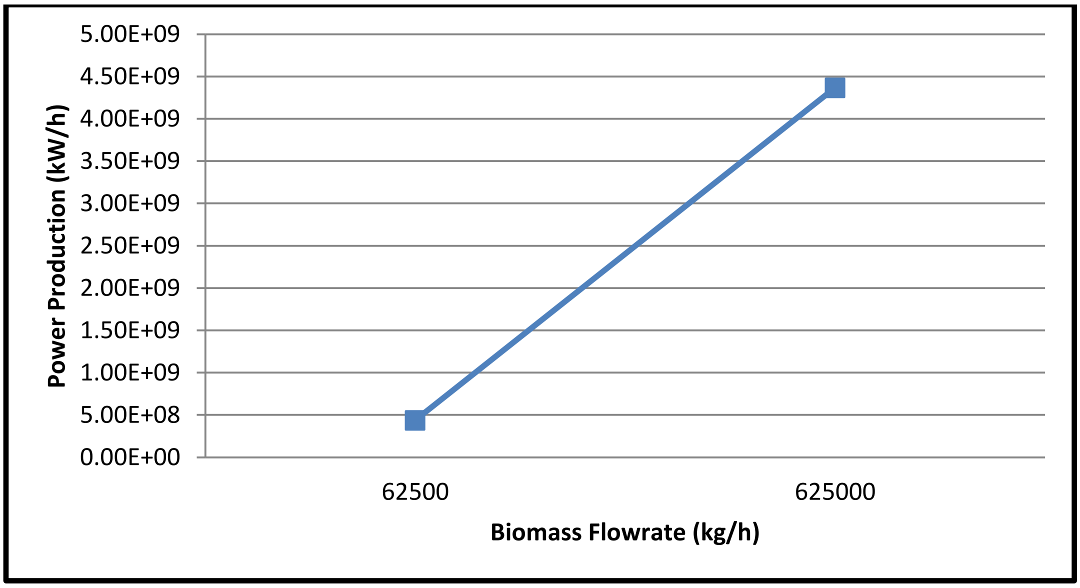


Figure 4-6 : Power production Based on Minimum and Maximum Biomass Availability

Currently, Malaysia is producing 15 000 tonnes of biomass per day [52]. This value is assumed in this project as the maximum amount of biomass to be used in electricity production. Minimum biomass availability is taken as 10% from the maximum amount.

Malaysia targeted to generate 1.27 GW of renewable energy by the year 2015 [53]. Based on the graph shown in figure 4-6, maximum electricity generated from biomass is able to achieve Malaysia's targeted amount of energy. Therefore, it is concluded that biomass has great potential to be source of electricity in Malaysia replacing fossil fuel in future. However, the result obtained need to be improved since this model is still undergoing a few corrections and is still unstable.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Increasing demand of electricity in Malaysia has encouraged the government to embark on alternatives energy sources. Biomass is identified as one of the potential source of electricity generation due to it abundant availability throughout the year in Malaysia. Various chemical conversion technologies can be applied for power generation from biomass resources such as pyrolysis, gasification, direct combustion and anaerobic digestion. Gas turbine and boiler-steam turbine are used in this project as combustion engine producing electricity. There are 12 possible routes identified to generate electricity from biomass and all the routes are summarized in a superstructure model. Based on the superstructure, linear programming model formulation has been developed to solve for the route having maximum electricity production in Malaysia. Result obtained shows that maximum electricity generation can be produced from biomass undergo pyrolysis process and gas turbine with upgraded bio-oil as biofuel. This result is in accordance with the study conducted by Bridgwater et al [15]. Apart from that, the maximum power generation for minimum and maximum biomass availability in Malaysia also being studied. It is concluded that, biomass can achieved the targeted amount of renewable energy needed in Malaysia by the year 2015 proving that biomass has great potential to replace fossil fuel in the future.

Therefore, as a conclusion all the three objectives of this study have been achieved which are to identify feasible routes of power generation from biomass resources, to develop a superstructure model and to perform parametric study solving the route producing maximum electricity production in Malaysia. However, future corrections and improvements need to be done on this model in order to make it more practical to be used in industrial application.

5.2 Recommendation

In achieving higher result accuracy, there are a lot of improvements can be conducted as this project started from basis. For future work, the model should considered environmental aspect in term of greenhouse gases (GHG) emission for each route. Besides, the route producing maximum electricity generation also can be check and balance by considering cost estimation in the model formulation. Introduction of nonlinearity in the model formulation taking account the energy balances and kinetic theory for each route also lead to better accuracy of the results obtained.

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APPENDICES

APPENDIX 1

PROGRAMMING FILES

Linear Programming Optimization

```
clear all;
close all;
clc;

global input_biomass;
input_biomass=370000;

% define the initial guess independent variables for optimization
X0=[0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 0.01 (1-
(0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01+0.01))];
%(f(1)+f(2)+f(3)+f(4)+f(5)+f(6)+f(7)+f(8)+f(9)+f(10)+f(11)))];
% define the lower bounds for independent variables
LB=(zeros(1,12));
% define the upper bounds for independent variables
UB=(ones(1,12));
% define the coefficients for the linear inequality constraints
A = [];
b = [];
% define the coefficients for the linear equality constraints
Aeq = [];
beq = [];
% define the options for the optimization solver
%options = optimset('LargeScale','off','Display','iter');
options = optimset('Algorithm','Active-set','Display',
'iter','MaxFunEvals',1e6,'MaxIter',1e6, ...
    'TolFun',1e-6,'TolConSQP',1e-6,'TolX',1e-6,'FunValCheck','on');
%options = optimset('Algorithm','interior-point','Display',
'iter','MaxFunEvals',1e6,'MaxIter',1e6, ...
  %  'TolFun',1e-6,'TolConSQP',1e-6,'TolX',1e-6,'FunValCheck','on');
% solving the optimization problem
[fraction,neg_power,exitflag,output,lambda,grad,hessian] =
fmincon(@electricity_max1,X0,A,b,Aeq,beq,LB,UB,@electricity_max1_constraint,options);
```

Objective Function

```
function [sum_power]=electricity_max1(f)

global input_biomass;
[electricity_production(1)]=electricity_route1(f(1)*input_biomass);
[electricity_production(2)]=electricity_route2(f(2)*input_biomass);
[electricity_production(3)]=electricity_route3(f(3)*input_biomass);
[electricity_production(4)]=electricity_route4(f(4)*input_biomass);
[electricity_production(5)]=electricity_route5(f(5)*input_biomass);
[electricity_production(6)]=electricity_route6(f(6)*input_biomass);
[electricity_production(7)]=electricity_route7(f(7)*input_biomass);
[electricity_production(8)]=electricity_route8(f(8)*input_biomass);
[electricity_production(9)]=electricity_route9(f(9)*input_biomass);
[electricity_production(10)]=electricity_route10(f(10)*input_biomass);
[electricity_production(11)]=electricity_route11(f(11)*input_biomass);

f(12)= 1- sum(f);

[electricity_production(12)]=electricity_route12(f(12)*input_biomass);

sum_power = sum (electricity_production);
sum_power = -1*sum_power;

end
```

Constraint Function

```
function [c, ceq]=electricity_max1_constraint(f)

global input_biomass;
[electricity_production(1)]=electricity_route1(f(1)*input_biomass);
[electricity_production(2)]=electricity_route2(f(2)*input_biomass);
[electricity_production(3)]=electricity_route3(f(3)*input_biomass);
[electricity_production(4)]=electricity_route4(f(4)*input_biomass);
[electricity_production(5)]=electricity_route5(f(5)*input_biomass);
[electricity_production(6)]=electricity_route6(f(6)*input_biomass);
[electricity_production(7)]=electricity_route7(f(7)*input_biomass);
[electricity_production(8)]=electricity_route8(f(8)*input_biomass);
[electricity_production(9)]=electricity_route9(f(9)*input_biomass);
[electricity_production(10)]=electricity_route10(f(10)*input_biomass);
[electricity_production(11)]=electricity_route11(f(11)*input_biomass);

f(12)= 1- sum(f);

[electricity_production(12)]=electricity_route12(f(12)*input_biomass);

sum_power = sum (electricity_production);
sum_power = -1*sum_power;

ceq= [sum(f)-1];
c= [(f)-(1);
    eps-(f);
    eps-(electricity_production)];
```

Route 1: gasification-gas cleaning-gas turbine

Route

```
function [electricity_production]=electricity_route1(input_biomass)
[output_gasifier]=calc_gasifier(input_biomass);
[hydrogen_yield]=calc_gascleaning(output_gasifier);
[electricity_production]=calc_gasturbine(hydrogen_yield);
end
```

Gasification

```
function [output_gasifier]=calc_gasifier(input_biomass)
output_gasifier=input_biomass*3.656;

% 3.656 is output/input gasifier flowrate ratio
end
```

Gas cleaning

```
function[hydrogen_yield]=calc_gascleaning(output_gasifier)
hydrogen_yield=output_gasifier*0.0261;

%0.0261 is hydrogen yield flowrate/output gasifier flowrate ratio
end
```

Gas turbine

```
function[electricity_production]=calc_gasturbine(hydrogen_yield)

% The operating conditions and process parameters for the gas turbine
% operation are based on the H2 as GT fuel journal

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio
k=1.401; % specific heat ratio of air at 15 degree celcius
```

```
m=1.332; % specific heat ratio of exhaust gases
nt=0.86; % efficiency of gas turbine (assumption)
nc=0.9; % efficiency of compressor (assumption)
LHV=121000; % lower heating value of hydrogen in kJ/kg from wikipedia
Ma=631.9; % mass flowrate of air in kg/s
Mf=hydrogen_yield; % mass flowrate of fuel gas(H2) in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4)); % mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 2: Gasification-gas cleaning-boiler-steam turbine

```
function [electricity_production]=electricity_route2(input_biomass)
[output_gasifier]=calc_gasifier(input_biomass);
[hydrogen_yield]=calc_gascleaning(output_gasifier);
[steam_production]=calc_boiler1(hydrogen_yield);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Gasification

```
function [output_gasifier]=calc_gasifier(input_biomass)
output_gasifier=input_biomass*3.656;

% 3.656 is output/input gasifier flowrate ratio
end
```

Gas cleaning

```
function[hydrogen_yield]=calc_gascleaning(output_gasifier)
hydrogen_yield=output_gasifier*0.0261;

%0.0261 is hydrogen yield flowrate/output gasifier flowrate ratio
end
```

Boiler

```
function[steam_production]=calc_boiler1(hydrogen_yield)

%EQUATION FOR HYDROGEN AS FUEL

Mf=hydrogen_yield;% mass flowrate of hydrogen fuel
nb=0.81; % efficiency of boiler
LHV=121000; % Lower Heating Value of hydrogen in kJ/kg from wikipedia
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*LHV*nb)/(hg-hf); % steam production in kg/hr

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)
```

```
%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```

ROUTE 3: Pyrolysis-steam reforming-gas turbine

Route

```
function [electricity_production]=electricity_route3(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[hydrogen_yield]=calc_steamreforming(output_fpyrolysis);
[electricity_production]=calc_gasturbine(hydrogen_yield);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Steam Reforming

```
function[hydrogen_yield]=calc_steamreforming(output_fpyrolysis)
hydrogen_yield=output_fpyrolysis*(60.4/109.1)*(1/12)*(1.365/1)*(2/1)*0.85;

% hydrogen yield in kg/hr
% weight percentage(wt%) of bio-oil or output fpyrolysis is C=60.4,H=6.9,O=41.8
% 60.4/109.1 is ratio of wt% of C per total wt% of bio-oil
% 1.365 is mole of H2 produced per mole of C in the feed
% 0.85 is percentage yield of H2 of the stoichiometric value based on Wang
% et al (1998)

end
```

Gas turbine

```
function[electricity_production]=calc_gasturbine(hydrogen_yield)

% The operating conditions and process parameters for the gas turbine
% operation are based on the H2 as GT fuel journal

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio
k=1.401; % specific heat ratio of air at 15 degree celcius
m=1.332; % specific heat ratio of exhaust gases
```

```
nt=0.86; % efficiency of gas turbine (assumption)
nc=0.9; % efficiency of compressor (assumption)
LHV=121000; % lower heating value of hydrogen in kJ/kg from wikipedia
Ma=631.9; % mass flowrate of air in kg/s
Mf=hydrogen_yield; % mass flowrate of fuel gas(H2) in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4)); % mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 4: Pyrolysis-hydrotreatment-steam reforming-gas turbine

Route

```
function [electricity_production]=electricity_route4(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[output_biofuel]=calc_hydrotreatment(output_fpyrolysis);
[hydrogen_yield]=calc_steamreforming1(output_biofuel);
[electricity_production]=calc_gasturbine(hydrogen_yield);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Hydro-treatment

```
function[output_biofuel]=calc_hydrotreatment(output_fpyrolysis)
output_biofuel=output_fpyrolysis*0.5;
% 0.5 is percentage of upgraded bio-oil yield after hydrotreatment process
end
```

Steam Reforming

```
function[hydrogen_yield]=calc_steamreforming1(output_biofuel)
hydrogen_yield=output_biofuel*(87.7/99.6)*(1/12)*(2.017/1)*(2/1)*0.85;

% hydrogen yield in kg/hr
% weight percentage(wt%) of upgraded bio-oil is C=87.7,H=8.9,O=3
% 87.7/99.6 is ratio of wt% of C per total wt% of upgraded bio-oil
% 2.017 is mole of H2 produced per mole of C in the feed
% 0.85 is percentage yield of H2 of the stoichiometric value based on Wang
% et al (1998)

end
```

Gas Turbine

```
function[electricity_production]=calc_gasturbine(hydrogen_yield)
```

```
% The operating conditions and process parameters for the gas turbine
% operation are based on the H2 as GT fuel journal

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio
k=1.401; % specific heat ratio of air at 15 degree celcius
m=1.332; % specific heat ratio of exhaust gases
nt=0.86; % efficiency of gas turbine (assumption)
nc=0.9; % efficiency of compressor (assumption)
LHV=121000; % lower heating value of hydrogen in kJ/kg from wikipedia
Ma=631.9; % mass flowrate of air in kg/s
Mf=hydrogen_yield; % mass flowrate of fuel gas(H2) in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4)); % mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 5: Pyrolysis-steam reforming-boiler-steam turbine

Route

```
function [electricity_production]=electricity_route5(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[hydrogen_yield]=calc_steamreforming(output_fpyrolysis);
[steam_production]=calc_boiler1(hydrogen_yield);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Steam Reforming

```
function[hydrogen_yield]=calc_steamreforming(output_fpyrolysis)
hydrogen_yield=output_fpyrolysis*(60.4/109.1)*(1/12)*(1.365/1)*(2/1)*0.85;

% hydrogen yield in kg/hr
% weight percentage(wt%) of bio-oil or output fpyrolysis is C=60.4,H=6.9,O=41.8
% 60.4/109.1 is ratio of wt% of C per total wt% of bio-oil
% 1.365 is mole of H2 produced per mole of C in the feed
% 0.85 is percentage yield of H2 of the stoichiometric value based on Wang
% et al (1998)

end
```

Boiler

```
function[steam_production]=calc_boiler1(hydrogen_yield)
```

```
%EQUATION FOR HYDROGEN AS FUEL

Mf=hydrogen_yield;% mass flowrate of hydrogen fuel
nb=0.81; % efficiency of boiler
LHV=121000; % Lower Heating Value of hydrogen in kJ/kg from wikipedia
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*LHV*nb)/(hg-hf); % steam production in kg/hr

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)

%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```

ROUTE 6: Pyrolysis-hydrotreatment-steam reforming-boiler-steam turbine

Route

```
function [electricity_production]=electricity_route6(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[output_biofuel]=calc_hydrotreatment(output_fpyrolysis);
[hydrogen_yield]=calc_steamreforming1(output_biofuel);
[steam_production]=calc_boiler1(hydrogen_yield);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Hydro-treatment

```
function[output_biofuel]=calc_hydrotreatment(output_fpyrolysis)
output_biofuel=output_fpyrolysis*0.5;
% 0.5 is percentage of upgraded bio-oil yield after hydrotreatment process
end
```

Steam Reforming

```
function[hydrogen_yield]=calc_steamreforming1(output_biofuel)
hydrogen_yield=output_biofuel*(87.7/99.6)*(1/12)*(2.017/1)*(2/1)*0.85;
```

```
% hydrogen yield in kg/hr
% weight percentage(wt%) of upgraded bio-oil is C=87.7,H=8.9,O=3
% 87.7/99.6 is ratio of wt% of C per total wt% of upgraded bio-oil
% 2.017 is mole of H2 produced per mole of C in the feed
% 0.85 is percentage yield of H2 of the stoichiometric value based on Wang
% et al (1998)

end
```

Boiler

```
function[steam_production]=calc_boiler1(hydrogen_yield)

%EQUATION FOR HYDROGEN AS FUEL

Mf=hydrogen_yield;% mass flowrate of hydrogen fuel
nb=0.81; % efficiency of boiler
LHV=121000; % Lower Heating Value of hydrogen in kJ/kg from wikipedia
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*LHV*nb)/(hg-hf); % steam production in kg/hr

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)

%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```

ROUTE 7: Pyrolysis-hydrotreatment-gas turbine

Route

```
function [electricity_production]=electricity_route7(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[output_biofuel]=calc_hydrotreatment(output_fpyrolysis);
[electricity_production]=calc_gasturbine2(output_biofuel);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Hydro-treatment

```
function[output_biofuel]=calc_hydrotreatment(output_fpyrolysis)
output_biofuel=output_fpyrolysis*0.5;
% 0.5 is percentage of upgraded bio-oil yield after hydrotreatment process
end
```

Gas Turbine

```
function[electricity_production]=calc_gasturbine2(output_biofuel)

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio (PI/P2)
k=1.401; % specific heat ratio of air at 15 degree celcius
m=1.332; % specific heat ratio of exhaust gases
nt=0.86; % efficiency of gas turbine (assumption)
nc=0.9; % efficiency of compressor (assumption)
LHV=45000; % lower heating value of biofuel in kJ/kg (assumption)
Ma=631.9; % mass flowrate of air in kg/s
Mf=output_biofuel; % mass flowrate of biofuel gas in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4));% mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 8: Pyrolysis-hydrotreatment-boiler-steam turbine

Route

```
function [electricity_production]=electricity_route8(input_biomass)
[output_fpyrolysis]=calc_fpyrolysis(input_biomass);
[output_biofuel]=calc_hydrotreatment(output_fpyrolysis);
[steam_production]=calc_boiler2(output_biofuel);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Pyrolysis

```
function [output_fpyrolysis]=calc_fpyrolysis(input_biomass)
output_fpyrolysis=input_biomass*0.7;

% 0.7 is percentage of bio-oil yield from biomass conversion based on Zhang et al
(2005)
end
```

Hydro-treatment

```
function[output_biofuel]=calc_hydrotreatment(output_fpyrolysis)
output_biofuel=output_fpyrolysis*0.5;
% 0.5 is percentage of upgraded bio-oil yield after hydrotreatment process
end
```

Boiler

```
function[steam_production]=calc_boiler2(output_biofuel)

%EQUATION FOR BIOFUEL AS FUEL

Mf=output_biofuel;% mass flowrate of fuel
nb=0.81; % efficiency of boiler
LHV=45000; % Lower Heating Value of biofuel in kJ/kg
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*LHV*nb)/(hg-hf);

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)

%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```

ROUTE 9: Biomass-boiler-steam turbine (direct combustion)

Route

```
function [electricity_production]=electricity_route9(input_biomass)
[steam_production]=calc_boiler(input_biomass);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Boiler

```
function[steam_production]=calc_boiler(input_biomass)

%EQUATION FOR DIRECT COMBUSTION

Mf=input_biomass;% mass flowrate of biomass as fuel
nb=0.81; % efficiency of boiler
GCV=15000; % Gross Caloric Value of biomass(wood)in kJ/kg
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*GCV*nb)/(hg-hf); % steam production in kg/hr

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)
```

```
%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```

ROUTE 10: Biomass-gas turbine (direct combustion)

Route

```
function [electricity_production]=electricity_route10(input_biomass)
[electricity_production]=calc_gasturbine3(input_biomass);
end
```

Gas Turbine

```
function[electricity_production]=calc_gasturbine3(input_biomass)

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio (PI/P2)
k=1.401; % specific heat ratio of air at 15 degree celcius
m=1.332; % specific heat ratio of exhaust gases
nt=0.86; % efficiency of gas turbine (assumption)
nc=0.9; % efficiency of compressor (assumption)
LHV=15000; % lower heating value of biomass in kJ/kg
Ma=631.9; % mass flowrate of air in kg/s
Mf=input_biomass; % mass flowrate of biofuel gas in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4));% mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 11: Anaerobic digestion-polymeric membrane-gas turbine

Route

```
function [electricity_production]=electricity_route11(input_biomass)
[output_digester]=calc_anaerobic(input_biomass);
[biomethane_yield]=calc_Pmembrane(output_digester);
[electricity_production]=calc_gasturbine4(biomethane_yield);
end
```

Anaerobic Digestion

```
function [output_digester]=calc_anaerobic(input_biomass)
output_digester=input_biomass*0.17; % 0.17 is percentage of biogas yield
end
```

Polymeric Membrane

```
function [biomethane_yield]=calc_Pmembrane(output_digester)
biomethane_yield=output_digester*0.3;
% 0.3 is percentage of bio-methane yield
end
```

Gas Turbine

```
function[electricity_production]=calc_gasturbine4(biomethane_yield)

T1= 1339; % gas turbine inlet temperature in degree celcius
T3=15; % air compressor inlet temperature in degree celcius
e=0.061; % expansion ratio
p=17; % gas turbine pressure ratio
k=1.401; % specific heat ratio of air at 15 degree celcius
m=1.332; % specific heat ratio of exhaust gases
nt=0.86; % efficiency of gas turbine from H2 as GT fuel journal
nc=0.9; % efficiency of compressor (assumption)
LHV=50000; % lower heating value of biomethane in kJ/kg
Ma=631.9; % mass flowrate of air in kg/s
Mf=biomethane_yield; % mass flowrate of biomethane gas in kg/s
Cpg= 1.15; %specific heat at constant pressure for flue gases
Cpa= 1.005; %specific heat at constant pressure for inlet air

t2= T1*(e^((m-1)/m));
T2= T1-(nt*(T1-t2)); % gas turbine outlet temperature in degree celcius

t4=T3*(p^((k-1)/k));
T4=((t4-T3)/nc)+ T3; % air compressor outlet temperature in degree celcius

Mg=Mf*LHV/(Cpg*(T1-T4));% mass flowrate of gas in kg/s
Wc=Ma*Cpa*(T4-T3); % compression work
Wt=Mg*Cpg*(T1-T2); % electricity produce
Wn=Wt-Wc; % net electricity produce in kW
electricity_production=Wn

end
```

ROUTE 12: Anaerobic digestion-polymeric membrane-boiler-steam turbine

Route

```
function [electricity_production]=electricity_route12(input_biomass)
[output_digester]=calc_anaerobic(input_biomass);
[biomethane_yield]=calc_Pmembrane(output_digester);
[steam_production]=calc_boiler3(biomethane_yield);
[electricity_production]=calc_steamturbine(steam_production);
end
```

Anaerobic Digestion

```
function [output_digester]=calc_anaerobic(input_biomass)
output_digester=input_biomass*0.17; % 0.17 is percentage of biogas yield
end
```

Polymeric Membrane

```
function [biomethane_yield]=calc_Pmembrane(output_digester)
biomethane_yield=output_digester*0.3;
% 0.3 is percentage of bio-methane yield

end
```

Boiler

```
function[steam_production]=calc_boiler3(biomethane_yield)

%EQUATION FOR BIOMETHANE AS FUEL

Mf=biomethane_yield; % mass flowrate of hydrogen fuel
nb=0.81; % efficiency of boiler
LHV=50000; % Lower Heating Value of biomethane in kJ/kg from wikipedia
hg=665; %enthalphy of saturated steam in kcal/kg at pressure of 10.54 kg/cm^2
hf=85; % enthalphy of feed water in kcal/kg

steam_production =(Mf*LHV*nb)/(hg-hf);% steam production in kg/hr

end
```

Steam Turbine

```
function[electricity_production]=calc_steamturbine(steam_production)

%operating conditions for steam turbine are assumed, which are also close
%to many industrial and research scale steam turbine processes

%steam turbine inlet temperature = 485degree celcius
%steam turbine inlet pressure = 63.7 bar
%steam turbine outlet presure = 4 bar

H1=3400; % enthalphy of steam in kJ/kg at inlet of turbine (from pressure-enthalphy
diagram)
H2=2600; % isentropic enthalphy of steam in kJ/kg at outlet of turbine (from
pressure-enthalphy diagram)
ns=0.8; % steam turbine efficiency
Ms=steam_production;

H3=H1-(ns*(H1-H2)); % actual enthalphy of steam in kJ/kg at outlet of turbine

electricity_production= (H1-H3)*Ms*(1/3600)% electricity production in kW

end
```