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# A Hybrid Renewable Energy System for a Rural Area in Africa

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# Preface

This thesis report describes my final project for the master study of Sustainable Energy Technology at the TU Delft, The Netherlands. The thesis is executed in section of Electrical Energy Conversion, Faculty of Electrical Engineering, Mathematics and Computer Science. This thesis is focusing on the feasibility of using hybrid renewable energy in Ikem, Africa.

During this project, I have received assistance and support from many people. I would like to thank Prof. Ferreira who gives me opportunity to do my thesis in his section and also my supervisor Sam Ani. I would like to thank Yi Zhou who always helps me with all the patience that he has.

Also I would like to thank Meriyanti for the loving and care; family in Indonesia especially my parent; Himmel, Handy, Chris, Daniel, Jarot for the valuable discussion; Indonesian friends in Delft. Finally, I would like to praise to the Lord Jesus for the strength as He said to me "The LORD himself goes before you and will be with you; he will never leave you nor forsake you. Do not be afraid; do not be discouraged." (Deuteronomy 31:8).

Albert Munthe

# Summary

In Africa, as a developing region, the introduction of sustainable energy presents an opportunity to provide a large number of people with a better source of energy resulting in a better quality of life while reducing the impact of global warming. Electricity is not available to many communities in Africa because the large capital investment required for the traditional electrical infrastructure has resulted in that a good reliable supply is only available in regions with strong economic and industrial activity and an existing grid infrastructure. The fact that renewable energy sources are also distributed sources offers an opportunity to save on the capital investment for the transportation and distribution of electricity.

Ikem in Nigeria has been chosen to be studied in this research. The proposed hybrid renewable energy system for Ikem consists of PV array, biomass combustion stirling engines and batteries. The continuity supply of renewable energy resources is sufficient and the performance of the whole hybrid renewable energy system is good due to the simulation.

The further research could be done to investigate the possibility of using hydro-power whether the data of rivers on Ikem is collected.

# Table of content

# 1. Introduction

Electricity is an important thing for a human life. Electricity affects every part of people lives and it is vital to the smooth functioning of a healthy economy and to ensure a healthy population. While generating electrical power the energy resources will be needed. Based on their availability and security, energy resources can be distinguished as fossil fuels that will be exhausted by exploiting them and the renewable energy that is sustainable but needs further technical improvement to be used efficiently.

Providing electricity to consumers is a long and complex process, starting from how to generate the electrical power, following by how to transmit the electrical power, and finally how to distribute or to transport electrical power from the power generation to consumers. Because of its complexity, providing electricity to users needs high investment, operational and maintenance cost, and high technology requirement as well as sufficiency of well-trained manpower. Though electricity has an important role in many aspects in human live in every part of the world but the availability is still limited in some developing countries.

There are many experiments and inventions related to electricity and its utilization since Otto von Guericke, the German physicist, experimented with generating electricity in 1650 until Thomas Alfa Edison invented electric lamp and finally developed commercial electric power in US in the late of 19th century. However, those inventions can not help two billion people or around one third of the world’s population [1] to have either access to electricity, or sufficient other non-traditional energy forms. This is happened because most of them live in rural and remote areas where national grid as well electricity infrastructures are too expensive to be provided. Rural electrification is a problem with abundance complexity which is caused of real situation such as the uneconomically low tariffs, low load factors and levels of demand, a lack of operational autonomy and, in some cases, extreme political interference. Facing with those problems rural electricity become uninteresting business for private utilities to get involved on it and only with good tactical national policy by government and international aid, the problems could be solved.

Providing electricity for rural and remote areas with good quality, stability and reliability considering low cost and low environmental impact by using hybrid renewable energy resources becomes technical challenge for engineers. This rural electrification development which is concerning about today and future needs could be classified as sustainable development.

## 1.1 Sustainability

Current development may lead to serious disturbances in ecological, economic and social subsystems. This disturbance will also happen in electricity development if fossil fuels as the one and only resources for generating electrical power are still using unwisely. Unequal prosperity and consumption distribution creates significant gap between rural and urban development and it becomes higher since the electricity is not available for rural area. United Nations Brundtlandt Commission in 1987 [2] declared the definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own demands ". This statement gives broader explanation about sustainability such as that sustainability plays a major role in a future-orientated social development, and also sustainable development links to the issue of conserving the natural basis for life for future generations to the claim for economic prosperity and social development of the people living at present.

Rural electrification as sustainable development is based on some criteria:

- Using pertinent technology (a distributed generation or autonomous system) to provide electricity for rural area makes electricity will be easily accessed to affordable and secure energy services for everyone.
- Using abundant renewable energy than only exploiting fossil fuel as electrical power resources makes more equitable allocation of resources and not exhausting resources.
- Using renewable energy means low environmental impacts (local, regional and global).

## 1.2 Problem statement

In Africa, as a developing region, the introduction of sustainable energy presents an opportunity to provide a large number of people with a better source of energy resulting in a better quality of life while reducing the impact of global warming that caused by anthropogenic activities. Electricity is not available to many communities in Africa because the large capital investment required for the traditional electrical infrastructure has resulted in that a good reliable supply is only available in regions with strong economic and industrial activity and an existing grid infrastructure. The fact that renewable energy sources are also distributed sources offers an opportunity to save on the capital investment for the transmission and distribution of electricity.

This research assesses one of many rural villages in Africa and investigates what kind of renewable energy resources available and how feasible those to be used for generating electricity. By doing that investigation and energy calculation for that site the model of hybrid renewable energy system and its components have to be designed. Finally, the question to this research is how feasible is the hybrid renewable energy system can supply the electricity demand for Ikem including the sufficiency of the renewable energy resources amount and the availability of the technology that will be applied.

## 1.3 Objectives of the thesis

This thesis is made to fulfill some goals, such as:

1 Exploring renewable energy resources for generating electrical power that is sustainable, environmentally benign and feasible to a rural village in Africa.
2 Designing the hybrid renewable energy system by analyzing the power generation ability with load demand characteristics of the rural village.
3 Modeling and simulating the system to evaluate performance of the system.

## 1.4 Scope of the thesis

Based on four pillar models of sustainable development, rural electrification development has to pay attention to industry (economic dimension), society (social dimension), environment (ecological dimension), and institutional dimension (boundary condition or regulation). In this thesis the technical analysis of a hybrid renewable energy system using simulation model is only the scope.

## 1.5 Methodology

In general the methodology of making this thesis based on some steps, starting from choosing a rural village in Africa that will be researched, and then collecting important data from the village chosen, afterwards making a computer simulation model for the proposed hybrid renewable energy system, running the simulation, analyzing the results and finally, make justification of the result.

More details of this methodology can be explained as follow:

1. Starting from identifying a rural village in Africa. Ikem is chosen for this research because the grid available is weak and there is a small industry that can improve the load factor.
2. Then collecting important data needed and making logical assumptions, the data are electricity consumption of households, industries, and public utilities & commercials.
3. Using data that had been collected to make curves of hourly load demand, the total electricity demand per year is be calculated.
4. Find potential renewable energy resources in that village, such as solar, wind, hydro, or biomass by measuring of each resources based on their parameters.
    a. Solar parameters: irradiance (kWh/m2).
    b. Wind parameters: wind speed, stability of the wind.
    c. Hydro parameters: volume flow rate and the elevation slope (head) of the river.
    d. Biomass parameters: kind of biomass with their caloric values, the amount per day, continuity and availability.

5. Make energy calculation of every potential renewable energy resources separately.
6. Determine the most appropriate combination of renewable energy resources to be proposed as a hybrid renewable energy system.
7. Make a model of the hybrid renewable energy with all the components involved.
8. After finishing the model then making computer simulation of the system.
9. Analyse the output resulted by the simulation.
10. Finally make a justification of the hybrid system.

## 1.6 Outline of the thesis

In this introduction section general information concerning sustainable development and rural electrification as background of this thesis are given.

Chapter Two will describes one rural village in Africa, the availability of potential renewable energy resources and load demand characteristics of that village.

Chapter Three presents literature study about possibilities of using renewable energy technologies that are suitable for the village.

Chapter Four tells about possibility of a hybrid renewable energy system including energy calculation and sizing the main components.

Chapter Five describes the model of a hybrid renewable energy system that will be performed to computer simulation. Analysis of the simulation results is included.

In chapter Six, conclusions are drawn concerning to the simulation result and recommendation also will be produced as response to conclusions.

## 2. Renewable energy resources and load profiles of Ikem

In this research, Ikem village in Nigeria has been chosen for the development of hybrid renewable energy system in Africa. The reasons for choosing this village because ratio electrification in Nigeria is relatively low, Nigeria is situated in a tropical area, near the equator line, so that the potential of renewable energy at least solar energy could definitely be an option even others options are proposed in this research, and most of the population live in rural area that is why distributed generation using renewable energy source should be proposed. Actually, the grid is available in Ikem nevertheless the supply of power is not reliable for supplying electric power continuously. By taking advantages of abundant renewable energy resources that available it will make the electricity more reliable. Another reason why Ikem has been chosen because there is a rice milling industry there, so the electricity that is reliable in that village strongly will support economical development and will give widely opportunity for local labours to be involved in. The industry also will improve the percentage of load factor, the ratio between average load and maximum load, therefore the load demand of that village become more flat than only for supplying residence load that will get its peak in the night. This is happen because industrial load will consume electricity in the morning till afternoon when the commonly load demand for rural area is low during that time.

Following are the brief information about Nigeria related to energy and society. Ratio electrification of Nigeria in 2005 was 46 % [3] which means only 60.5 million of population was electrified and the rest of 71.1 million of population was not yet serviced. Around 70 % [2,3] of population lives in rural area which is only 19 % (in 1999) [6] of those connected with the power grid/electricity. From that statistics values, the development of rural electricity becomes most important issue of electricity development in Nigeria. Many obstacles are faced in developing rural electrification, because of its unique characteristics instead of electricity for urban area which can be built using usual business pattern. The obstacles are low value of load factor brings about the utility has to provide large capacity that only cover the short time of peak hours energy demand, also difficulty to value of cost and benefits of rural electrification become the obstruction, further more the low rate of return and the high risks of this project can only solved through special national programmes and financing arrangements such as subsidies towards the initial investments, and long-term, low-interest, or interest free, loans as well. In simple way can be said that that rural electrification has always been considerably more expensive than the supply to urban areas and, as a consequence, utilities have been reluctant to extend the service to rural areas. That is why development of a renewable energy system in terms of distributed generation could be a solution instead of using conventional method which is a centralized power system with the high costs of grid extensions, and environment degradation involved also have to be taken in to consideration.

## 2.1 The availability of renewable energy resources

Ikem is in Isi-Uzo Local Government Area, Enugu State, Nigeria with geographical coordinates is 6° 47' 0" North, 7° 42' 0" East [7] and about 180 meters above sea level. It is a rural village situated in the undulating lowlands of northern Enugu State, south east Nigeria, near its border with Benue State. At the University of Nigeria Nsukka meteorological station (6° 51′ 57′′ North, 7° 25′ 27′′ East, 396 m), the average annual rainfall from 1966 to 1995 is about 1500 mm yearly [7]. This location is a close approximation for Ikem as well.

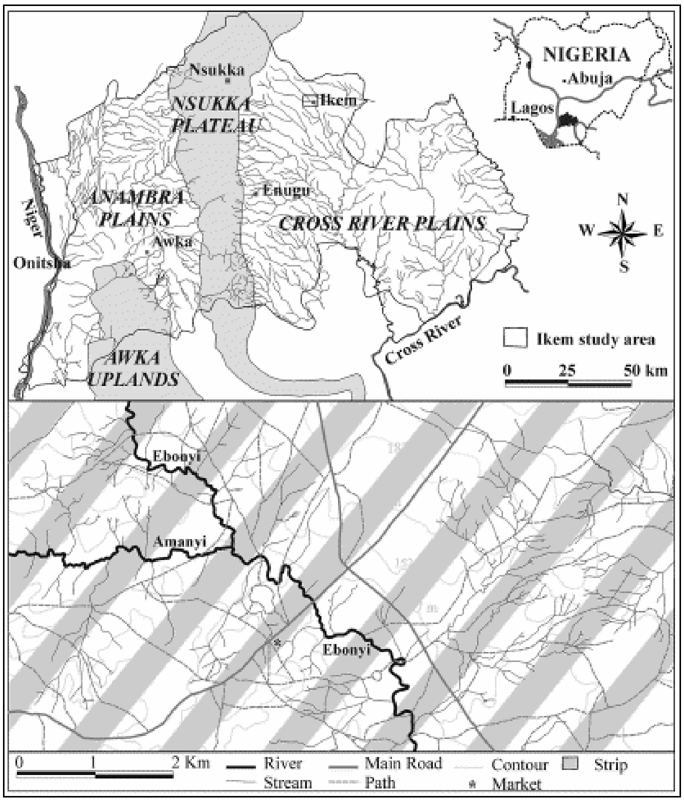


Figure 2.1. Photo of Ikem village and rivers streams [7]

Most of the inhabitants are farmers except for few workers from Isi Uzo Local Government Area (LGA) Secretariat, Ikem and Ikem General Hospital. About 80% of the population is engaged in small-scale oil palm (*Elaeis guineensis*) and root crop farming [7]. Yam, cassava, cashew, maize, palm oil, and rice are the main agricultural produce. Ikem is traversed by two rivers, Ebonyi and Amanyi River that can be seen in Figure 2.1 and is a network of streams which makes transportation of rich agricultural harvests difficult, especially during the heavy rainy periods between April and October. Only one major road, a badly pot-holed and almost impassable, passes through Ikem to join the Enugu-Abakaliki expressway. From previous description, it is possible to use the river for mini/micro hydropower to generate electricity.

Table 2.1. Climate data of Enugu

| Month | Air temperature | Relative humidity | Daily solar radiation - horizontal | Atmospheric pressure | Wind speed | Earth temperature |
|---|---|---|---|---|---|---|
| | °C | % | kWh/m²/d | kPa | m/s | °C |
| January | 26.3 | 53.7% | 5.95 | 99.0 | 2.1 | 27.9 |
| February | 26.7 | 59.7% | 6.07 | 98.9 | 2.2 | 28.6 |
| March | 26.3 | 75.4% | 5.70 | 98.8 | 2.1 | 27.8 |
| April | 26.0 | 82.1% | 5.29 | 98.9 | 2.0 | 27.1 |
| May | 25.9 | 83.8% | 4.97 | 99.0 | 1.9 | 26.8 |
| June | 24.9 | 85.1% | 4.59 | 99.2 | 2.1 | 25.6 |
| July | 24.2 | 83.8% | 4.20 | 99.3 | 2.4 | 24.8 |
| August | 24.2 | 82.9% | 3.97 | 99.3 | 2.5 | 24.7 |
| September | 24.3 | 85.2% | 4.23 | 99.2 | 2.3 | 24.9 |
| October | 24.6 | 84.8% | 4.59 | 99.1 | 1.7 | 25.2 |
| November | 24.7 | 80.7% | 5.18 | 99.0 | 2.0 | 25.3 |
| December | 25.2 | 66.0% | 5.60 | 99.0 | 1.8 | 26.2 |
| **Annual** | 25.3 | 77.0% | 5.02 | 99.1 | 2.1 | 26.2 |
| Source | NASA | NASA | NASA | NASA | NASA | NASA |
| | | | Measured at (m) | | 10 | 0 |

NASA also provides some information related to renewable resources that available in Enugu (closest representative town of Ikem), which can be seen in table 2.1. The data was collected from RETScreen Clean Energy Project Analysis Software [8]. Actually, data for Ikem is not available but Enugu is the best reference location for Ikem since Ikem is situated in Enugu state. Data in table 2.1 shows that solar radiation has a good value yielding energy.

Table 2.1 also gives value of average wind speed measured in 10 meters height is 2.1 m/s. The higher the position the faster the wind speed will be get. Commonly wind tower height is 12 - 36 m. Equation (2.1) can be used for calculating the wind speed between 10 - 50 meter height.

$$V(h) = V(href) \text{ x } \frac{\ln\left(\frac{h}{zo}\right)}{\ln\left(\frac{href}{zo}\right)} \tag{2.1}$$

where:

h: certain height (m)
href: reference height at which wind speed measured (m)
V(h) : wind speed at certain height (m/s)
V(href): actual wind speed measured at certain height (m/s)
zo: roughness height (m)

For this case: href = 10 m/s, V(10m) = 2.1 m/s, zo= 0.03 m. So the wind speed at 10-50 meters can be seen in table 2.2.

Table 2.2. wind speed at certain heights

| h (m) | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 |
|---|---|---|---|---|---|---|---|---|---|
| V(h) (m/s) | 2.1 | 2.2 | 2.4 | 2.4 | 2.5 | 2.6 | 2.6 | 2.6 | 2.7 |

Every wind turbine operates between the cut-in and the cut-out wind speed. This means that the turbine only produces energy with wind speeds within the operating range of the turbine. Cut in wind speed collected from manufacturer, Fortis, varies between 2.5 m/s to 4 m/s while the rated wind speed that will produce rated power varies from 13 m/s to 17 m/s. It means even average wind speed at 50 m height of 2.7 m/s seems too slow that can be exploited.

Table 2.3 shows residues from rice milling industry with their energy contents that have potential biomass resources for generating electricity. Energy contents are expressed as either High (gross) Heating Value (HHV) or Lower (net) Heating Value (LHV). For fuels containing Hydrogen, water is a product of combustion and is always formed as steam. HHV is the amount of heat produced by the complete combustion (including condensation of combustion products) of a unit quantity of fuel. LHV is heat produced by combustion when the steam does not condense so the 'latent' heat of steam is unavailable will make the caloric value lower.

Table 2.3. Potential biomass resources from rice residues [9]

| Residues | Energy Content | |
|---|---|---|
| | HHV (J/g) | LHV (J/g) |
| Rice husk/hull | 16140 | 15270 |
| Rice straw | 16280 | 15340 |

Finally, based on those data can be conclude that renewable resources available in Ikem that can be used for generating electric power are:

1. Solar energy with relatively high average daily solar radiation of 5.02 kWh/m$^2$.
2. Hydro power using river flow of Ebonyi and/or Amanyi.
3. Biomass combustion that can be fueled using residues of a rice milling industry.

## 2.2 The characteristics of load demand

Ikem is a village which electricity grid has been already connected to this village in low reliability so the capacity and continuity of electricity supply is limited. To provide electricity using renewable energy then load demand of population in this village should be determined. Data investigation and collection directly through to the site was not done but collecting information from a person originated from Nigeria and combining with literatures have been used in making logical assumption in this research.

The values in table 2.4 are assumed, except the values for households based on literature [10]. This rough calculation is not sufficient for designing a hybrid renewable energy system but it needs to be more detail specified in an hourly load demand pattern.

Table 2.4. Estimated Power requirements per day

| Quantity | Description | Power (kW) |  | Average duration (h) | Energy demand (kWh) |
|---|---|---|---|---|---|
|  |  | Unit demand | Total demand |  |  |
| 2 | Secondary schools | 3 | 6 | 7 | 42 |
| 6 | Primary schools | 2 | 12 | 6 | 72 |
| 1 | Local govt. secretariat | 3 | 3 | 8 | 24 |
| 10 | Street lights | 0.1 | 1 | 12 | 12 |
| 1 | District hospital | 10 | 10 | 15 | 150 |
| 200 | Households | 0.5 | 100 | 5 | 500 |
| 1 | Rice milling industry | 100 | 100 | 10 | 1000 |

From table 2.4 above load demand of Ikem can be divided in three categories, which are:

1. Public utilities which are consist of secondary schools, primary schools, local government secretariat, and street lights.
2. Critical load that is energy demand for supplying district hospital.
3. Households
4. Industry

### 2.2.1 Hourly load demand curves

Load demand curves have been made by using logical assumption referring that load demand varies in time, depends on season, and depends on the inhabitant presence in a room; that is why load demand curves are erratic and quite choppy over the time. In the tropical area there are only two seasons namely the sunny season (November to March) [7] and the rainy season (April to October), nevertheless these two different seasons are assumed will not give different usage of electricity especially in rural area whereas the electricity is used for lighting at the most. Apparently load demand variation for each season in sub tropics area which has four different seasons (summer, fall, winter and spring) is highly significant especially in developed countries which many automatic controlled electric appliances used by.

Moreover, when it is winter many heaters will be used while air conditioned will be used in summer period.

In making exact forecasting for load demand is rather impossible since too many parameters are involved. However the roughly load demand patterns in one area should be determined for knowing approximately about the base load, peak load, load factor and also how long the peak load duration happens will be. Every load demand curve with its characteristics will be further explained.

1. Public utilities

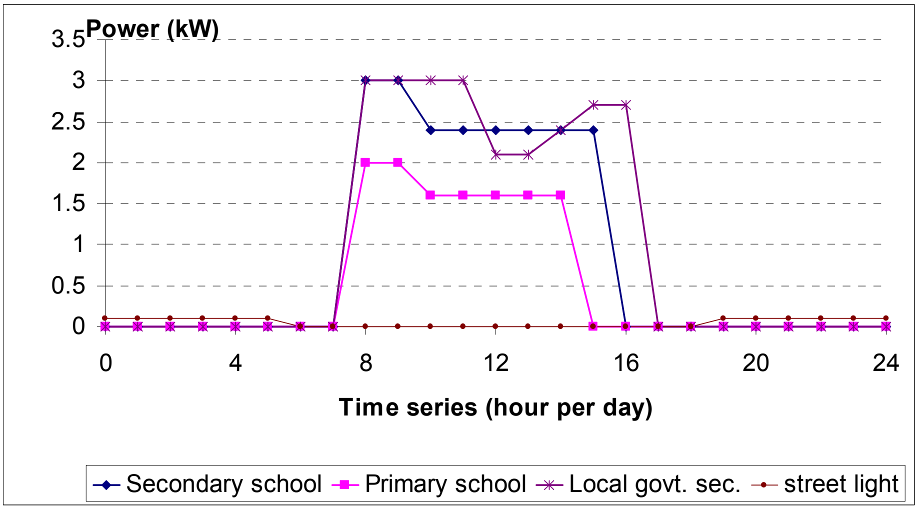


Figure 2.2. Averaged hourly load demand of public utilities

Figure 2.2 shows the variation of each component of public utilities load demand curves hour by hour in one day.

Secondary school:

- There are 2 secondary schools and the further explanations will be assumed for every single school uniformly.
- At 07.00 the load starts to increase and reaching its peak load as 3 kW at 08.00 as assumed this school is operating since 8 am until 3 pm in the afternoon.
- At 10.00 the load quite decreases since the sun already fully shines at this moment and the load about 2 kW will be constant until the school is over at 3 pm.

- At 16.00 the load is no longer needed and the activities totally finished and the school will be closed.
- The most electricity needed is for lighting.
- $$Load\ Factor\ =\ \frac{Average\ Load\ (Watts)}{Maximum\ Load\ (Watts)} \qquad (2.2)$$

  Using equation (2.2) will gives load factor is 27 %.

Primary school:

- There are 6 primary schools and the further explanations will be assumed for every single school uniformly.
- The characteristic of load demand for primary school is quite the same as secondary school. The differences are the duration of the activities (8 am up to 2 pm, one hour earlier) and the number of rooms available make energy consumption lower compare to secondary school.
- The peak load is between 7 to 8 am with 2 kW power are needed.
- Using equation (2.2) will give load factor of 24 %.

Local government secretariat:

- This office starts the activities at 8 am and will be closed at 4 pm. During this time fluctuation happens and the lowest load at this range is around 12.00 – 13.00 because the officers get some rest at that moment.
- Peak load happens during 8 to 11 hours with 3 kW and decrease to 2 kW during break session. The load is zero when there is no activity held in the office.
- Using equation (2.2) will give load factor of 32 %.

Street light:

- There are 10 street lights and the further explanations will be assumed for every single street light uniformly.
- The street light will be turn on at 19.00 and will be turn off at 05.00 with constant value of load demand, 100 Watts.
- Using equation (2.2) will give load factor of 48 %.

2. Critical load

The district hospital becomes critical load for this village as a remote area because most of medicines or vaccines need refrigeration for their storage to make them still can be used well for a certain period. Moreover for special treatment to the patients some electrical equipments will be used for instance for surgery. The load curve of critical load or hospital can be seen in figure 2.3 and the explanation about it is described as followed:

- Since hospital always operates so that the base load is around 3 kW and the demand never goes to zero.
- Peak load will be reached at 8 am to 4 pm since many medical actions will be taken on that range time. Out of that range the electricity used only for lighting mostly.
- The peak load is around 10 kW.
- Using equation (2.2) will give load factor of 60 %.

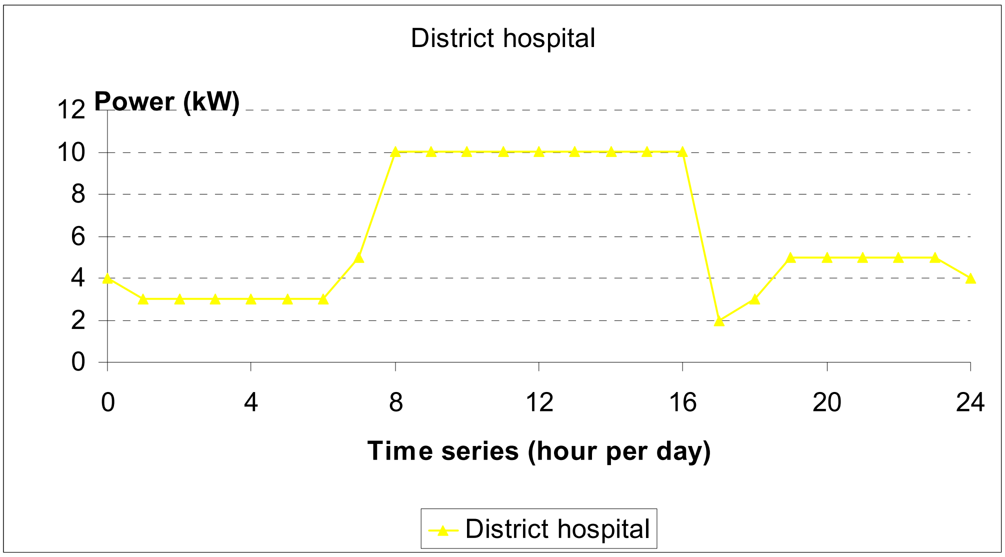


Figure 2.3. Averaged hourly load demand of hospital

3. Households

Mostly, households in rural area in Nigeria only use small number of electric appliances such as lamp for lighting, radio, and television. Energy for lighting is the most highly demanded by the people. Adeoti et. al. in their research shows that daily energy demand of one household in mostly rural area in Nigeria is around 2324.5 Wh [10]. This value was sampled from 480 rural households in Nigeria with 120 households per village. Breakdown of that energy demand can be seen in table 2.5.

Table 2.5. Household energy demand of rural area [10]

| Factor | Average duration of use/day (h) | Average daily power requirements/household/day (Wh) |
|---|---|---|
| Lighting requirements | 6.1 | 1921.5 |
| Radio requirements | 5.8 | 352.6 |
| Television requirements | 4.2 | 50.4 |
| Total energy or power requirement/household/day | | 2324.5 |

Based on values shown in table 2.5, hourly load demand for lighting, radio and television as electric appliances of households can be derived as figure 2.4. There are 200 households approximately and the further explanations will be assumed for every single household in Ikem uniformly.

Lighting:

- People use lamps in the house when the night comes and there is no sunshine anymore around 6 pm to 6 am.
- Peak load happens during 7 to 9 pm, afterwards only a small number of lamps will be used but the load will somewhat increase at 4 to 5 am when people getting up or praying in the morning. When the sun rises around 6.30 am up to 6 pm usually people do not use lamp.
- Peak load is around 320 Watts and the base load is around 32 Watts

Radio:

- People use their radio mostly since 7 pm to 9 pm, with peak load around 61 Watts.
- During break hour around 12 am, people also could be using their radio.

Television:

- The characteristics of television that used is almost the same with radio, with peak power around 12 Watts.

Total of every household load demand:

- The accumulation of all variables of household load parameters will reach its peak load as 380 Watts during 7 to 9 pm, and gives base load as 38 Watts.
- The highest contribution to this load is by lighting.
- Load Factor is 24 %.

Total of energy demand:

- Daily energy demand of every household is 2 kWh.

Yearly energy demand of every household is 850 kWh.

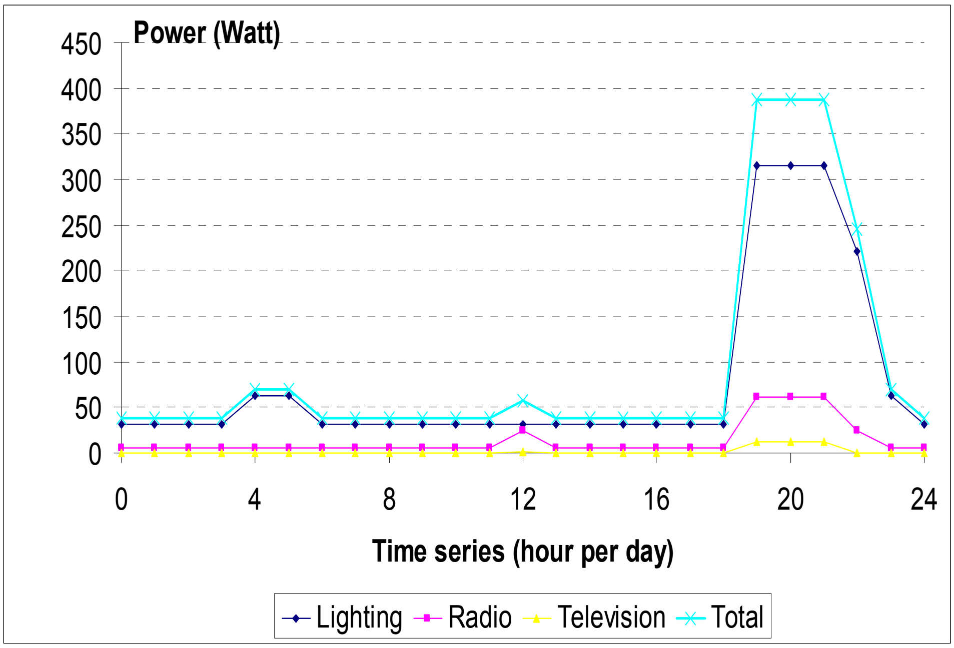


Figure 2.4. Averaged hourly load demand of a household

4. Industry

   In Ikem, there is a small scale industry of rice milling which has the function to rind the rice apart from the husk and also from its branch. Many agricultural products are yielded in Ikem and to increase the economical value of those products rice milling industry have been built as one of the solutions. Most of energy that is needed in this industry is using for rotating the motor of milling machine. The totally differences can be seen with characteristics of load demand in households sector that using energy mostly at night for lighting but in industrial sector the load commonly use in the day and will reach its peak also in the daytime. The hourly load curve as shown in figure 2.5 can be seen.

   From the figure 2.5 can be seen that the load start to rise at 7 am and lies down at 7 pm because the industry work hour is during 8 am to 6 pm. The peak load of 100 kW happens around 8 am to 9 am and 3 pm to 6 pm. At 12.00 up to 13.00 there is declining of load because of the break session. Most of the loads are electrical machines. The load factor is around 40 %. Total energy demand of the industry is 1 MWh per day where 365 MWh per year.

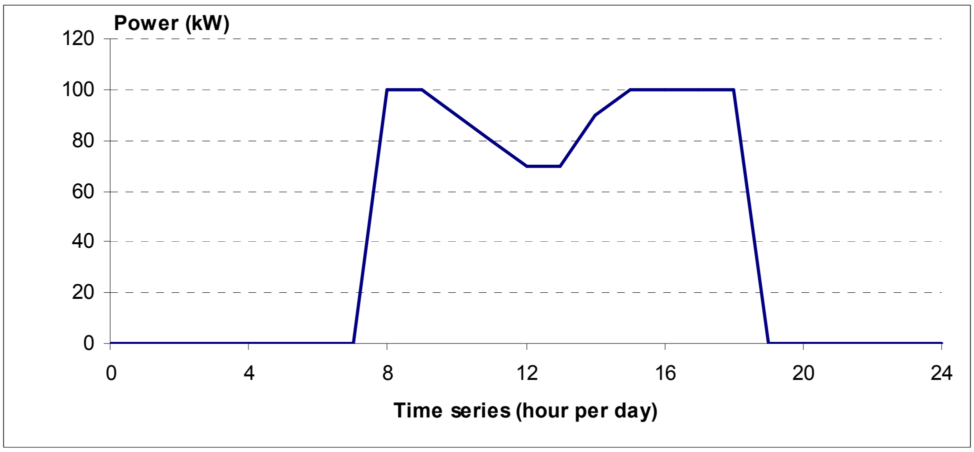


Figure 2.5. Averaged hourly load demand of industry

### 2.2.2 Total load demand

Those all curves show the electricity demand needed for every single primary school, secondary school, local government secretariat, street light, hospital, households, and industry. To make the whole electricity demand of Ikem should be multiplied with the number of each variable as shown in table 2.4. The curves in total number are to be shown in figure 2.6.

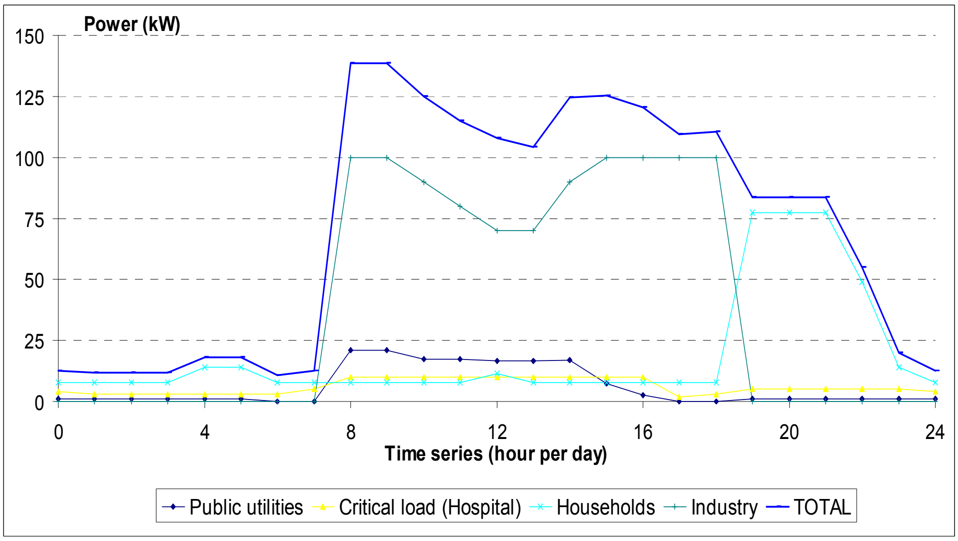


Figure 2.6. Total hourly load demand

From figure 2.6 can be seen that peak load around 140 kW happens at 8 to 9 am, and still in the high demand in between 2 to 3 pm varies between 124 kW to 125 kW. This high demand is mostly for industrial sector demand. The base load is 12 kW between 1 to 3 am. During night between 7 pm to 9 pm the energy are mostly demanded by households for supplying their lighting. The highest load during night is between 7 to 9 pm around 80 kW.

The load factor is 51% which means the average demand in entire time is approximately half from the maximum time. This number is quiet good for electricity supplier perspective because of the gap between the peak load and average energy used is not so high so that the power capacity need to be built is not so large. This happens because there is abundant load demand needed by industry in daytime otherwise the electricity only demanded in the night time for lighting only.

The total daily energy needed for Ikem is 2 MWh and 640 MWh in a year. This assumption has been made with ignoring the Saturday, Sunday and holidays which are on those day difference load demand happened usually the amount is smaller than loads shown in figure 2.6. The ignorance made because too many unknown parameters in making assumption for Saturday, Sunday, holidays load demand curves and there would not be insufficient energy generating since the load on those day is less than normal week day. On those days the public services are close and the activity in industry not as effective as normal week day.

The total load demand characteristics shown in figure 2.6 will be used for further calculation in this research.

# 3. Possible renewable energy technologies

In this chapter all possibilities of potential renewable energy for generating electricity that suitable to Ikem village will be discussed. The load demand of Ikem and the potential renewable energy resources have been already known as shown in previous chapter. The suitable renewable energy technologies that can be applied to that village are hydropower, biomass combustion, photovoltaic and combination among them will be explained in this chapter.

## 3.1. Hydropower

Hydropower technology is a proven and mature technology and capable of providing electricity for 24 hours a day due to the availability of water. Hydropower systems are derived from the hydrological climate cycle, where water precipitated in high regions (mountains) develops high energy potential. This energy potential through water flow will turn water turbines coupled to generators to produce electricity. Energy potential is a function of Height difference and water volume, thus to produce higher output of electricity can be achieved by increasing volume of water or creating larger height difference. Using dams as water storage can raise volume and level of water moreover can compensate the water supply fluctuation. For increasing difference of height, a water tower can be built to collect the water that is pumped when there is excess power. This method is usually being used for a water pump storage scheme.

There are 3 main types of hydropower systems, namely impoundment, diversion and pumped storage [11]. The impoundment uses a dam to store water from the river and the water released can be controlled to meet the fluctuating load demand. Diversion or so-called run-of-the-river facility diverts some of the water from the river that is channeled along the side of a valley through a penstock before being dropped into the turbine. The working principal of a pumped storage facility is storing energy by pumping water from a lower reservoir to an upper reservoir when the load demand is low and during period of high load demand, the water is released back to the lower reservoir for generating electricity.

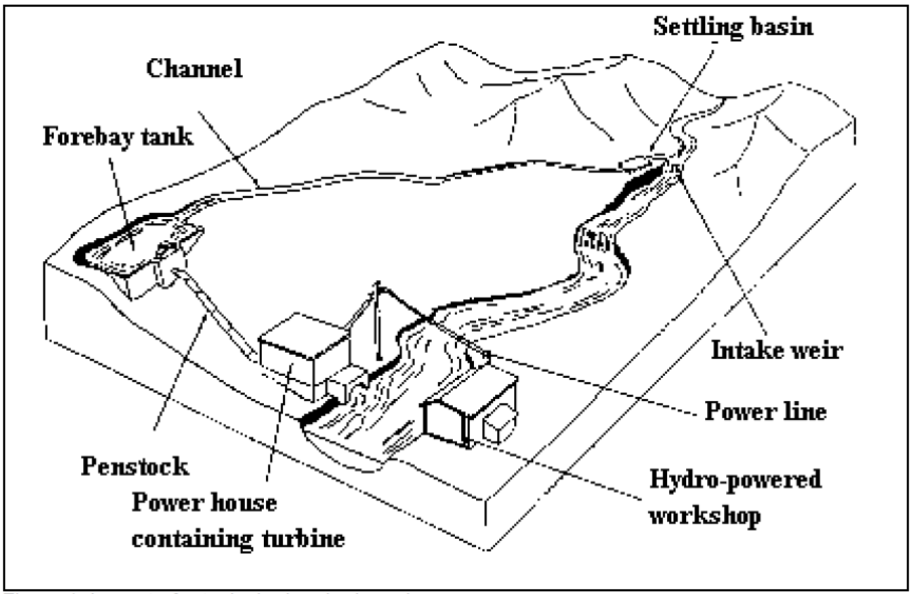


Figure 3.1. Layout of a typical micro hydro scheme

For a rural village such as Ikem, using run-of-river method would be the best choice because it requires no water storage that will reduce the complexity and the development cost of the system. The main components of run-of-the-river are showed in figure 3.1. When using this method, the production of electricity power obviously depends on the topographical and hydrological condition of Ikem. While the power produced by this method is not sufficient for covering whole load demand, then developing a small dam also could be an option to increase power output.

### 3.1.1. Energy calculation

Parameters that should be identified for calculating the electrical power production by using hydropower are the head through which the water flows and the flow rate of the water. There are two rivers lies on Ikem however the data regarding flow rate of the river and real topographical situation where the rivers flows for determining the head is difficult to be identified due to the lack of real data. Based on the normal surface land without any hills therefore the flow rate of the water river is assumed to be 1.5 $m^3/s$ and then the head is 5 meter height since there is no mountain. These values will be used as flow rate and head for further calculation. There are two possibilities that these values could be identified as shown in figure 3.2. The shape of the river path could be assumed that there is a barrier that makes the water does not flow straightly but rather turn around finding the lowest surface. So it can be assumed that the bigger the curly shape of the river flow the higher different height could be available. Moreover the advantage of building hydropower on the curly shape is to reduce the distance for diverting some of the water and releasing back to the river and also reducing materials for the channel as well.

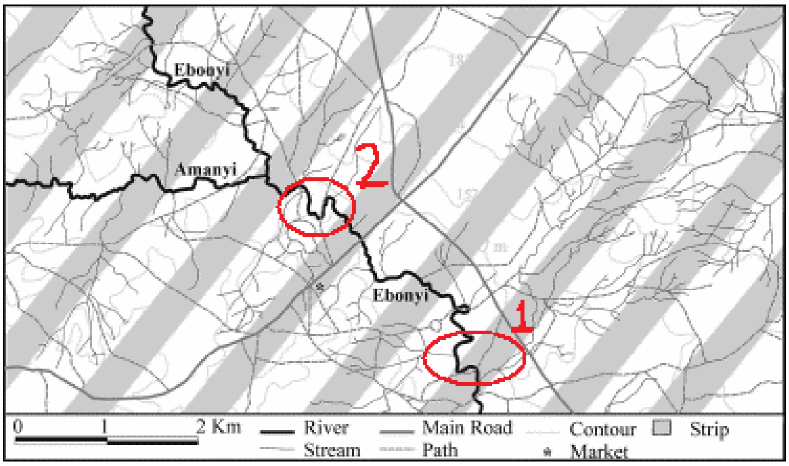


Figure 3.2. Hydropower physical location

The calculation of hydropower output can be proposed by using equation (3.1).

$$P = H_{gross} \times \rho_{water} \times g \times Q \times \eta_{total} \tag{3.1}$$

Where:

$P$ : Power output (Watt)

$H_{gross}$ : gross hydraulic head (meter)

$\rho_{water}$ : density of water ($kg/m^3$) = 1000 $kg/m^3$

$g$ : acceleration due to gravity ($m/s^2$) = 9.81 $m/s^2$

$Q$ : flow rate of the turbine ($m^3/s$)

$\eta_{total}$ : total system efficiency

Power losses within a hydropower system are penstock, manifold, turbine, drive, and generator losses. By multiplying all the efficiencies of those components, the total system efficiency of 0.51 is determined. This value is quite a good estimation for micro-hydro scheme to generate electricity [11]. Using equation 3.1 the power output that will be produced is 40 kW which means 900 kWh of energy will be yielded in a day. Figure 3.3 shows the output of hydropower for constant power output. From that figure shows that the power production is not enough to supply all the power demand continuously. The load demand can be covered only if there are approximately 4 areas equal to the origin area for achieving the peak load demand. Otherwise, building a small dam could be a suitable solution.

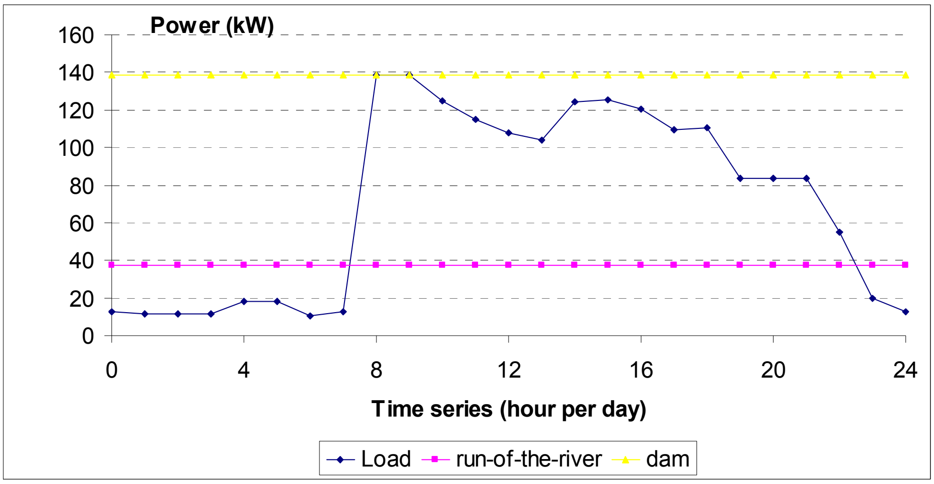


Figure 3.3. Output of hydropower

In the figure 3.3, the calculation of hydropower by building a small dam for covering the load demand is also shown. Building a dam is a cost intensive however it can be reduced by empowering local people to participate in the development of the dam. Peak load of Ikem is around 140 kW, using equation (3.1) so the flow rate that should be reached for this load is 5.54 $m^3/s$. In order to supply this flow rate the volume of the dam should be 500,000 $m^3$. If the dam that will be built is a circle shape with 2 meters depth then the diameter of the dam is 552 meters. Using a small dam with 552 m diameter and 2 m depth will produce power output of 140 kW that will cover every load demand continuously. The benchmarking between ROR and using small dam with 3 options of dam size can be seen in table 3.1. The output power curve against load demand can be seen in figure 3.3.

Table 3.1. Power output of ROR and using small dam

| | ROR | small dam | | |
|---|---|---|---|---|
| Max. Power output (kW) | 40 | 150 | | |
| Daily Energy production | 900 kWh | 2 MWh | | |
| Dam | - | option 1 | option 2 | option 3 |
| *volume (m3)* | - | 500000 | 500000 | 500000 |
| *shape* | - | circle | circle | circle |
| *depth (m)* | - | 2 | 3 | 5 |
| *diameter (m)* | - | 550 | 450 | 350 |

Based on the calculation of reliable electricity supply for Ikem by using hydropower, impoundment by building small dam is the best method since using run-of-the-river, as the easiest method cannot reach peak load of the energy demand.

### 3.1.2. Turbine selection

The function of the turbine is to convert the energy by striking moving water into shaft power. Turbines can be divided into two categories: impulse and reaction and each category are divided into high, medium and low head as shown in table 3.2.

Table 3.2. Classification of turbine types [12]

| | Head pressure | | |
|---|---|---|---|
| Turbine Runner | High | Medium | Low |
| Impulse | Pelton<br>Turgo<br>Multi-jet Pelton | Crossflow<br>Turgo<br>Multi-jet Pelton | Crossflow |
| Reaction | | Francis<br>Pump-as-turbine (PAT) | Propeller<br>Kaplan |

The impulse turbine relies on the velocity of water to rotate the turbine wheel; that is why high head condition is the most appropriate situation for this type. The reaction turbine depends on the pressure rather than velocity to rotate the turbine wheel and all blades maintain constant contact with the water.

The choice of turbine will depend mainly on the pressure head available and the design flow for the proposed hydropower installation. Since 5 meters is categorized as low head so there are 3 choices of turbines: crossflow, propeller and Kaplan. Then the kaplan turbine is chosen because of its characteristics which is shown in figure 3.4 fulfills the requirement of the site and the wide availability and commonly used of it instead of using the crossflow turbine. Figure 3.4 is the range of utilisation of the Kaplan Turbine of Ossberger GmbH manufacturer.[13] It can be seen that 5 m head and 1.5 m3/s flow rate are inside the utilization range of the Kaplan turbine. From Ossberger manufacturer data sheets is known that model K of Kaplan turbine fit with the site requirements.

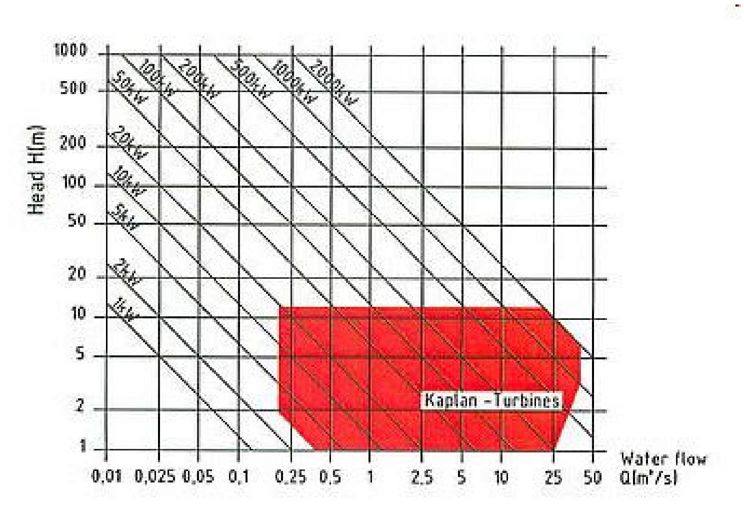


Figure 3.4. The range of utilisation of the Kaplan Turbine

The operational range of K model of Kaplan turbine is shown below:

- Runner Diameter (m) = 0.25 - 0.9
- Head (m) = 1 - 12
- Q ($m^3$/s) = 0.2 – 5.3
- Power Output (kW) = 3 - 500

### 3.1.3. Specification

The specification of possible hydropower system that can be built in that village can be seen in table 3.3. The assumptions about the flow rate and the head that has been made are based on normative justification related to the topographical situation in Ikem, nevertheless the real data is strongly needed to apply this potential hydropower technology into the proposed hybrid renewable energy system. The possibility of hydropower as shown in table 3.3 seems become a good potential resources however since the value is not real data therefore that hydropower will not be chosen as proposed hybrid renewable energy in this research.

Table 3.3. Specification of the hydropower system

| SPECIFICATION | Value |
|---|---|
| *TURBINE* | |
| type | Kaplan |
| model | K |
| Max. Output (kW) | 150 |
| *GENERATOR* | |
| Max. Capacity (kW) | 150 |
| *DAM* | |
| shape | Circle |
| depth (m) | 2; 3; 5; 10 |
| diameter (m) | 550; 450; 350; 250 |

## 3.2. Photovoltaic system with batteries

Solar energy is freely available in abundance and is the primary energy source. There are two different ways to convert solar energy in yielding electricity. The first is converting solar energy directly into electricity that takes place in semiconductor devices called solar cells. This process is also known as photovoltaic (PV) or solar cells energy conversion. The second one is accumulation of heat in solar collectors to rotate the generator to yield electricity, this technology also known as solar collectors or solar boiler even solar thermal. This research will furthermore focus on the PV technology instead of solar thermal due to the following reasons:

- The PV can be used for small-scale generation unlike solar thermal that is usually used for large-scale power generation.
- Although solar thermal technology has been developed earlier than PV, nowadays the improvement and applications of PV are more advanced than the solar thermal. Although several have been built and operated successfully, solar thermal power plants are still a maturing technology [14]. This fact also strengthen by hybrid technologies matrix issued by DOE [15] that solar thermal technology still in R&D stage.
- To be applied in many areas especially in rural areas, PV technology is easier to be to be built and maintained and more accessible from the market than the solar thermal. It is proved that as a total installed capacity of more than 350 $MW_e$ representing over 90% of the world's installed solar capacity only located in California [16].

- Using solar thermal will be more efficient in CHP application where the thermal supply is also needed. Frequent manual cleaning of the mirror of solar thermal technology to prevent the film from dust, dirt, oils, and water spots is needed and it requires higher labor costs. The dirt will reduce mirror reflectivity tremendously because any light reflected from the mirror passes through the surface film twice [14]. These reasons cause the diffusion of the solar thermal application is limited.

This research will focus on PV technology and the utility of the battery bank as a reserve power supply when no sunshine available. This will surely increase the reliability of the system.

### 3.2.1. Photovoltaic

The advantages of the PV solar energy are environmentally benign, no use of fuels and water, clean technology (no emissions, pollutants, odor or liquids to spill), electricity is generated wherever there is light (solar or artificial), PV operates even in cloudy weather conditions, long lifetime, no noise because of no moving parts attached on it, minimal maintenance requirements, and modular, can be also designed for a power plant that suitable for remote area. The drawbacks are PV cannot be operated without light, high initial costs that overshadow the low maintenance costs and lack of fuel costs, large area needed for large scale applications, PV generates direct current: special DC appliances or inverters are needed in off-grid applications energy storage is needed, such as batteries that also will explain later in this chapter.

#### 3.2.1.1. Technology of PV

An overview of the different PV technologies that are used or being developed can be seen in table 3.4. Today's commercial PV systems convert sunlight into electricity with efficiency ranging from 7 - 17%. They are highly reliable and most producers give at least 20 years guarantee on module performance. Crystalline silicon based solar cells amounted to 95% of the total production and were the dominant solar cell technology.

Table 3.4. Overview of PV application technologies [18]

| Material | Structure | Technology | Market Share |
|---|---|---|---|
| Silicon (Si) | Single-crystalline (sc-Si)<br>Multi-crystalline (mc-Si)<br>Ribbons (mc-Si) | Wafers | 34%<br>54%<br>3% |
|  | Amorphous (a-Si :H) | Thin film | 6% |
| Compound semiconductors, e.g. CdTe, $CuInSe_2$ (CIS), GaAs | Multi-crystalline | Thin film | 2% |
| Organic material: dye sensitized (Grätzel) cell, bulk donor-acceptor hetero junction cell | Amorphous | Thin film | < 1 % |

According to the highest market share, the multi-crystalline silicon is chosen for this research. Multi-crystalline silicon consists of small grains of mono-crystalline silicon. These cells are easier and cheaper to be manufactured than mono-crystalline, but they tend to be less efficient. Nevertheless, the grains production in such a way process are relatively large in size, and oriented in a top-to-bottom direction to allow light penetration deeply into each grain, to increase their efficiency. These improvements have enabled commercially available multi-crystalline silicon PV modules to reach efficiencies of over 14%.

High-efficiency PV module using silicon nitride multi-crystalline silicon cells, BP 3160 that produced by bp solar will be used for this research. The characteristics can be seen in table 3.5.

Table 3.5. BP 3160 Characteristics

| Characteristics of BP 3160 | Value |
|---|---|
| Nominal voltage [V] | 24 |
| Maximum power ($P_{max}$) [W] | 160 |
| Voltage at Pmax ($V_{mp}$) [V] | 35.1 |
| Current at Pmax ($I_{mp}$) [A] | 4.55 |
| Warranted minimum $P_{max}$ [W] | 152 |
| Short-circuit current ($I_{sc}$) [A] | 4.8 |
| Open-circuit voltage ($V_{oc}$) [V] | 44.2 |
| Temperature coefficient of $I_{sc}$ [%/°C] | 0.065±0.015 |
| Temperature coefficient of $V_{oc}$ [mV/°C] | -(160±20) |
| Temperature coefficient of power [%/°C] | -(0.5±0.05) |
| NOCT (Air 20°C; Sun 0.8 kW/$m^2$ ; wind 1 m/s) [°C] | 47±2 |
| Number of Solar Cells (125mm x 125mm) | 72 |
| Matrix connected in series | 6x12 |

The information from table 3.5 is measured under standard condition with irradiance 1000 W/m2 and cell temperature is 25 °C. The module is operated in 24 Volt DC and will produce 160 W of maximum power. The I-V characteristics of the module including short circuit current, open-circuit voltage, and current/voltage at maximum power for 4 different temperatures can be seen in figure 3.5.

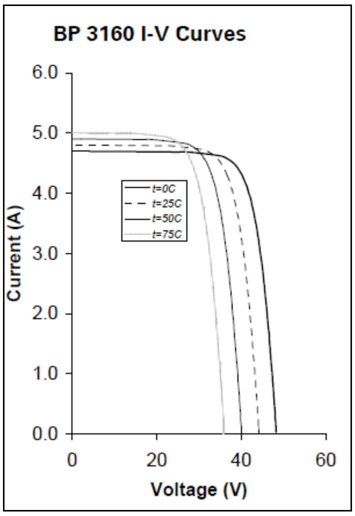


Figure 3.5. I-V characteristics of BP 3160

Using the curves shown in Figure 3.5, the maximum power point Power output (PMPP) can be calculated by using equation (3.1) and the result shown in table 3.6:

$$P_{MPP} = P_{MPPref} \times V_{OC} \times I_{SC} / (V_{OCref} \times I_{SCref}) \qquad (3.1)$$

Table 3.6. $P_{MPP}$ for different temperatures

| Temperature (°C) | $V_{OC}$ (V) | $I_{SC}$ (A) | $P_{MPP}$ (W) |
|---|---|---|---|
| 0 | 50 | 4.7 | 177.2 |
| 25 | 45 | 4.8 | 162.9 |
| 50 | 40 | 4.9 | 147.8 |
| 75 | 35 | 5 | 132 |

### 3.2.1.2. Other components of PV system

The PV system mainly consists of three parts: PV modules that already discussed in previous section, electrical load that already explained in chapter 2, and balance of the system that consists of mounting structures, energy storage, charge regulators, and inverters [19].

The main purpose of the mounting structure is to hold the PV modules safe in the place that means resistance against wind forces and prevention from thefts. The mounting structure also has to minimize the module reflection and brings the module easily to access for repairing or maintenance. The cost structure must be low. The mounting structure will not be further discussed in this research.

The main technologies for storing electricity systems are electrochemical (batteries and flow-cell), the storage of kinetic energy (flywheels) and the potential for the storage of energy in the form of pumping water and air such as pumped hydro-power and compressed air energy storage. In this research the system will use valve regulated lead-acid batteries because the battery is the simplest way for storing the energy and commonly used. Main difficulty of using battery is the relatively high cost and the large amount required for large-scale applications. The following factors should be considered when selecting a battery for PV applications:

- Operating temperature range (e.g.: -15°C to 50°C)
- Self discharge rate (% per month)
- Cycle life to 80% depth of discharge (DOD)
- Charge efficiency from 20% discharged
- Capacity (Ah) at 10 hr & 100 hr rates (C10 & C100)
- Required frequency for topping up the electrolyte
- Robustness for transporting to the site
- Resistance to overcharging
- Cost

In this research, the valve regulated lead-acid battery will be proposed to use because this lead-acid battery is sealed that has a safety hazard due to overpressure risks when overcharging, and there is always a safety valve present, hence the name valve-regulated. The more detailed explanation about the valve regulated lead-acid battery that used in this research will be shown in next section.

The charge regulator is used for protecting the battery from overcharge or excessive discharge. In setting charge and discharge voltage limits should be suited to the battery type and the operating temperature because it can significantly affect maximum operational life of a battery. The high temperatures tend to reduce the battery life because of corrosion and accelerate self-discharge. . High temperatures tend to reduce battery life because they accelerate corrosion, self-discharge and increase out gassing during charging. The resistance of lead-acid batteries to freezing is reduced when they are discharged, so batteries should be kept charged when they are left in low temperature conditions during the winter.

PV module that is used to charge the battery normally operates around the constant voltage that is selected according to the local temperature. However, some regulators PV system employs the maximum power point tracker (MPPT), which automatically permits the PV module operating in the voltage that produces a maximum power output. Such regulators employ electronic DC-DC converter that is required to keep the output at the required system voltage. The benefit of using the MPPT depends on the application and should be weighed against its additional cost and reliability risks.

Inverter used to transform DC to AC power, make wave shaping of the output AC power, and also as the regulation of the effective value of output voltage. Its reliability and efficiency characteristics become important features of an inverter. In general, inverters have efficiencies ranging from 90% to 96% for full load and from 85% to 95% for 10% load. Technology for high switching frequency inverters (usually 20 kHz or higher) can be done by using switch-mode power semiconductor devices. Power MOSFETs and bipolar transistors are used in low power inverters, while thyristors used in high power applications. Novel devices, such as insulated-gate bipolar transistor (IGBT) inverters are capable of handling several hundred kW, running at frequencies up to 50 kHz. They delivered the AC output wave, which has a form very close to the pure sinusoidal one, with a little filtering on the output. This removes the bulky, expensive, and energy-consuming power filters.

### 3.2.2. Lead acid batteries

Batteries are a long-established means of storing electricity in the form of chemical energy. Lead-acid batteries are classified as secondary batteries, which can be recharged and are suited in bulk energy storage. After discharge, these batteries can be recharged electrically to their original state by passing current through them in the opposite direction of the discharge current. As an energy-storage device, these batteries connected to and charged by a prime energy source supply energy to the load demand. Other types of secondary batteries are nickel–cadmium (NiCd), sodium–sulphur, sodium–nickel chloride (ZEBRA), and lithium ion.

In this research valve regulated lead-acid (VRLA) batteries are used because the technology of lead-acid batteries has already being invented since long time ago in 1859 by the French physicist, Gaston Planté and commonly used usually for car moreover they provide a cost-competitive that is why they are suitable to be used in electrical power systems. The VRLA battery is the newer designation of the conventional flooded lead-acid batteries which containing only a limited amount of electrolyte ("starved" electrolyte) absorbed in a separator or immobilized in a gel. The immobilization of the electrolyte allows batteries to operate in different orientations without spillage. The major advantages and disadvantages of VRLA batteries can be seen in table 3.7.

Table 3.7. Major advantages and disadvantages of VRLA batteries [20]

| Advantages | Disadvantages |
|---|---|
| Maintenance free | Should not be stored in discharged condition |
| Moderate life on float service | Relatively low energy density |
| High-rate capability | Lower cycle life than sealed nickel-cadmium battery |
| High charge efficiency | Thermal runaway can occur with incorrect charging or improper thermal management |
| No "memory" effect (compared to nickel-cadmium battery) | More sensitive to higher temperature environment than conventional lead-acid batteries |
| "State of charge" can usually be determined be measuring voltage | |
| Relatively low cost | |
| Available from small single-cell units (2 V) to large 48 V batteries | |

The theoretical information about batteries mostly derives from The Handbook of batteries, written by Linden and Ready. The lead-acid battery consists of two electrodes positive and negative. The positive electrode is made from lead oxide ($PbO_2$) while the other is manufactured from lead (Pb), where in between there is electrolyte to make chemical reaction happens.

The reaction at the positive electrode is

$$PbO_2 + 3H^+ + HSO_4^- + 2e^- \Leftrightarrow 2H_2O + PbSO_4$$

The reaction at the negative electrode is

$$Pb + HSO_4^- \Leftrightarrow PbSO_4 + H^+ + 2e^-$$

Overall reaction becomes

$$PbO_2 + Pb + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + 2H_2O$$

Those reactions are totally reversible reactions which will flow to the right in discharging and to the left for charge condition.

When a charged battery connected to the load the electron will flow from negative electrodes to the positive electrode through external circuit generating current while the ions will move through the electrolyte. The electrolyte is a solution of a sulphuric acid and water and that molecules of $H_2SO_4$ will ionize in the water of the solution to supply the ionic current carriers of $H^+$ and $HSO_4^-$.

A unique aspect of the VRLA design is that the majority of the oxygen generated within the cells at normal overcharge rates is recombined within the cell. The pure lead-tin grids used in the construction minimize the evolution of hydrogen on overcharge. Most of the hydrogen generated within the cell is released to the atmosphere through the vent or through the plastic container. Oxygen will react with lead at negative electrode in the presence of $H_2SO_4$ as quickly it can diffuse to the lead surface,

$$Pb + HSO_4^- + H^+ + \tfrac{1}{2}O_2 \Leftrightarrow PbSO_4 + H_2O$$

In a flooded lead-acid battery this diffusion of gasses is a slow process, and virtually all the H2 and O2 escape from the cell rather than recombine.

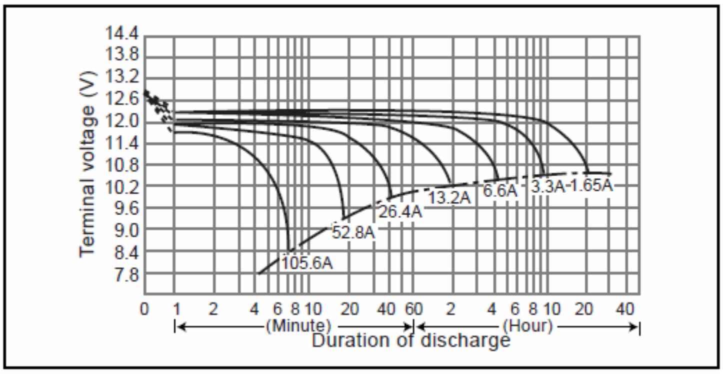
In theory, the lead-acid battery will produce 1 Ah of energy through the electrochemical reaction of 4.5 grams of lead oxide and 3.9 grams of lead with 3.7 grams of sulphuric acid.

Type of valve-regulated lead-acid (VRLA) battery that is used in this research is of Panasonic LC-R1233P. The lifetime of this battery is 3 to 5 years. The specification of this battery can be seen in table 3.8.

Table 3.8. Specification of Panasonic LC-R1233P

| | | |
|---|---|---|
| Nominal Voltage | | 12 V |
| Rated Capacity (20 hour rate) | | 33 Ah |
| Dimension | Length | 195.6 mm |
| | Width | 130 mm |
| | Height | 155 mm |
| | Total Height | 180 mm |
| Approx. mass | | 12 kg |

Good quality batteries of this type can normally be expected to have operational life of 5 years if they are properly maintained and used in a PV system with a suitable charge controller. Longer operational life may be achieved if the maximum depth of discharge is limited, but shorter lifetimes must be expected if the batteries are mistreated. Cycles of varying duration and depth with frequent incomplete recharge periods between discharges becomes a challenge to both battery design and sizing of the battery stack because this type of operation can lead to an apparent fading of overall capacity. Prolonged cycling operation with improper recharging can be damaging the battery therefore the characteristics of discharging which have almost the same characteristics with charging should be known. Discharge characteristics of this battery t 25 $^{o}$C can be seen in figure 3.6.



| | | |
|---|---|---|
| Capacity (note)<br>77°F (25°C) | 20 hour rate (1.65A)<br>10 hour rate (3A)<br>5 hour rate (5.4A)<br>1 hour rate (20A) | 33Ah<br>30Ah<br>27Ah<br>20Ah |
| | 1.5 hour rate discharge Cut-off voltage 10.5 V | 13.4A |
| Internal Resistance | Fully charged battery 77°F (25°C) | Approx. 7mΩ |

Figure 3.6. Discharge characteristics of Panasonic LC-R1233P

Characteristics of the batteries will be used as a reference in modeling this type of battery.

## 3.3. Biomass combustion

Biomass resources come from plants or animal substances such as trees, waste products and animal by-products. Solar energy is stored as chemical form in biomass. Water from the earth combines with carbon dioxide from the atmosphere in the photosynthesis process that is driven by solar energy will produce carbohydrates (sugars) that form the building blocks of biomass. When biomass is combusted efficiently, stored energy that is formed in the chemical bonds of the structural components of biomass is released. Oxygen from the atmosphere combines with the carbon in the biomass to produce carbon dioxide and water. This cycling process shows that biomass is a renewable resource and carbon neutral when biomass is produced in sustainable way.

Biomass can be combusted to provide heat then subsequently converted into other forms of energy as well as electricity. Combustion is the most mature conversion technology utilized for biomass. However the efficiency of combustion is relatively low and mostly used for large-scale application.

There are two types of conversion technologies for biomass utilisation: thermochemical conversion and biochemical conversion [21].

1. Thermochemical conversion
    a. Gasification: is a conversion process that partial oxidation of solid biomass particles into a producer gas which consists of CO, $H_2$, $CH_4$, and $CO_2$ occurred [22].

       Three general steps in gasification are [23]:
        - First step is the particle drying process where all water is evaporated from the biomass material.
        - Secondly, the pyrolisis process where the material is broken up into volatiles and a char residue.
        - Finally, in the oxidation zone of the reactor, the volatiles, a mixture of different organic and anorganic compounds are oxidized by the gasification agent and part of the char is reduced from carbon dioxide and water into hydrogen and carbon monoxide.

       Three main categories of gasification reactor designs are [22]:
        - Fixed-bed reactors: the gasification agent velocity in the reactors is rather low, therefore it steadily flows through the biomass particles. Preferred option for small-scale application especially with co-current design which employs the same flow direction for biomass particles and the gasification agent.

        - Fluidised-bed reactors: employ a higher gasification agent velocity and a bed consisting of particles inert bed material such as sand.
        - Entrained flow reactors: employ an even higher gasification agent velocity and result in an evenly distributed particle/gasification agent stream within the reactor.
    b. Pyrolisis: the conversion of solid or liquid biomass into a mixture of liquid, gaseous, and solid intermediate fuels in the absence of air [24].
    c. Liquefaction: whereas gasification and pyrolisis mainly produce the intermediate fuel with endothermic chemical reactions and require a certain temperature level, liquefaction tries to cleave the large biomass feedstock macromolecules by applying high pressure and only low levels of heat [21].
    d. Ranking of thermochemical conversion technologies: [21]

| | Gasification | Pyrolisis | Liquefaction |
|---|---|---|---|
| conversion level | +++ | ++ | ++ |
| simplicity | ++ | ++ | - - - |
| plant cost | ++ | ++ | - - - |
| conversion time | + | + | + |
| applicability to scale | +++ | ++ | - - |

2. Biochemical conversion
    a. Anaerob digestion: the bacteria-driven conversion of biomass to biogas in the absence of oxygen results in the depletion of the biomass' oxygen content for the metabolisms [25]. To achieve this, biomass is filled into a reactor and kept at the respective temperature level needed by the bacteria present.
    b. Fermentation: the processes that convert biomass into Ethanol (EtOH) and consist of two consecutive steps: first, biomass starch is converted to sugars using enzymes, afterwards the sugars are fermented to EtOH using yeast. The solid residues of fermentation, which still contain considerable amounts of biomass, can then be used for combustion or gasification [21].

c. Ranking of biochemical conversion technologies: [21]

| | AD | Fermentation |
|---|---|---|
| conversion level | ++ | ++ |
| simplicity | +++ | - - - |
| plant cost | +++ | - - |
| conversion time | + | ++ |
| applicability to scale | +++ | - |

There are two types of generation technologies using biomass:

1. Heat-driven generation
    a. Stirling engines: are designed to use a cycle of heating and cooling a working gas; the gas is compressed, heated and expanded and then it is cooled. Due to the expansion it produces work at a piston. The net work produced is thus the piston work minus the work needed to compress the gas. A generator unit then converts the piston motion into electricity [21].
    b. Externally fired microturbines: are gas turbines for a power range of less than 500 kWe. Although most turbines employ combustion chambers and expand the combustion air to generate shaft motion, some designs use heat exchanger technology similar to the stirling heat exchangers to heat the turbine working gas. In this case, the process is called externally fired gas turbine (EFGT) and the engine can be operated based on all combustion fuels, similar to the stirling technology [21].
2. Fuel-driven generation
    a. Microturbines: are small, predominantly aeroderivative turbines using a comparably simple design and a generator directly mounted on the turbine shaft [14, 15].
    b. Gas engines and internal combustion engines: gas engines can be defined as Internal Combustion Engines (ICE) running on gases such as natural gas, producer gas or biogas. Most gas engines are spark ignition engines, whereas ICE can be either compression ignition or spark ignition engines, however, most ICE can also be converted to run on gas [21].

3. Ranking of generation technologies: [21]

| | Stirling | EFGT | MT | ICE |
|---|---|---|---|---|
| full eficiency | - - | - - | + | +++ |
| part efficiency | - - | - - | + | +++ |
| load flexibillity | - | - | ++ | ++ |
| investment cost | - - - | - - | - | +++ |
| maintenance | ++ | ++ | +++ | - - - |
| emissions | ++ | ++ | +++ | - - - |
| development level | + | ++ | ++ | +++ |

Many processes can be chosen for every case in biomass combustion. Based on data shown in table 3.9 stirling engine would be the best option for this research according to small-scale application.

Table 3.9. Closed processes for power production by biomass combustion [28]

| Working medium | Engine type | Typical size | Status |
|---|---|---|---|
| Liquid and vapour (with phase change) | Steam turbine | 500kW$_e$ - 500MW$_e$ | Proven technology |
| | Steam piston engine | 25kW$_e$ - 1.5MW$_e$ | Proven technology |
| | Steam screw engine | Not established, 500kW$_e$ - 2MW$_e$ estimated | One demonstration plant with 730kW$_e$ and turbine from commercial screw compressor |
| | Steam turbine with organic medium (ORC) | 400kW$_e$ - 1.5MW$_e$ | Some commercial plants with biomass |
| Gas (without phase change) | Closed gas turbine (hot air turbine) | Not established, similar to steam turbine, probably large due to cost and efficiency | Concept and development |
| | Stirling engine | 1kW$_e$ - 100kW$_e$ | Development and pilot |

### 3.3.1. Stirling engines

In this research, stirling engines technology will be used since it can be properly used for small-scale power generation while other technology usually used for large-scale. The stirling engine has been conceived around since 1816, however, not widely used. The advantages using the stirling engine are:

- It can achieve the highest efficiency of any heat engine and perform "theoretically" up to the full Carnot efficiency, however in practice its efficiency reduced by friction.
- It can be implemented with any type of heat source including biomass since it based on external combustion.

- It produces constant output power so it is ideal for base load generation in renewable energy systems.
- It is easy to operate because almost everyone can operate a controlled flame used for a heat source.

Based on those advantages, the stirling engine is suitable to be used as power generation in a village such as Ikem.

#### 3.3.1.1. Working Principles of a Stirling Engine

The stirling engine acts as the prime mover of the system. It uses the temperature difference between its hot and cold end (of the working gas chamber) to establish a cycle of fixed mass gas consisting of four main processes: cooling, compression, heating and expansion. Thus, the stirling engine converts thermal energy (supplied by the heat source) into mechanical work. The shaft, or output, of the stirling engine will be fit to the rotor of the generator. The mechanical principles of a stirling engine are demonstrated in figure 3.7.

The burner heats the air, which is in a closed system. Due to the heat expansion of the air, the piston and the flywheels are put in motion. While the piston moves toward the flywheels, the displacer piston in the displacer cylinder is pushed into the cylinder head. Since the displacer piston does not have a seal, the hot air moves past it into the fin-cooled displacer cylinder. Here, the temperature is approximated 300 °C lower, the cooled air causes a vacuum, which pulls in the piston and keeps the flywheels turning. This rotary motion causes the displacer piston to be drawn back into the displacer cylinder, the cooled air rushes into the cylinder head. It heats up again, expands and thus provides power. Figure 3.8 describes working principles of a stirling engine in T/s diagram.

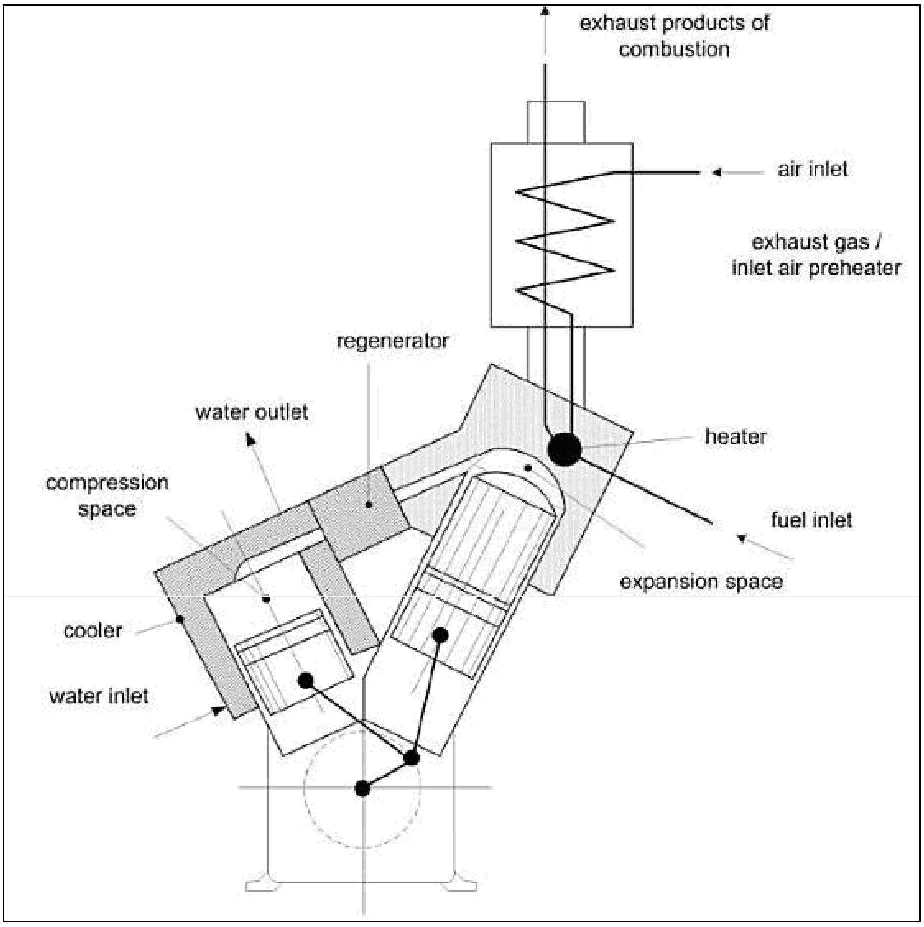
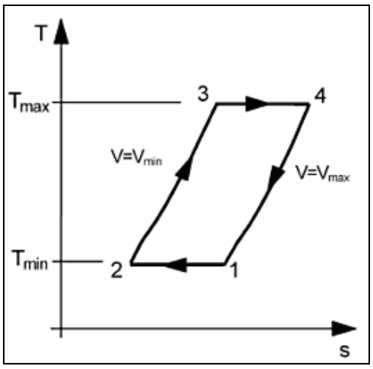


Figure 3.7. V-shaped stirling engine [29]



2-3 Heating at constant volume: The gas is heated while the volume remains constant. The pressure increases.
3-4 Expansion: With constant temperature, the gas is allowed to expand over a piston. The piston drives a crankshaft.
4-1 Cooling: Gas is allowed to cool, while the volume remains constant. The Pressure decreases.
1-2 Compression: Gas is compressed while the temperature remains constant. The piston drives the crankshaft further.

Figure 3.8. T/s diagram of the stirling engine [28]

The problem related to the stirling engine utility is corrosion or fouling caused by the hot flue gasses from the combustion of solid, liquid or gaseous fuels that usually happened at the heat exchanger surface. Therefore heat exchanger should be made from special materials or should be built in such a way that can be easily cleaned. The efficiency of a stirling engine is around 15-30 % for producing electricity.[28]

### 3.3.1.2. Application of a Stirling Engine

Nowadays, many biomass combustion using stirling engines already tested and developed. Here is the information about them:

- In India, about 100 Stirling engines were installed in the late 1980s.[27]
- At the Technical University of Denmark, a new Stirling engine has been developed for utilization of biomass (H. Carlsen, written communication, 1996). The rated electrical output of the engine is 36 kW. So far, the engine has been tested using natural gas for about 100 hours, and the biomass combustion unit has been separately tested for 400 hours; the efficiency of the engine was about 35% at full load.
- A 30 kWe stirling engine developed in Denmark and in use as a demonstration plant in combination with an automatic wood furnace. The specification is Hermetical 4-cylinder type engine operated at 4 bar, 620°C/40°C.
- A 30 kWe prototype plant has reached approximately 20% electric efficiency in CHP operation. Up to 28% efficiency is aimed at by improving the process and scaling up to 150 kWe.[30]
- 35 kWe Stirling engine for biomass combustion plants. (from courtesy of Henrik Carlson, Denmark)
- A 70 kWe stirling engine with two 4-cylinder engines in series in operation a biomass-fired combustion plant in Austria since 2005 with electrical efficiency around 12 %.[28]
- Sunpower has developed and delivered a variety of free-piston Stirling power generators at power levels ranging from 35 We to 7.5 kWe.
- A Biomass-Fired 1 kWe Stirling Engine Generator, Biowatt $^{TM}$, is for applying in South Africa. The system includes free-piston stirling engine, two-stage biomass pellet burner, cooling and starting sub-systems. The engine is designed for a life over 40,000 hours and life tests on going. Its efficiency is around 23%, and will rise over 85% in cogeneration applications.[31]
- A Small-scale CHP Pilot Plant based on a 35 kWel Hermetic Four Cylinder Stirling Engine for Biomass Fuels was designed and erected in cooperation between Technical University of Denmark and MAWERA Holzfeuerungsanlagen GesmbH in Austria.[33]

- NASA has made many researches of using stirling engine applications and many more stirling engines have been designed by manufacturers with lower power output.

### 3.3.1.3. Components

Based on the experience of smooth running of a small-scale CHP pilot plant in Austria done in cooperation between Technical University of Denmark and MAWERA Holzfeuerungsanlagen GesmbH causes this stirling engine combustion plant would be suitable to be used for this research. The following information about technical specifications and operational experience has been collected from Biedermann et. al., 2004.[33] The nominal electric power output of the plant is 35 kW$_{el}$ and the nominal thermal output amounts to 220 kW$_{th}$. The plant operates fully automatically. The plant has run for more than 5000 hours on that time using wood chips as fuel with very satisfactory results. In this research only electrical power output would be needed not in a CHP scheme and as the fuel of the combustion, straws and husks of the waste rice milling industry would be used.

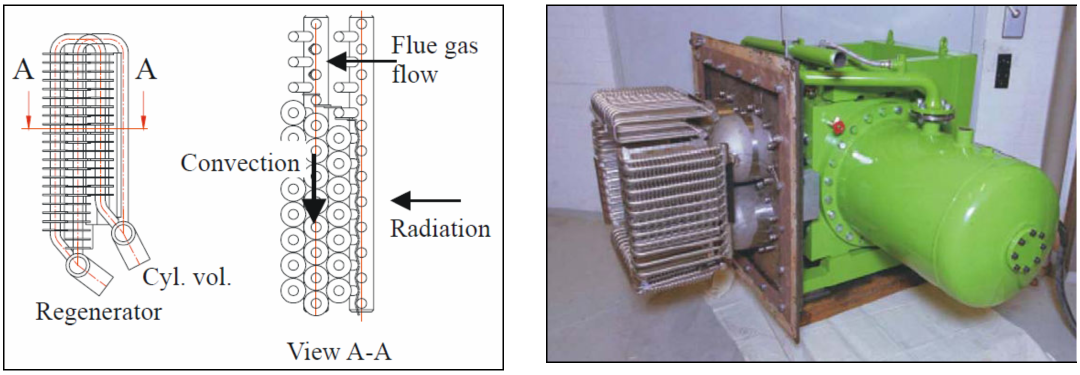


Figure 3.9. (a) Sketch of hot heat exchanger
(b) 35 kW stirling engine before installation in the furnace

The components and other important information that CHP plant used will be adopted for this research for generating electricity. They are can be summarized as follow:

- The heat input from fuel combustion is transferred to the working gas through a hot heat exchanger at high temperature, typically between 680 $^{o}$C to 780 $^{o}$C. The heat that is not converted into work on the shaft is rejected to the cooling water in a cold heat exchanger at 25 °C to 75 °C.

- The temperature of the combustion air needs to be preheated with the flue gas leaving the hot heat exchanger by means of an air preheater to obtain the efficiency. In this stage, the combustion air is raised to 500 °C – 600 °C, resulting in very high temperatures in the combustion chamber.
- Helium is used as working gas at a maximum mean pressure of 4.5 MPa.
- The engine has four cylinders arranged in a square with the cylinders parallel to each other.
- The four hot exchangers (one for each cylinder) are designed as panels forming a square combustion chamber, where radiation from the combustion is transferred directly to the panels.
- The engine is designed as hermetically sealed unit.
- The built-in asynchronous generator which is also used as starter motor, has 6 poles corresponding to an engine speed of approximately 1000 rpm when coupled directly to the power grid (50 Hz AC).
- Specification of the 35 kW$_{el}$ Stirling engine

| | |
|---|---|
| Nominal electric power (kW) | 35 |
| Bore (mm) | 142 |
| Stroke (mm) | 76 |
| No. of Cylinders | 4 |
| Speed (rpm) | 1010 |
| Mean pressure (Mpa) | 4.5 |
| Working gas | Helium |
| Temperature of heat exchanger (°C) | 750 |
| Engine weight (kg) | 1600 |

- Using several bearings with a larger type to improve the lifetime of the engine.
- The hot heat exchanger consists of 23 tubes with an outside diameter of 13.7 mm. The tubes are U-formed connecting the cylinder manifold with the regenerator manifold, as shown in Figure 3.9a. It has 12 half-tubes for the radiation part while the remaining 36 half-tubes are used for convective heat transfer. Fins are used for enhancing the heat transfer area.
- The furnace is equipped with underfeed stoker technology. The stirling engine is mounted in horizontal position downstream of the secondary combustion chamber for convenient maintenance (figure 3.10). The air preheater and economizer are placed on top of the furnace in order to achieve a compact

design of the plant. To remove fly ash particles from the hot gas heat exchanger, a pneumatic and fully automatic cleaning system was developed and installed.

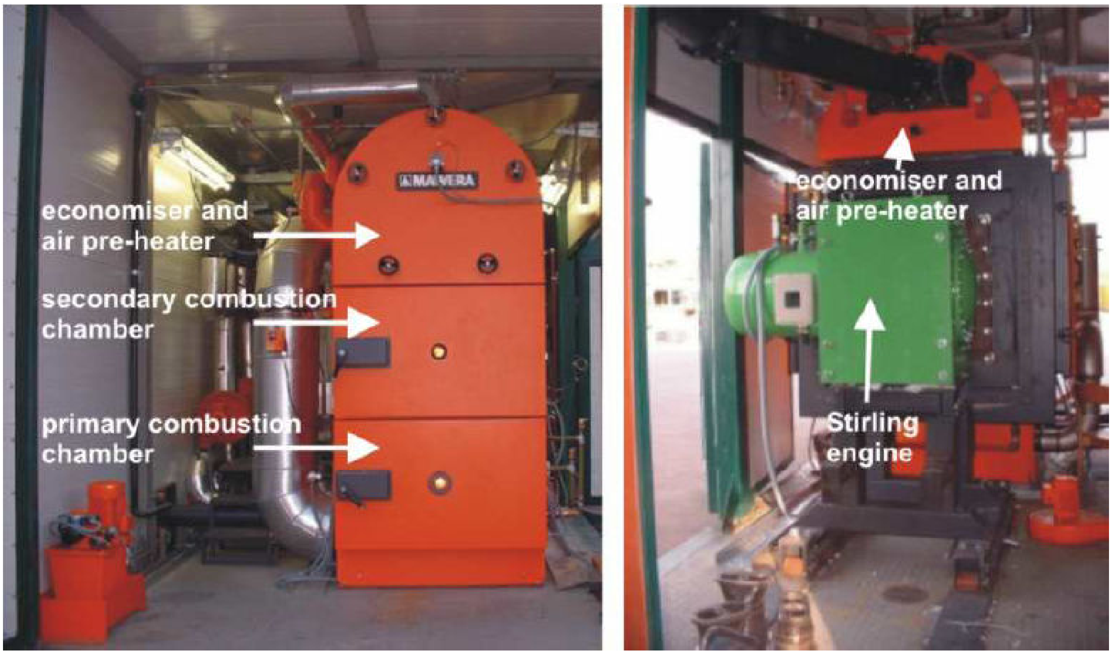


Figure 3.10. CHP Pilot plant with 35 $kW_{el}$ stirling engine

- Average result of test runs performed at the 35 kWel pilot plant compared to design targets is shown in table 3.10

Table 3.10. Test run of 35 $kW_{el}$ stirling engine

| | Design target | Obtained during test runs |
|---|---|---|
| Temperature of the preheated air (°C) | 550 | 360 |
| Temperature of the cooling water at Stirling cooler inlet (°C) | 55 | 61 |
| Electric power output (kW) | 35 | 31 |
| Thermal power output-Stirling engine (kW) | 105 | 124 |
| Thermal power output-CHP plant (kW) | 215 | 272 |
| Fuel power input (kW) | 291 | 337 |
| Fuel consumption (w.b.)<br>(water content approx. 30 wt%) (kg/h) | 85 | 96 |
| Electric efficiency-Stirling Engine (%) | 25 | 20 |
| Overall electric efficiency-CHP plant (%) | 12 | 9.2 |
| Overal efficiency-CHP plant (%) | 85.9 | 90 |

- With more than 5,000 hours of successful operation, this plant can be considered as a role to utilize biomass combustion using stirling engines.

# 4. Proposed Hybrid Renewable Energy System (HRES)

In this chapter, the combination of renewable energy technologies for generating electricity that suitable to Ikem village will be discussed. The load demand of Ikem and the potential renewable energy resources have been already known as shown in previous chapter. The suitable renewable energy technologies that can be applied to that village are hydropower, biomass combustion, and photovoltaic. Since the actual information about the river is not known then the hybrid renewable energy system consists of photovoltaic with battery storage and biomass combustion. This HRES would be connected to the grid that available in Ikem but the grid is weak. The schematic of the system can be seen as Figure 4.1.

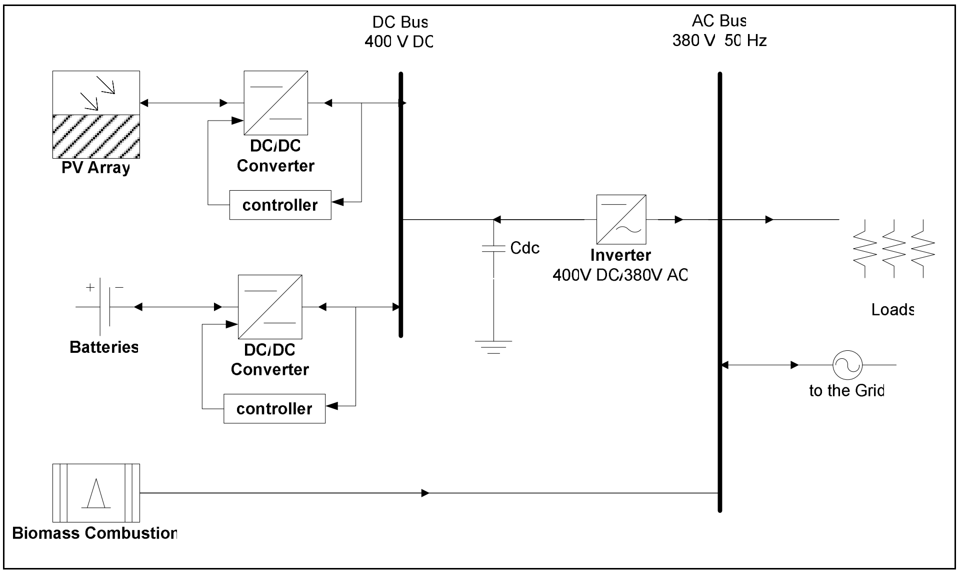


Figure 4.1. Topology of the HRES

The proposed hybrid renewable energy consist of:

1. PV array:
    a. Type: 24 V; 160 Wp of multi-crystalline silicon cells
    b. Number of modules: 1056
    c. Total maximum power output: 170 kWp
2. Biomass combustion:
    a. Type: 3 x 35 kW Stirling engines
    b. Total maximum power: 105 kW

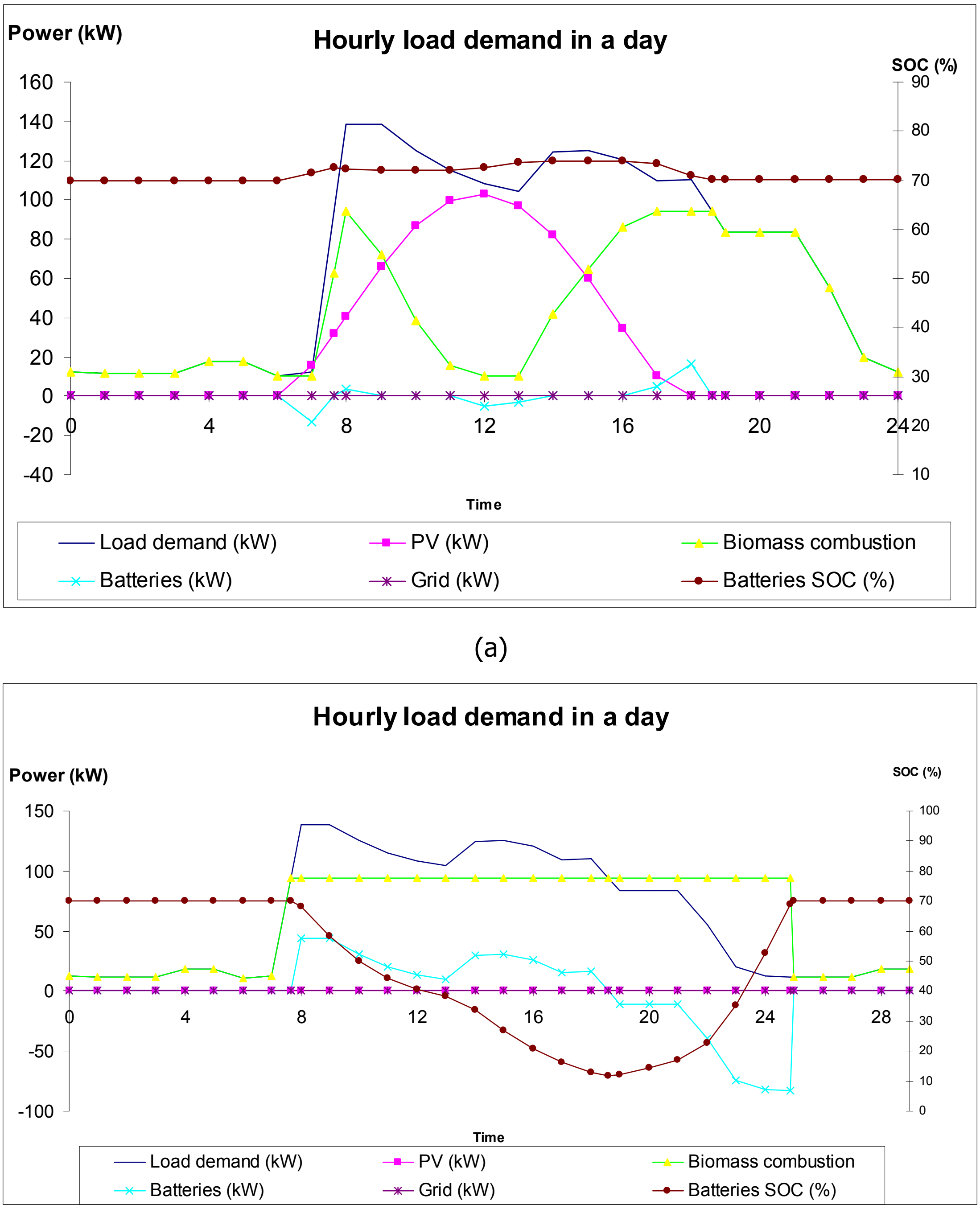
3. Batteries:
    a. Type: 12 Volt, 33 Ah of valve regulated lead acid battery
    b. Number of batteries: 928
    c. Total maximum capacity: 370 kWh

## 4.1. Energy calculation

Figure 4.1 shows the systems starting from the generation, transportation and distribution of the electricity to consumers. The capacity size of each renewable technology is derived by calculating the load demand that should be covered by power generators. Ikem's load demand characteristic of has been detailed discussed in the previous chapter. Figure 4.2(a) shows the Ikem's load demand profile and the composition of each renewable energy technology that will supply the load. This calculation shown in figure 4.2(a) is used to determine the PV capacity. The total energy supplied by the PV array is 700 kWh.

The PV generates electric power as function of solar irradiances and the output cannot be controlled. The Biomass combustion output can be controlled thus the fluctuation of the biomass combustion power output will be the result of load demand subtracted by the PV power output. Power output of biomass combustion will always be controlled to fit between the load and the power generation but when the power output of the biomass combustion reaches its minimum or maximum power then the excess and the deficit of power should be compensate to the batteries or grid.

Another composition of power output profile is shown in Figure 4.2(b). This Figure shows the system response when there is no sunshine in a day. This scheme is used to calculate the capacity of the batteries. The total energy supplied by the PV array is 260 kWh.



(a)

(b)

Figure 4.2. Load demand and power generation scheme

## 4.2. Sizing of each components

After knowing the load demand then sizing of the power generation of each renewable energy technology can be made. This HRES consists of biomass combustion, PV array and batteries. In sizing each technology has different method.

For biomass combustion the capacity is justified based on the maximum power will be generated. For PV array, the capacity of PV will be decided by calculating the minimum power of the PV that have to be able to supply the load together with biomass in the whole 24 hours. The PV and biomass power will supply the load and will not drawn power from the grid or batteries. The capacity of batteries is also based on how much battery will supply energy for how many days. These days are also called as autonomy days that the system in emergency condition will be safely supplied only by the batteries power.

Steps in sizing of each renewable technology are shown as follow:

- Firstly, decide the capacity of biomass combustion. The biomass combustion consists of 3 units of 35 kW biomass stirling engines, that will produce 105 kW of maximum power. These engines operate between 10% up to 90% of its maximum output and will only shut down for maintenance purposes.
- Secondly, the capacity of PV will be decided by calculating the minimum power of the PV that have to be able to supply the load together with biomass in the whole 24 hours. The PV and biomass power will supply the load and will not drawn power from the grid or batteries.
- Finally, the batteries capacity is the difference between the energy demand and energy output of the biomass without influence of PV at all. Therefore the batteries and biomass can supply the load whenever there is no sun for fully a day.

The resume of the calculation can be seen in table 4.1.

Table 4.1. resume of energy calculation

| | Maximum Output (kW) | Energy (kWh) | Power/Capacity |
|---|---|---|---|
| Load demand | 140 | 1,800 | - |
| Biomass | 105 | | 105 kW |
| PV | | 700 | 700 kWh |
| Batteries | | 260 | 260 kWh |

### 4.2.1. Biomass combustion capacity and resources availability

The biomass combustion will use 3 stirling engines with 35 kW each therefore they could produce 105 kW. The capacity of stirling engines would be able to supply 1.2 MWh of energy load demand.

The most important thing of biomass combustion in this research is the availability of the biomass resources. The fuel of biomass combustion is straws and husks that is by-product of rice milling industry. The calculation of the biomass resources in this case straws and husks is shown as follow.

Parameter should be known:

- The detailed energy content of husks and straws has been shown in table 2.3. For further calculation the low heating value (LHV) will be used.
    - Rice husks: 15,270 J/g
    - Rice straws: 15,340 J/g
    - Average : 15,305 J/g
- Every 1 $m^2$ area of rice production will produce 0.125 kg of husks and 0.5 kg of straws. [35] It means ratio production of husks : straws = 1 : 4.
- Biomass combustion using stirling engine generator with overall efficiency approximately 12 %.

Table 4.2. Calculation of biomass requirement

| | Daily | Yearly |
|---|---|---|
| Energy demand/day (MWh) | 1.2 | 420 |
| Engine efficiency = 12 % | 0.12 | |
| Energy input/day (MWh) | 10 | |
| Energy input/day (MJ) => 1 MWh = 3600 MJ | 35000 | |
| Average LHV of husks/straws (J/g) | 15,300 | |
| Husks/straws needed (tons) | 2 | 800 |
| 1 m2 = 0.125 kg of husks + 0.5 kg straws | | |
| Production ratio (kg/m2) | 0.6 | |
| Area production (ha) | 0.5 | 130 |

Considering those parameters, the calculation can be made as shown in table 4.2. The amount of biomass resources, which are husks or straws, needed for a year is 800 tons. This amount can be achieved by 130 hectares area of rice farming and it is feasible for Ikem since most of the village area is used for agriculture and 80% of inhabitants work as a farmer[36]. Assumed that the harvest period happened twice in a year therefore the requirement of rice farming area needed only half of the previous value. For some types of rice, it is possible to be harvested three times in a year that will much reduce the requirement of rice farming area.

### 4.2.2. Sizing of PV array

Sizing of a PV system means determining how much energy is required to run the system and how many PV modules are needed to generate it. The energy yield of a PV system depends on the type of PV modules, the characteristics of a PV inverter, the orientation of the modules, and meteorological conditions. In sizing PV array and batteries the method used is based on Miro Zeman. [37]

Sizing of a PV array and batteries can be calculated using the following design rules.

- Determine the total load current and operational time
- Add system losses
- Determine the solar irradiation in daily equivalent sun hours (ESH)
- Determine total solar array current requirements
- Determine optimum module arrangement for solar array
- Determine battery size for recommended reserve time

1. Determine the total load current and operational time

   Before starting determining the current requirements of loads of a PV system the nominal operational voltage of the PV system has to be decided. When knowing the voltage, the next step is to express the daily energy requirements of loads in terms of current and average operational time expressed in Ampere-hours [Ah]. For AC loads the energy use has to be expressed in the DC energy requirement since PV modules generate DC electricity. The DC equivalent of the energy use of an AC load is determined by dividing the AC load energy use by the efficiency of an inverter. By dividing the DC energy requirement by the nominal PV system voltage the Ah is determined.
2. Add system losses

   Some components of the PV system, such as charge regulators and batteries use energy to perform their functions. The system components has its losses since they need energy to operate where the energy used by the components denote as system energy losses. Therefore, the total energy requirements of loads, which were determined in step 1, are increase by a factor in order to compensate for the system losses.

3. Determining the solar irradiation in daily equivalent sun hours (ESS)

   How much energy a PV module delivers depends on several factors, such as local weather patters, seasonal changes, and installation of modules. PV modules should be installed at the correct 'tilt-angle' in order to achieve best year-round performance. It is also important to know whether a PV system is expected to be used all-year round or only during a certain period of a year. The energy produced in winter is much less than yearly average and in the summer months the generated energy can be more that the average.

   In the PV language, 1 equivalent sun means the solar irradiance of 1000 W/m$^2$. This value corresponds to the standard, at which the performance of solar cells and modules is determined. The rated parameters of modules are determined at solar irradiance of 1 sun.

   In Ikem, the average annual solar radiation is 5.02 kWh/m$^2$ per day that already shown in table 2.1. One sun delivers 1000 W/m$^2$ that is equal to 1 kW/m$^2$. It means the equivalent sun hours of Ikem is 5 h/day .

4. Determine total solar array current requirements

   The current that has to be generated by the solar array is determined by dividing the total DC energy requirement of the PV system including loads and system losses (calculated in step 2 and expressed in Ah) by the daily equivalent sun hours (determined in step 3).

5. Determine optimum module arrangement for solar array

   Usually the PV module producers manufacture a whole series of modules that differ in the output power. The PV module that will be used in this research is silicon nitride multi-crystalline silicon cells, BP 3160 that produced by bp solar and the manufacturer data sheet could be seen in table 3.5. The optimum arrangement of modules is the one that will provide the total solar array current (as determined in step 4) with the minimum number of modules. Modules can be connected in series of in parallel to form an array. When modules are connected in series, the nominal voltage of the PV system is increased, while the parallel connection of modules results in a higher current in the PV system.

   The number of modules in parallel is calculated by dividing the total current required from the solar array (determined in step 4) by the current generated by module at peak power (rated current in the specification sheet). The number of modules in series is determined by dividing the nominal PV system voltage with the nominal module voltage (in the specification sheet under configuration). The total number of modules is the product of the number of modules required in parallel and the number required in series.

This method is used for calculating roughly estimation of PV array sizing. In this research, modification of this method is made since the hourly load demand and the solar irradiance are known to make estimation more accurate. The total energy supplied by PV shown in figure 4.2(a). Total modules required are 1056 and need 1200 m2 of area for their location. The detailed calculation can be seen in table 4.3.

Table 4.3 PV array sizing

| | | Parameter | Calculation |
|---|---|---|---|
| 1 | Energy supplied by the PV | | |
| | PV max output in AC (kW) | 100 | |
| | Efficiency of DC/DC converter | | 0.95 |
| | Efficiency of inverter | | 0.95 |
| | PV max output in DC (kW) | 114 | |
| | Nominal DC Voltage (V) | | 24 |
| | Current in DC (kA) | 4.7 | |
| 2 | Add system losses | | |
| | System losses (0.1%) | | 1.01 |
| | Current in DC (kA) | 4.8 | |
| 3 | Determine total solar array current requirements | | |
| | required total current (kA) | 4.8 | |
| 4 | Determine optimum module arrangement for solar array | | |
| | Current at Pmax ($I_{mp}$) of BP3160 (A) | | 4.55 |
| | Nr of modules in parallel | 1056 | |
| | Module voltage (V) | | 24 |
| | Nr of modules in series | 1 | |
| | Total modules | 1056 | |
| | Area of each module ($m^2$) | | 1.125 |
| | Total area needed ($m^2$) | 1200 | |
| | PV module Maximum output (Wp) | | 160 |
| | PV array Maximum Output (kWp) | 170 | |

### 4.2.3. Sizing of Batteries

Batteries in this system will only operate when there is excess or deficit power of power output from PV and biomass. In normal condition the amount of excess or deficit power is relatively small that is around 20 kWH for charging and discharging in a day that can be seen in figure 4.2.(a). Nevertheless for calculating the total capacity of the batteries the system is assumed that not connected to the grid and the sun is not available for that day. In that condition the power is provided only by the biomass and the batteries. This will provide the system reliability in the worst case. This condition can be seen in figure 4.2.(b) that shows how the batteries charging and discharging in completely one cycle. The amount energy of charge and discharge in that condition is 260 kWh. Therefore the total battery needed is 928. The detailed calculation can be seen in table 4.4.

Table 4.4. Batteries sizing calculation

| | | Parameter | Calculation |
|---|---|---|---|
| 1 | Determine the total load current and operational time | | |
| | Load of Ikem in AC (kWh) | 260 | |
| | Efficiency of DC/DC converter | | 0.95 |
| | Efficiency of inverter | | 0.95 |
| | Load in DC (kWh) | 291 | |
| | Nominal DC Voltage (V) | | 24 |
| | Capacity in DC (kAh) | 90.8 | |
| 2 | Add system losses | | |
| | System losses (20%) | | 1.2 |
| | Capacity in DC (kAh) | 12 | |
| 3 | Determine battery size for 1 day reserve time | | |
| | total DC requirements (kAh) | 12 | |
| | reserve time capacity (day) | | 1 |
| | Battery capacity required (kAh) | 12 | |
| | operate the battery for a safe operation | | 0.8 |
| | minimal battery capacity (kAh) | 15 | |
| | Nominal DC Voltage (V) | | 24 |
| 4 | Using Panasonic LC-R1233P | | |
| | Battery voltage (V) | | 12 |
| | Battery capacity (Ah) | | 33 |
| | Nr. of bateries in series | 2 | |
| | Nr. of bateries in parallel | 464 | |
| | Total batteries needed | 928 | |
| | Area of each battery 195.6mm x 130 mm ($m^2$) | | 0.025 |
| | Total area needed ($m^2$) | 24 | |
| | Energy maximum of batteries output (kWh) | 370 | |

## 4.3. Physical location

For the location of power generator of each renewable energy technology will be systematically feasible and low cost. The biomass combustion will be built integrated with rice milling industry since the fuel comes from waste of rice milling industry. The

PV array will be placed at the roofs of public building that is safe and will not get shadowed. The batteries should be placed in the place that the temperature is quite clement to improve their lifetime. The possible location of PV modules and the battery as shown in table 4.5.

Table 4.5. Possible location of PV modules and batteries

| | | PV/building | | Batteries | |
|---|---|---|---|---|---|
| | Quantity | PV modules | Area (m2) | Batteries | Area (m2) |
| Industri | 1 | 100 | 120 | - | - |
| Local govt. secretariat | 1 | 296 | 350 | 928 | 24 |
| District hospital | 1 | 100 | 120 | - | - |
| Secondary schools | 2 | 70 | 80 | - | - |
| Primary schools | 6 | 70 | 80 | - | - |
| Total | | 1056 | 1230 | 928 | 24 |

# 5. Simulation

The topology and the size of each renewable power generators already discussed in previous chapter. The performance of the system is investigated by a simulation using matlab. Firstly, the renewable energy power generators are designed and then put them to the power system model to check whether the power supply meets the load demand. The schematic of the hybrid renewable energy system is shown in figure 5.1.

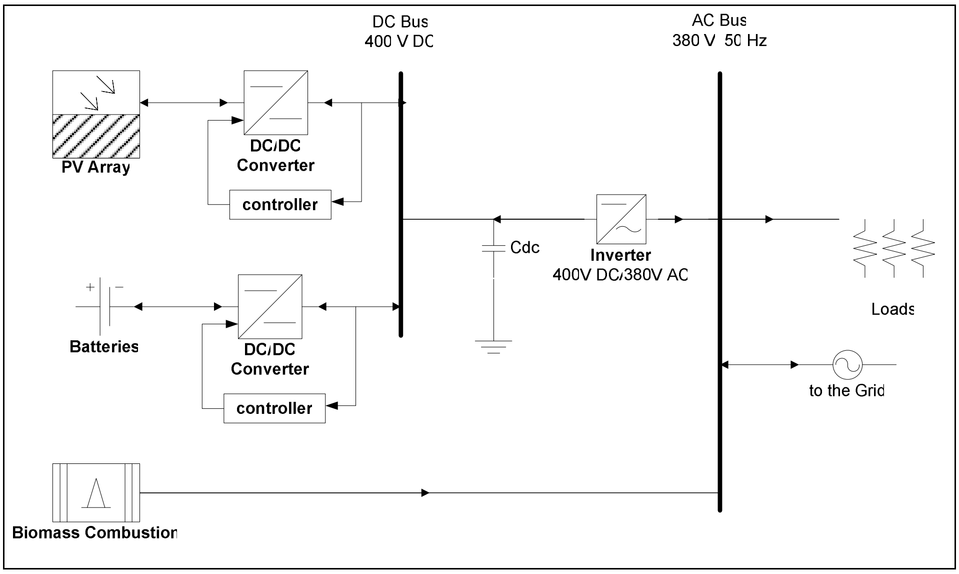


Figure 5.1. The simulation model

The HRES consists of PV array, batteries, biomass combustion, inverter, load and controllers. Some of the HRES components are further explained and result of the simulation also provided.

## 5.1. Model of HRES components

The models that will be further explained is the photovoltaic module, the battery, and the working principal of the controller. The biomass combustion is represented by using a synchronous generator.

### 5.1.1. Photovoltaic

The model of the PV module is designed based on the mathematical model developed in Riso National Laboratory. [38] The PV module structure using matlab simulink is shown in figure 5.2.

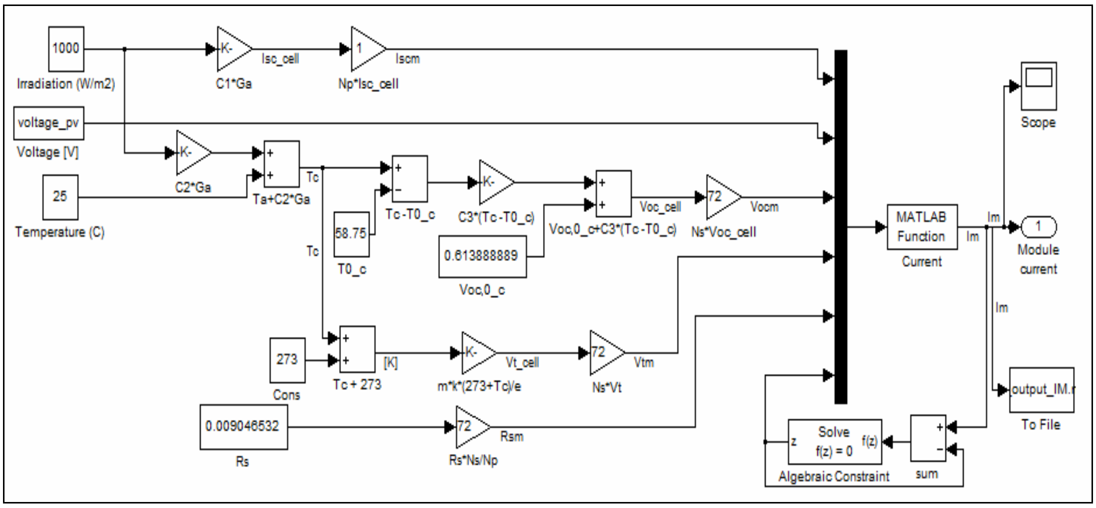


Figure 5.2. PV module model

The step sof designing the PV module model is shown as follow.

MODULE DATA FOR STANDARD CONDITIONS

$$P^M_{\max,0}\text{, } I^M_{SC,0}\text{,} V^M_{OC,0}\text{, } N_{SM}\text{, } N_{PM} \tag{5.1}$$

CELL PARAMETERS FOR STANDARD CONDITIONS

$$P^C_{\max,0} = P^M_{\max,0} / (N_{SM}, N_{PM})$$

$$V^C_{OC,0} = V^M_{OC,0} / N_{SM}$$

$$I^C_{SC,0} = I^M_{SC,0} / N_{PM} \tag{5.2}$$

$$V^{\,C}_{t,0} = mkT^C / e$$

$$v_{OC,0} = V^C_{OC,0} / V^{\,C}_{t,0}$$

$$FF = (v_{OC,0} - \ln(v_{OC,0} + 0.72)) / (v_{OC,0} + 1)$$

$$FF_0 = P^C_{\max,0} / (V^C_{OC,0} I^C_{OC,0})$$

$$r_s = 1 - FF / FF_0$$

$$R^C_S = r_S V^C_{OC,0} / I^C_{SC,0}$$

CELL PARAMETERS FOR OPERATING CONDITIONS $\boldsymbol{(V^M, T_a, G_a)}$

$$C_1 = I^C_{SC,0} / G_{a,0}$$

$$I^C_{SC} = C_1 G_a$$

$$T^C = T_a + C_2 G_a \tag{5.3}$$

$$V^C_{OC} = V^C_{OC,0} + C_3 (T^C - T^C_0)$$

$$V^C_t = mk(273 + T^c) / e$$

MODULE CURRENT FOR OPERATING CONDITIONS

$$I^M = N_{PM} I^C_{SC} [1 - \exp((V^M - N_{SM} V^C_{OC} + I^M R^C_S N_{SM} / N_{PM}) / N_{SM} V^C_t))] \tag{5.4}$$

Where the symbols are:

| | | |
|---|---|---|
| $I_{sc}$ | Short-circuit current | [A] |
| $V_{oc}$ | Open-circuit voltage | [V] |
| $V_t$ | Thermal voltage | [V] |
| $e$ | Electron charge, $e = 1.602 \cdot 10^{-19}$ | [C] |
| $I_{ph}$ | Photocurrent | [A] |
| $I_D$ | Diode current | [A] |
| $k$ | Boltzmann constant, $k = 1.381 \cdot 10^{-23}$ | [J/K] |
| $T_a$ | Ambient temperature | [°C] |
| $T_c$ | Cell temperature | [°C] |
| $G_a$ | Irradiation | [W/m$^2$] |

This model represents a BP-3160 PV module produced by BP solar. [39] All the constants within the model in figure 5.2 is derived from manufacturer data sheet as shown in table 5.1.

Table 5.1. BP 3160 Characteristics

| Characteristics of BP 3160 | Value |
|---|---|
| Nominal voltage [V] | 24 |
| Maximum power ($P_{max}$) [W] | 160 |
| Voltage at Pmax ($V_{mp}$) [V] | 35.1 |
| Current at Pmax ($I_{mp}$) [A] | 4.55 |
| Warranted minimum $P_{max}$ [W] | 152 |
| Short-circuit current ($I_{sc}$) [A] | 4.8 |
| Open-circuit voltage ($V_{oc}$) [V] | 44.2 |
| Temperature coefficient of $I_{sc}$ [%/°C] | 0.065±0.015 |
| Temperature coefficient of $V_{oc}$ [mV/°C] | -(160±20) |
| Temperature coefficient of power [%/°C] | -(0.5±0.05) |
| NOCT (Air 20°C; Sun 0.8 kW/$m^2$ ; wind 1 m/s) [°C] | 47±2 |
| Number of Solar Cells (125mm x 125mm) | 72 |
| Matrix connected in series | 6x12 |

To validate the model comparing I-V curves from the manufacturer and model output has been done as shown in the figure 5.3. It shows that the model output has almost the same shape with the manufacturer data sheet.

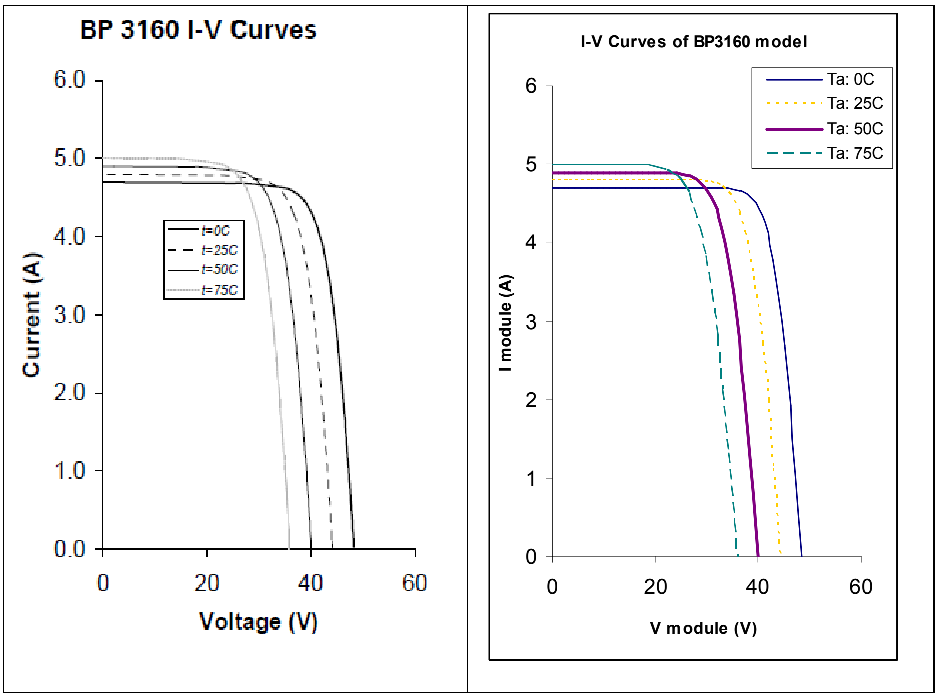


Figure 5.3. I-V curves (a) from manufacturer data sheet (b) from simulation

When the irradiations increase, the temperatures also increase following this formula: $\Delta Ga = 0.08\%/\Delta C$.

The higher the temperature, the lower the power output will be produced, that is shown in figure 5.4.

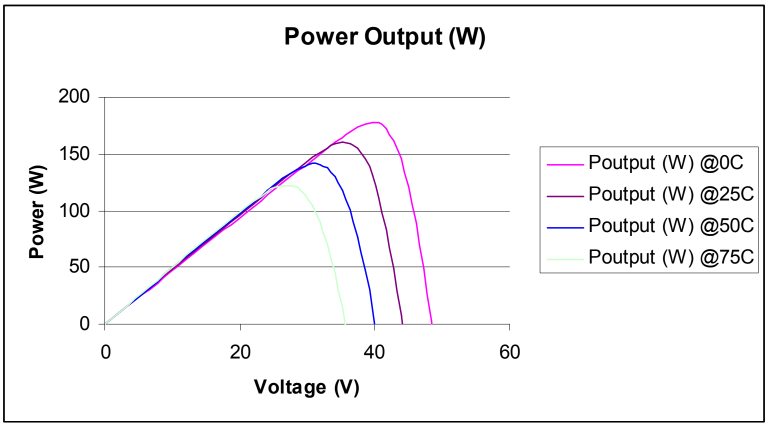


Figure 5.4. Power output

The average efficiency of the PV module is 14 %, this value is simulated by the model and the result as shown in table 5.2. The efficiency is calculated by using equation 5.5.

$$\eta = \frac{P_{\max}}{P_{in}} = \frac{I_{\max} V_{\max}}{A G_a} \tag{5.5}$$

Table 5.2. The module efficiency resulted from simulation

| I max (A) | V max (V) | A (m2) | Ga (W/m2) | Efficiency |
|---|---|---|---|---|
| 2.3 | 38.4 | 1.125 | 500 | 16% |
| 4.4 | 36 | 1.125 | 1000 | 14% |
| 6.7 | 31.2 | 1.125 | 1500 | 12% |
| Average | | | | 14% |

Fill factor is the ratio of the maximum power that could be delivered to the load and product of $I_{SC}$ and $V_{OC}$. Fill factor of the PV module is 73%, it means the PV module has a good cell quality since it is higher than 70%. The calculation of fill factor is based on equation 5.6. and the detailed result is shown in table 5.3.

$$FF = \frac{P_{\max}}{V_{oc} I_{sc}} = \frac{V_{\max} I_{\max}}{V_{oc} I_{sc}} \tag{5.6}$$

Table 5.3. The module fill factor resulted from simulation

| Ga (W/m2) | I max (A) | V max (V) | Isc (A) | Voc (V) | FF |
|---|---|---|---|---|---|
| 500 | 2.3 | 38.4 | 2.4 | 48 | 78% |
| 1000 | 4.4 | 36 | 4.8 | 45.6 | 73% |
| 1500 | 6.7 | 31.2 | 7.2 | 43.2 | 67% |
| Average | | | | | 73% |

The figure 5.5. shows that the power output will be higher whenever the irradiation increases. The simulation is made by changing the input irradiation and keeps the temperature constant.

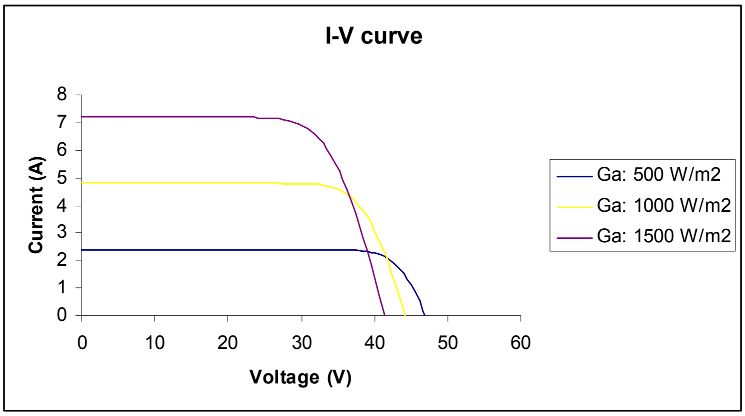


Figure 5.5. Influence of irradiation

To know influence of the temperature to the power output is shown in figure 5.6. The higher the temperature, the lower the power output will produce.

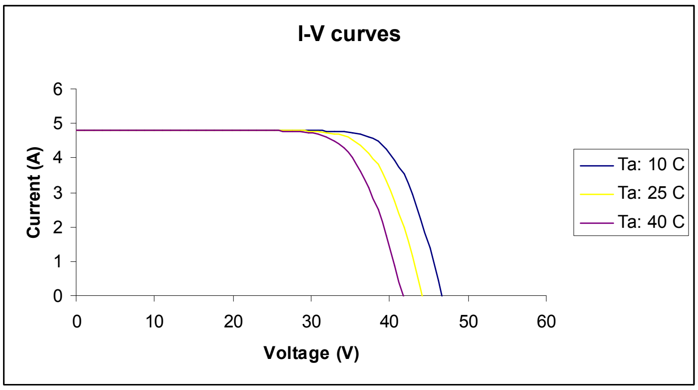


Figure 5.6. Influence of temperature

The figure 5.7. shows how the I-V curves characteristics in terms of modules in series or parallel. To double the voltage, the PV can be series and to double the current the PV should be connected in parallel.

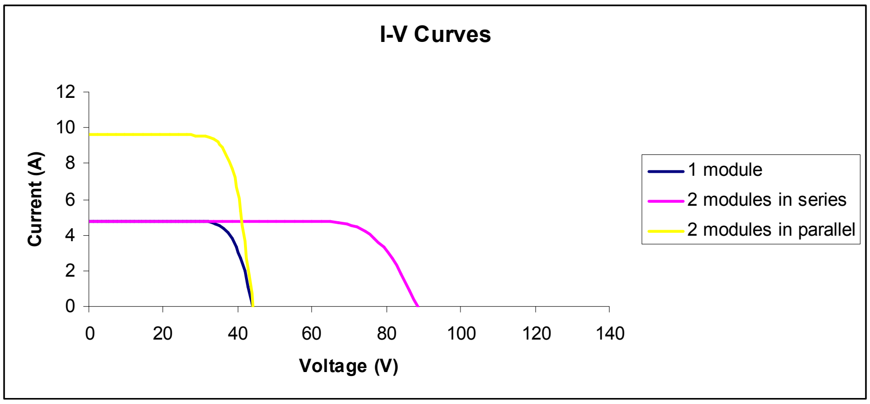


Figure 5.7. Modules in series and parallel

## 5.1.2. Batteries

The battery model provided in matlab SimPowerSystems is used for this research which is shown in figure 5.8. [40]

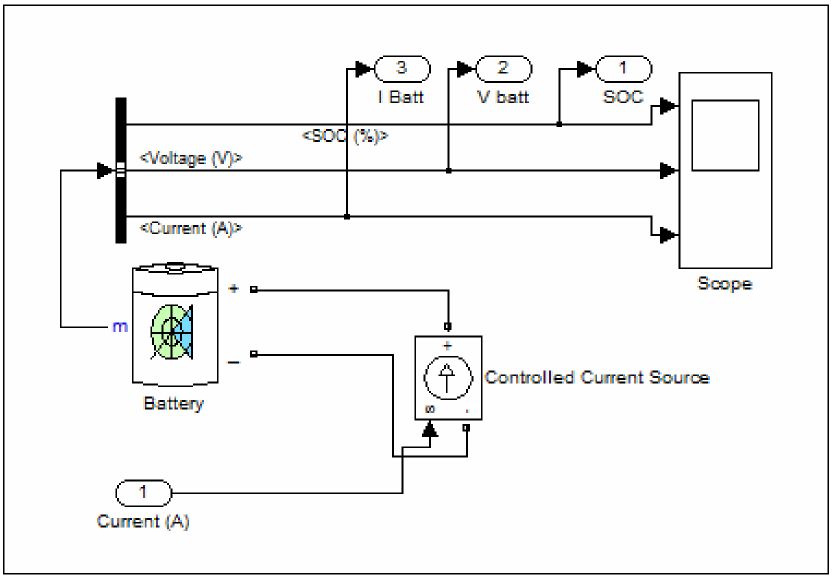


Figure 5.8. The Battery model

The Battery block implements a generic model parameterized to represent most popular types of rechargeable batteries. The equivalent circuit of the battery is shown in figure 5.9.

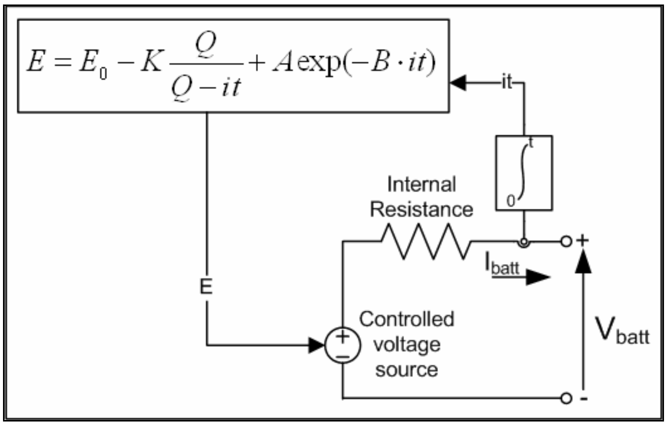


Figure 5.9. The equivalent circuit of Battery model

Where:

E = No load voltage (V)

E0 = Constant voltage (V)

K = Polarization voltage (V)

Q = Battery capacity (Ah)

A = Exponential voltage (V)

B = Exponential capacity (Ah)

The model has been made to represent the characteristics of the lead acid battery, which is Panasonic LC-R1233P that used as reference for this research. Specifications of the Panasonic LC-R1233P are shown as follow:

- Nominal voltage: 12 V
- Rated capacity (20 hour rate): 33 Ah
- Duration of discharge vs discharge current could be seen in figure 5.10.

Using block parameters, the battery model can be set to a lead-acid battery as proposed to this research and the parameter related to it can be easily chosen. The parameter chosen is shown in figure 5.11.

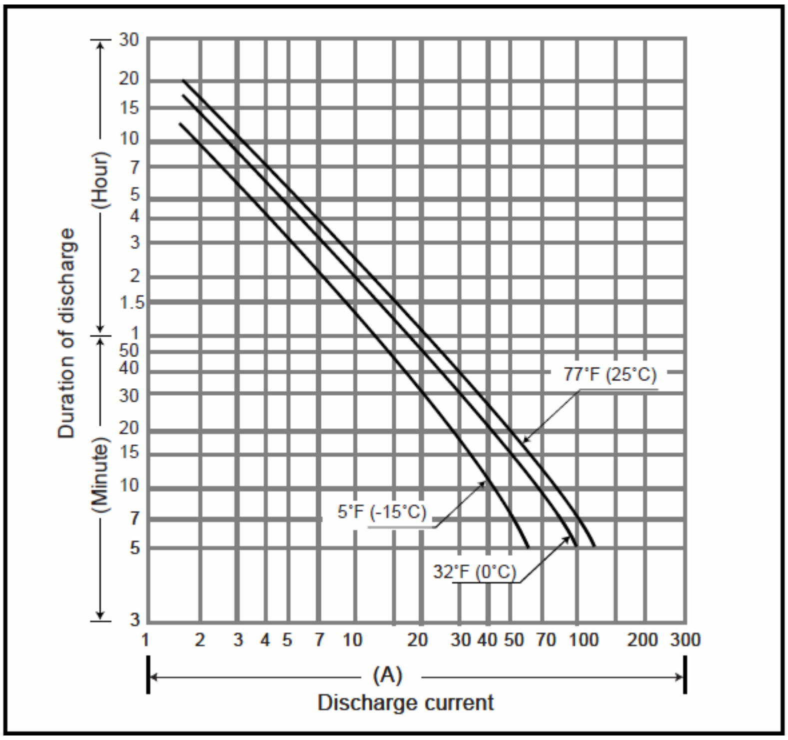
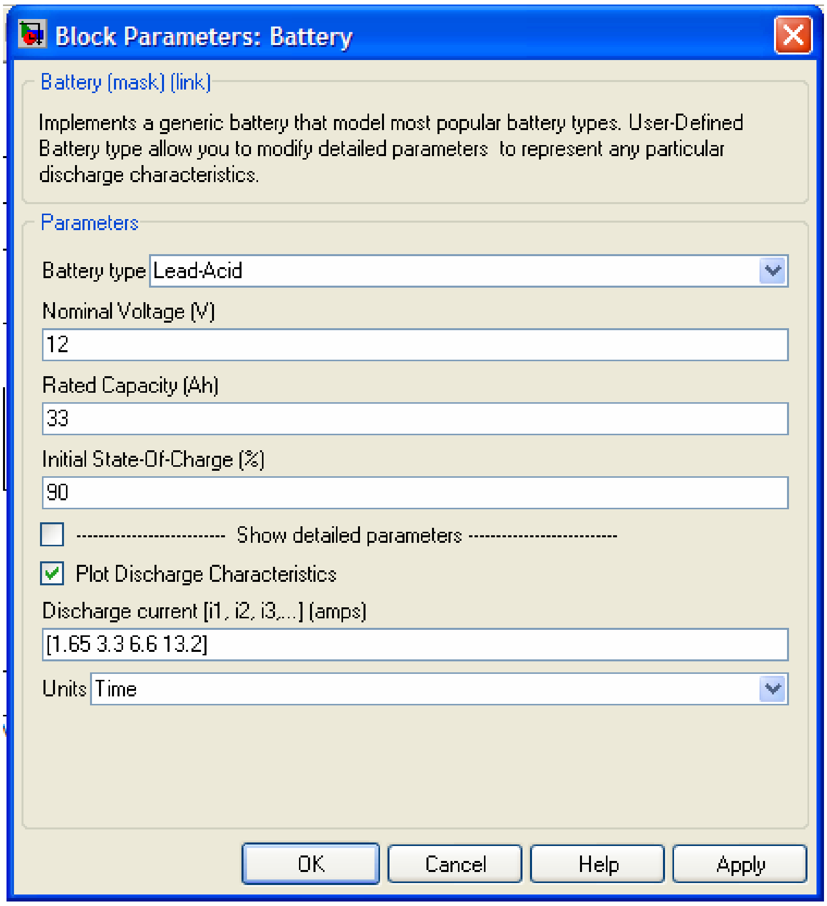


Figure 5.10. Duration of discharge vs discharge [41]


**Block Parameters: Battery**

Battery (mask) (link)

Implements a generic battery that model most popular battery types. User-Defined Battery type allow you to modify detailed parameters to represent any particular discharge characteristics.

Parameters

Battery type Lead-Acid

Nominal Voltage (V)
12

Rated Capacity (Ah)
33

Initial State-Of-Charge (%)
90

☐ ------------------------ Show detailed parameters ------------------------

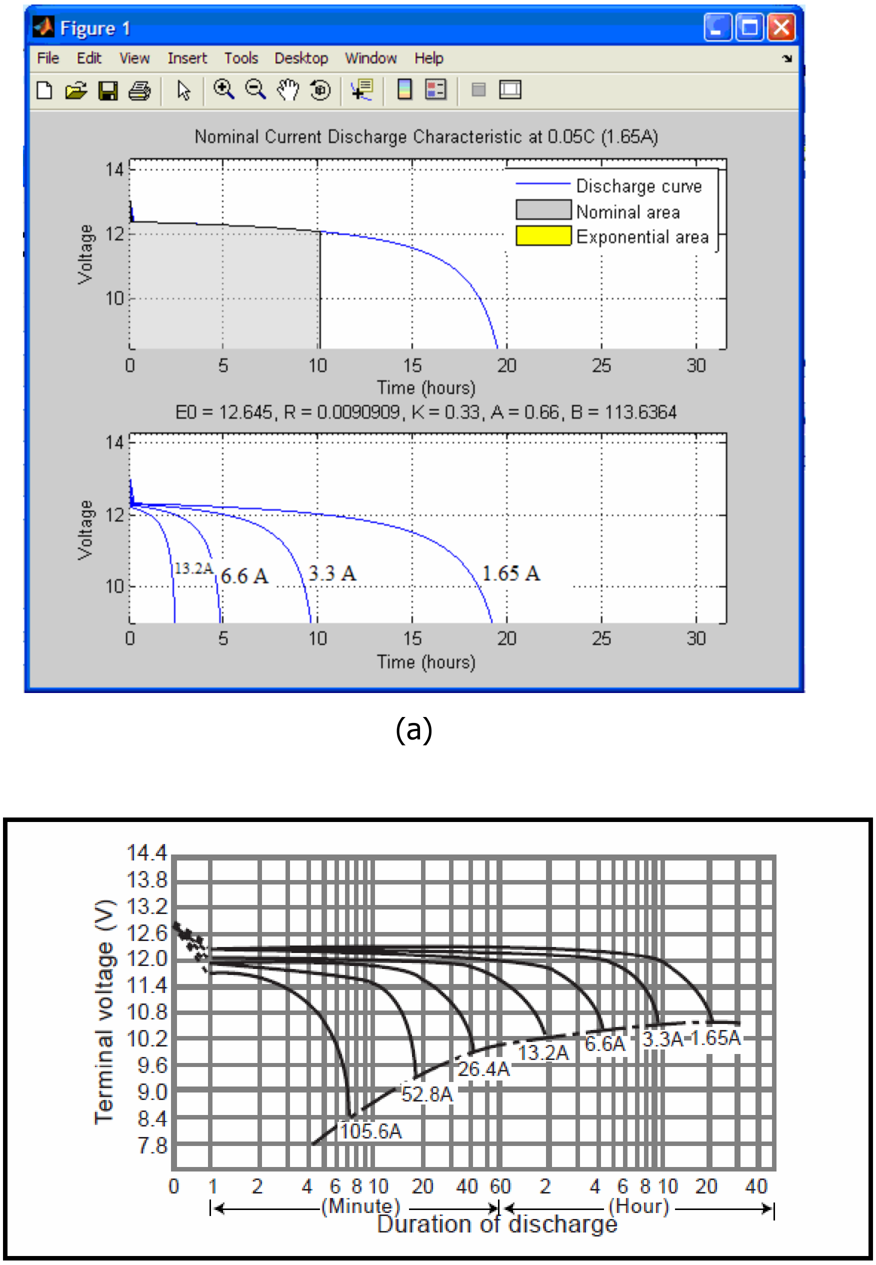
☑ Plot Discharge Characteristics

Discharge current [i1, i2, i3,...] (amps)
[1.65 3.3 6.6 13.2]

Units Time

Figure 5.11. Block parameter of the battery

Then the validation is made to the battery model and the result is shown in figure 5.12. The curves produced between the simulation and manufacturer data sheet show the same characteristics therefore this model is suitable to be used.



(a)

(b)

Figure 5.12. Nominal Current discharge characteristics

(a) Simulation

(b) manufacturer data sheet at 25 $^0$C

The battery is charging, it means the battery current is negative while the current is positive it means the battery is discharging. The output of the battery scope shows that convention which is shown in figure 5.13.

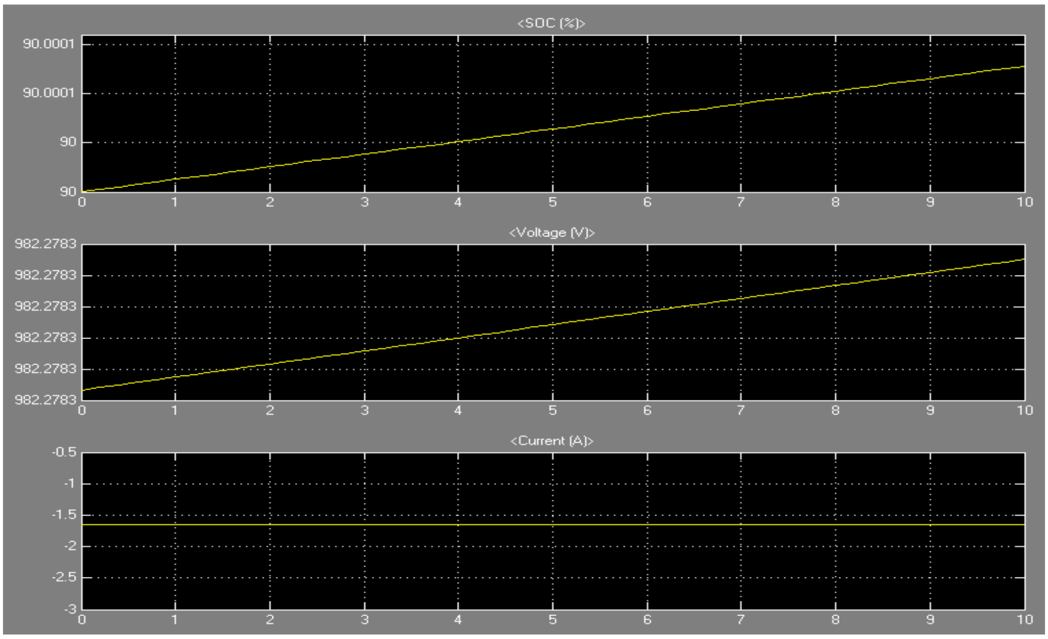


Figure 5.13. Battery is charging

### 5.1.3. Controller

The controller principal working is the DC Capacitor as shown in the figure 5.14 will sense the difference power between the DC/DC converter and the inverter based on this equation:

$$C\frac{dV_{dc}}{dt}=\frac{P_{in}}{V_{dc}}-\frac{P_{out}}{V_{dc}} \tag{5.7}$$

Then the fluctuation of the DC capacitor voltage gives signal/current to the PI controller to control the time-switching of the DC/DC converter.

PI controller using the equation below will match the reference value of the voltage to keep the voltage constant.

$$V_{dc} = \frac{1}{C_{dc}}\int\frac{(P_{in} - P_{out})}{V_{dc}}dt \tag{5.8}$$

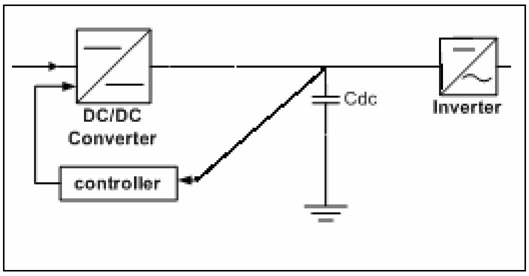


figure 5.14. Circuit of controller

## 5.2. Simulation

Scenarios of the simulation consist of 4 different conditions, and there are two simulations for each which is steady state and dynamic simulation. Steady state simulation shows how the generators coordinate each other due to control scheme. The dynamic simulation is proposed to investigate what would be happened to the system when the load fluctuation is occurred. Dynamic simulations will assess the system while in the 20th second the load is increased instantaneously. In the simulation, the load step-up done by adding another load that connected to the grid is a step function which is generated at 20 second. This load step-up will affect the system and the result will be analysed. For the grid-disconnected scenario, the grid would be disconnected to the system within the 30 second and the result also will be examined.

**Scenario 1**: Sunshine, grid-connected, batteries-standby

a. The steady state scheme

The PV power output is function of solar irradiance. The biomass power output is the result of the difference power between load demand and PV output. The power output of biomass can be controlled and will fluctuate to match the PV output and load demand while it is in the range of operational range of the biomass combustion. While the power should be provided by biomass is below its minimum limit or higher than its maximum then the excess or deficit power will flows-out to or flows-in from the grid.

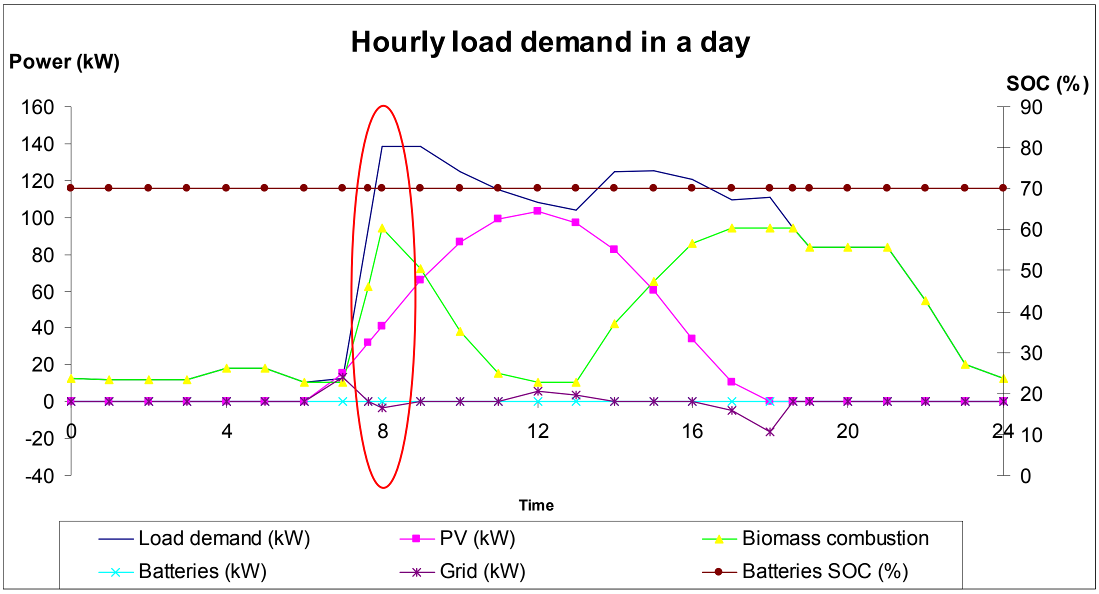
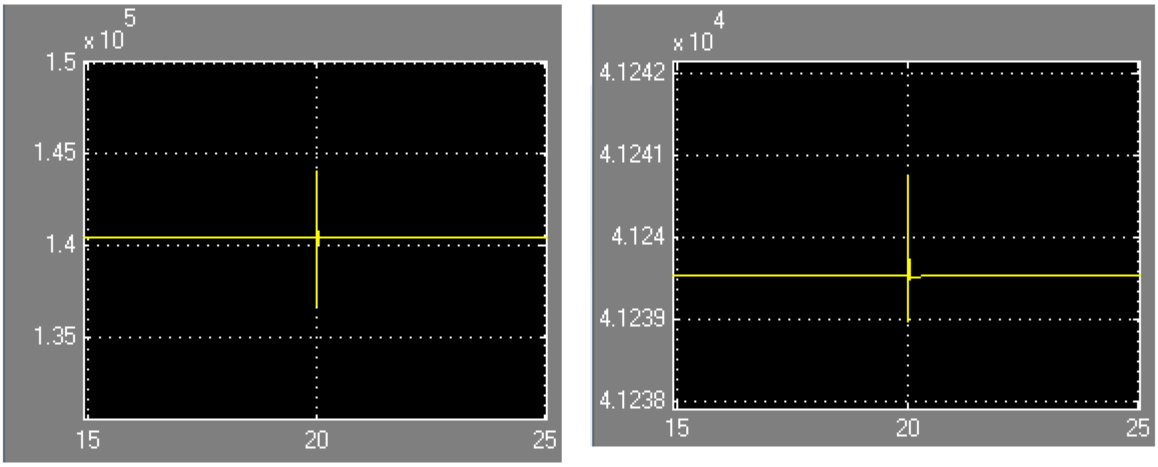


Figure 5.15. steady state condition of scenario 1

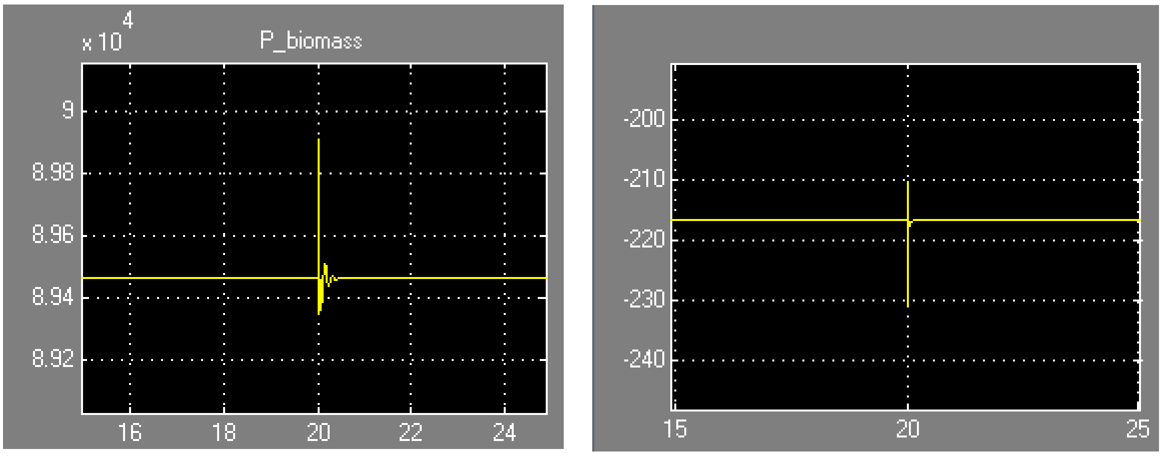
b. Dynamic simulation (load step-up at 20th second)

The dynamic simulation is made at 08:00 hours the status of each generator, batteries and grid can be seen in figure 5.15 while the result of the dynamic simulation is shown in figure 5.16.

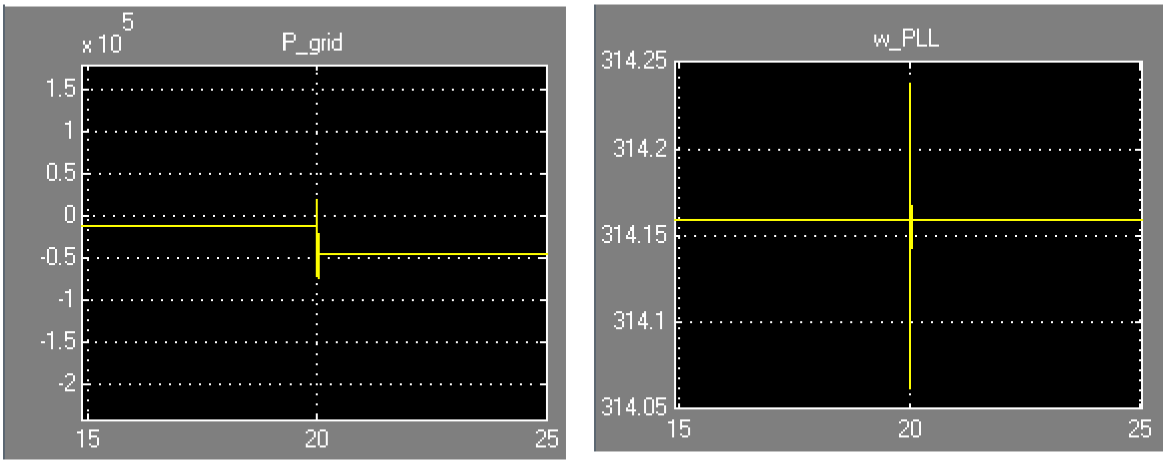


(a) Load demand

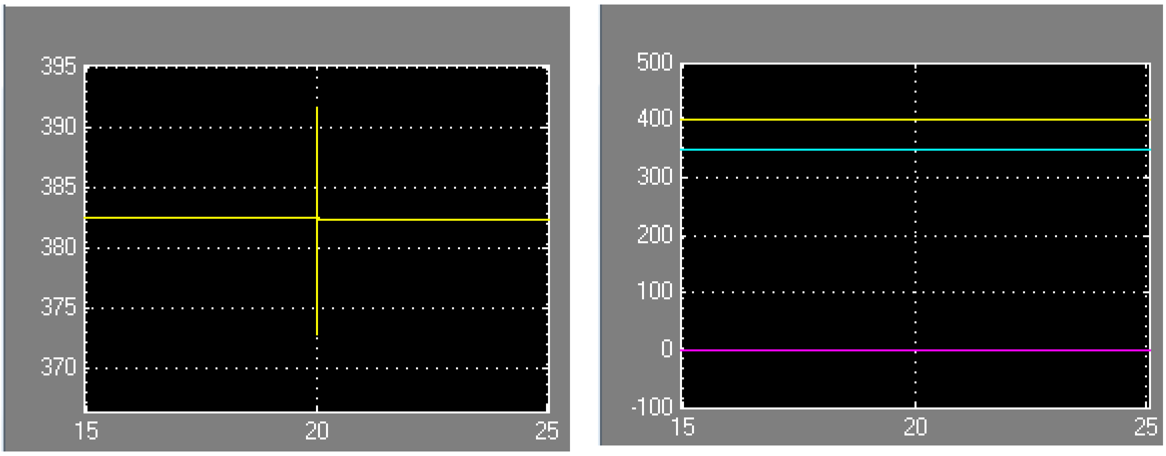
(b) PV Power Output



(c) Biomass Power Output (d) Batteries Power



(d) Grid Power (e) Grid Frequency (omega)



(f) Grid Voltage (g) DC Voltage

Figure 5.16. dynamic simulation result of scenario 1

**Scenario 2**: Sunshine, grid-disconnected, batteries-connected

a. The steady state scheme:

The same description with scenario 1 but the excess or deficit power will flows-out to or flows-in from the batteries.

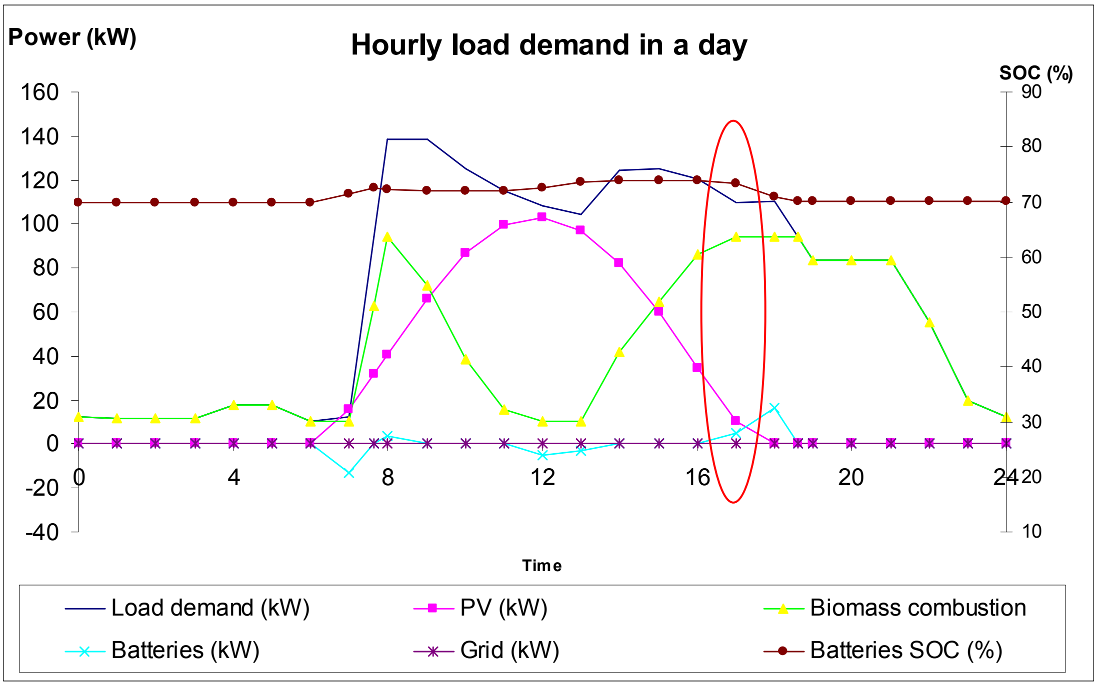
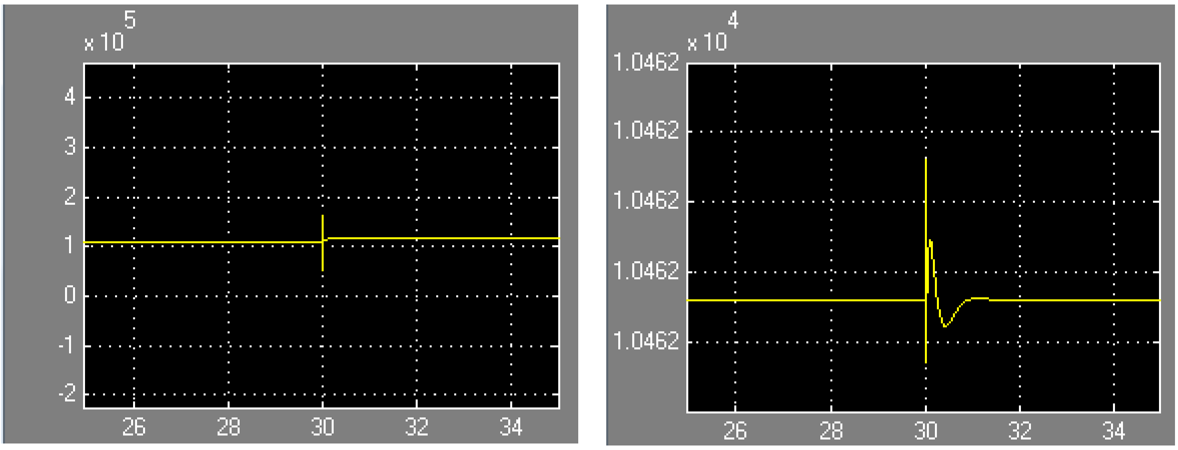


Figure 5.17. steady state condition of scenario 2

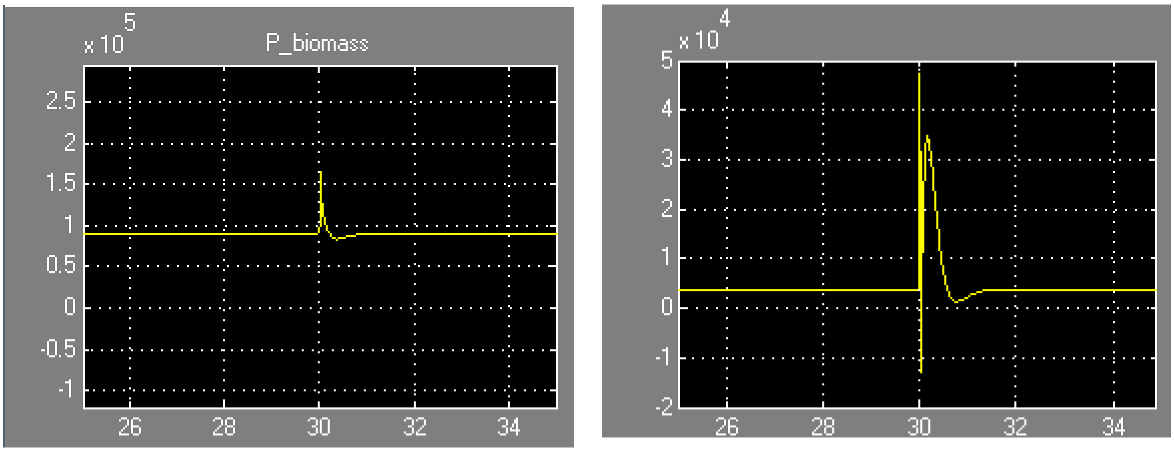
b. Dynamic simulation (grid-disconnected at 30th second)

The dynamic simulation is made at 17:00 hours the status of each generator, batteries and grid can be seen in figure 5.17 as a steady state condition while the result of the dynamic simulation is shown in figure 5.18.

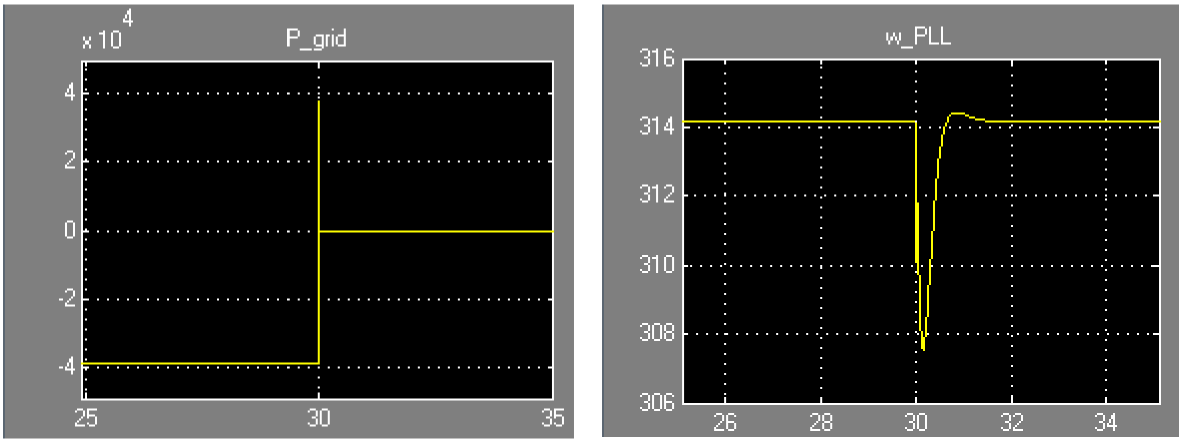


(a) Load demand

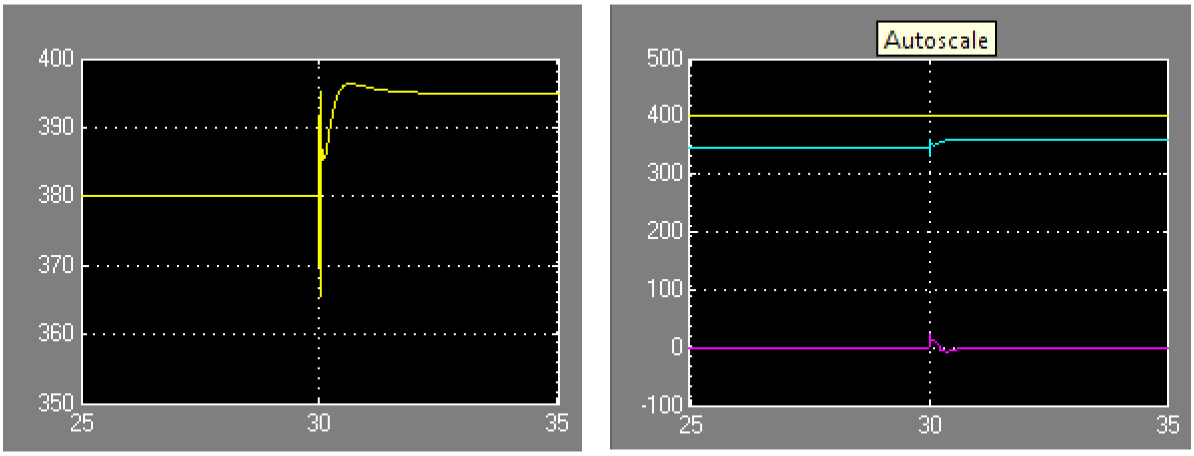
(b) PV Power Output



(c) Biomass Power Output (d) Batteries Power



(d) Grid Power (e) Grid Frequency (omega)



(f) Grid Voltage (g) DC Voltage

Figure 5.18. dynamic simulation result of scenario 2

**Scenario 3**: No-sunshine, grid-connected, batteries-standby

a. The steady state scheme

In this steady state condition there is no sun available, therefore the power supply only depends on the biomass combustion. The biomass will provide energy to the load but when the load cannot be reached by the biomass then the grid will supply the rest of the load demand.

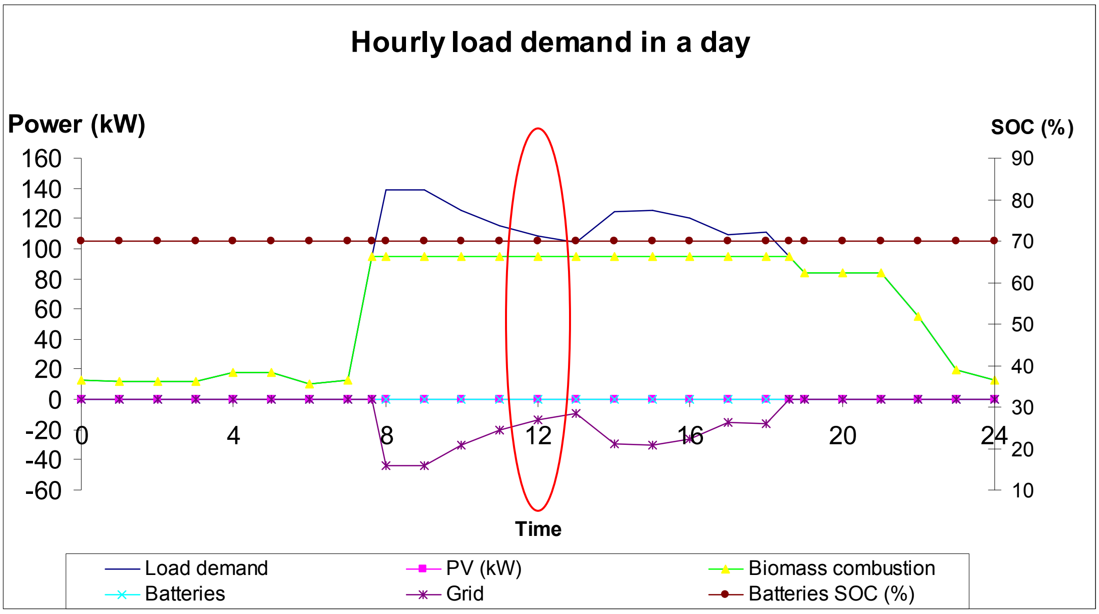
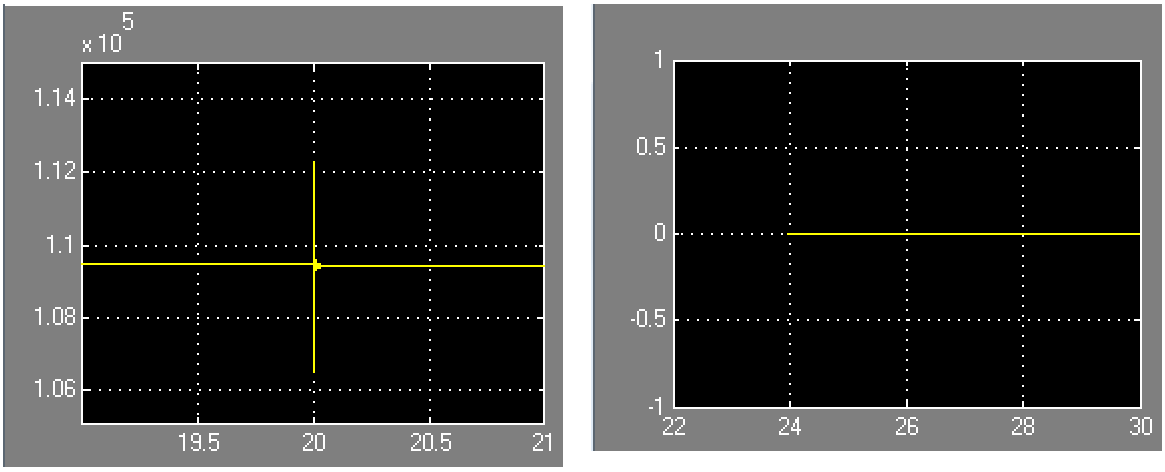


Figure 5.19. steady state condition of scenario 3

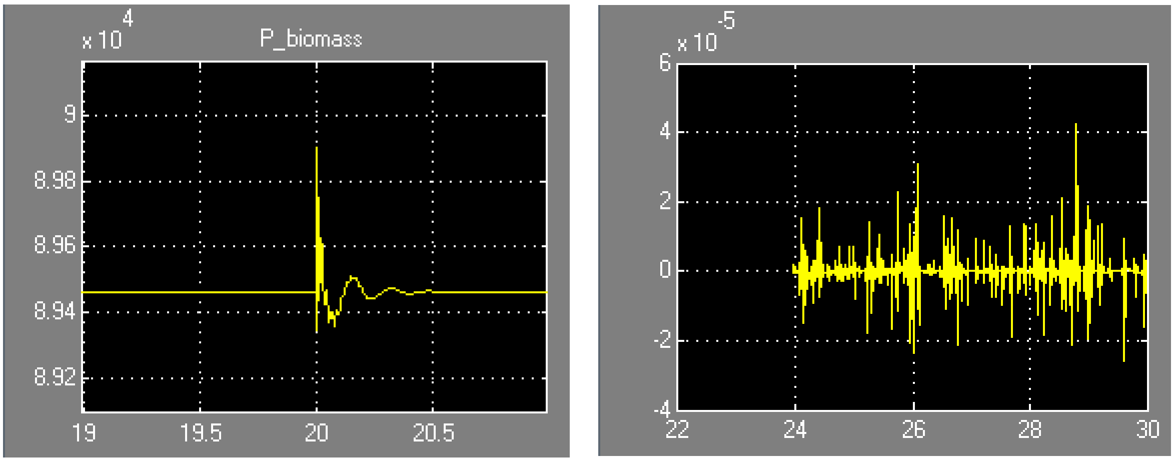
b. Dynamic simulation (load step-up at 20th second)

The dynamic simulation is made at 12:00 hours the status of each generator, batteries and grid can be seen in figure 5.19 as a steady state condition while the result of the dynamic simulation is shown in figure 5.20.



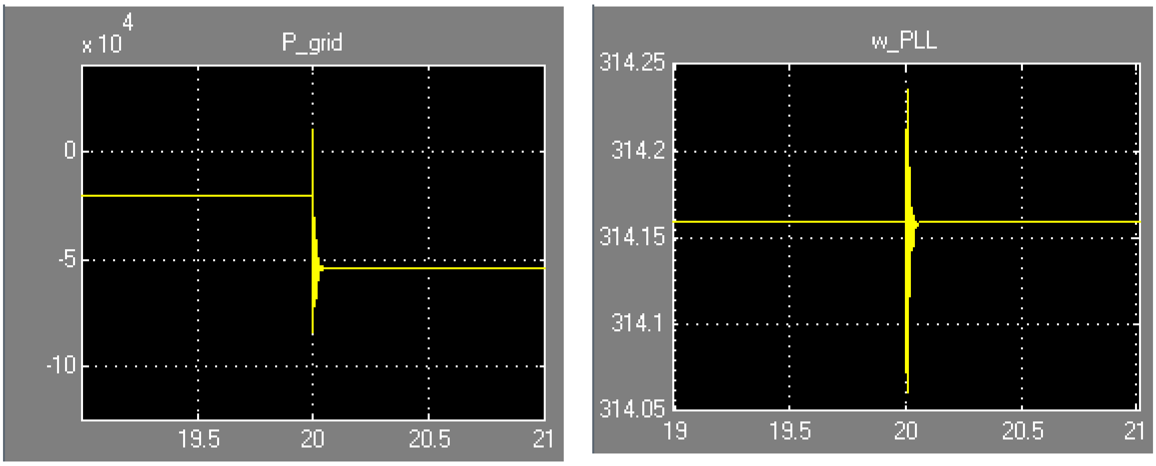
(a) Load demand

(b) PV Power Output



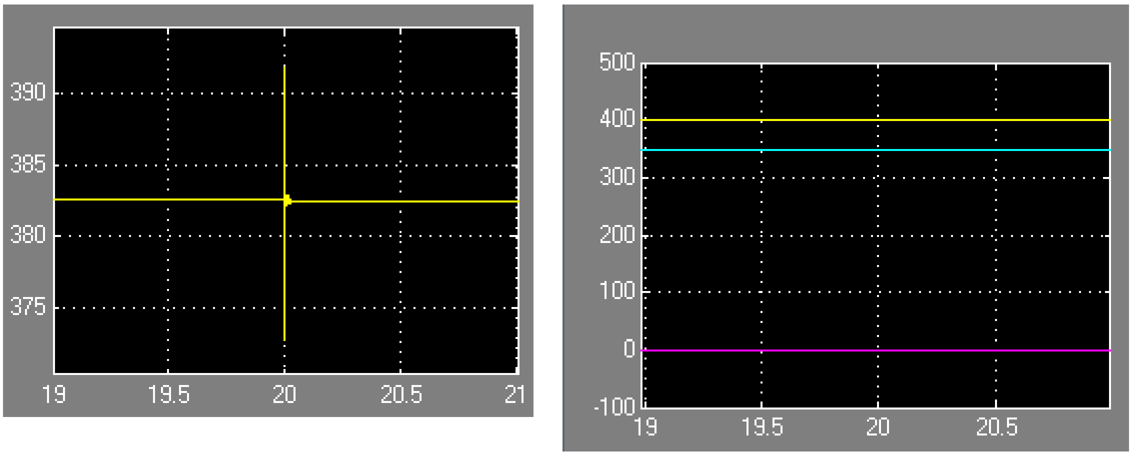
(c) Biomass Power Output

(d) Batteries Power



(d) Grid Power

(e) Grid Frequency (omega)



(f) Grid Voltage

(g) DC Voltage

Figure 5.20. dynamic simulation result of scenario 3

**Scenario 4**: No-sunshine, grid-disconnected, batteries-connected

a. The steady state scheme

In this steady state condition there is no sun available, therefore the power supply only depends on the biomass combustion and the batteries. When the supply of the biomass is not enough then the batteries are discharging. The batteries will be charged when there is excess power of biomass due to the load. The cycle of charge and discharge will be completely finished in 24 hours period. It means the capacity of battery will be constant in 24 hours period. It can be seen in the figure 5.21 that the state of charge (SOC) of the batteries remains the same.

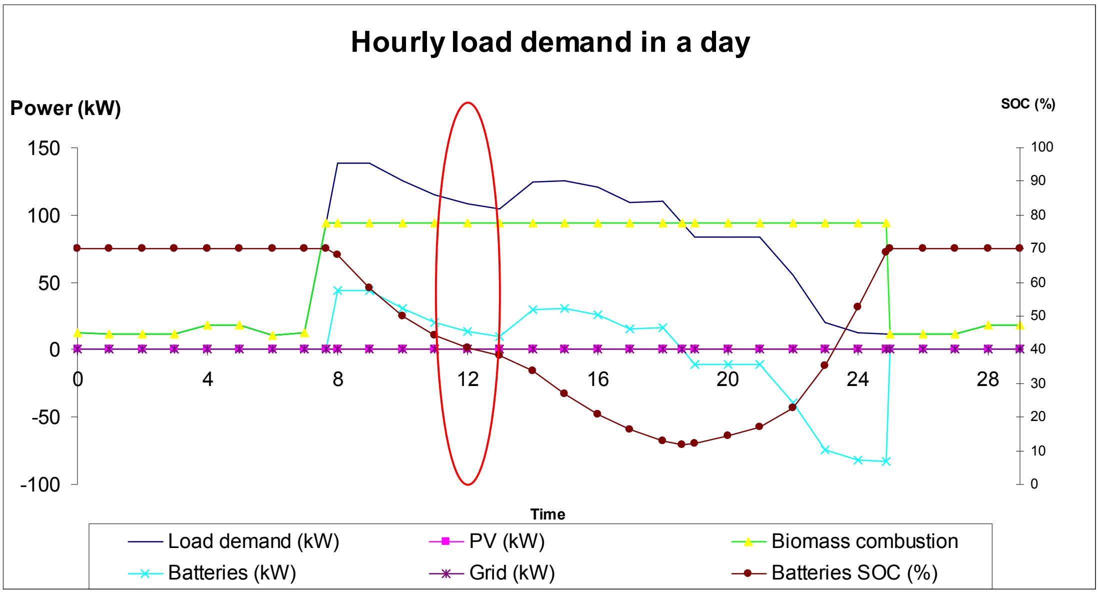
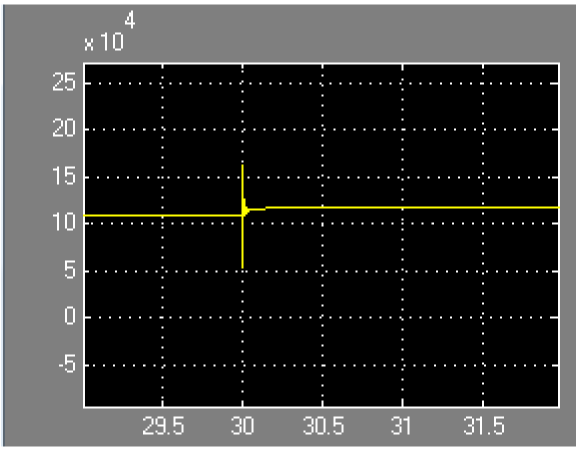


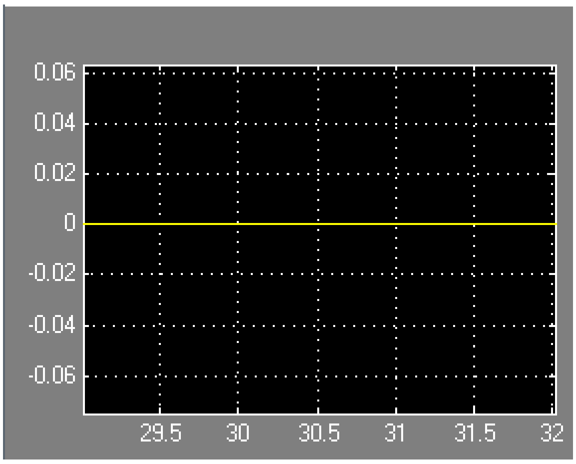
Figure 5.21. steady state condition of scenario 4

b. Dynamic simulation (grid-disconnected at 30th second)

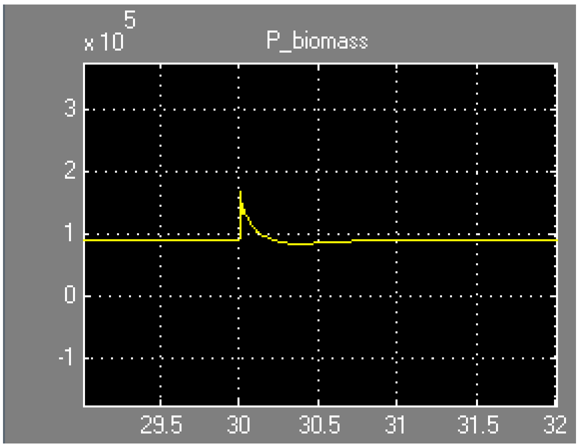
The dynamic simulation is made at 12:00 hours the status of each generator, batteries and grid can be seen in figure 5.21 as a steady state condition, while the result of the dynamic simulation is shown in figure 5.22.



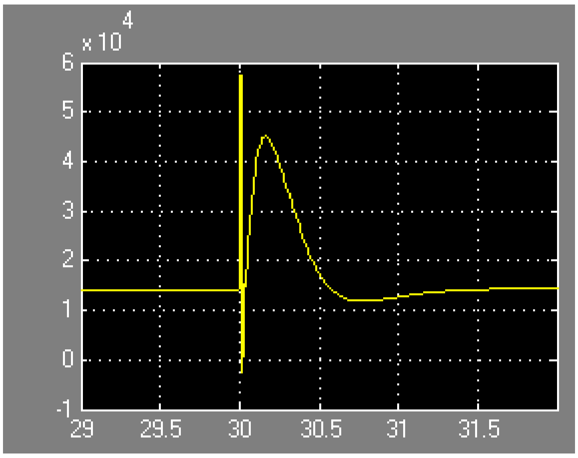
(a) Load demand



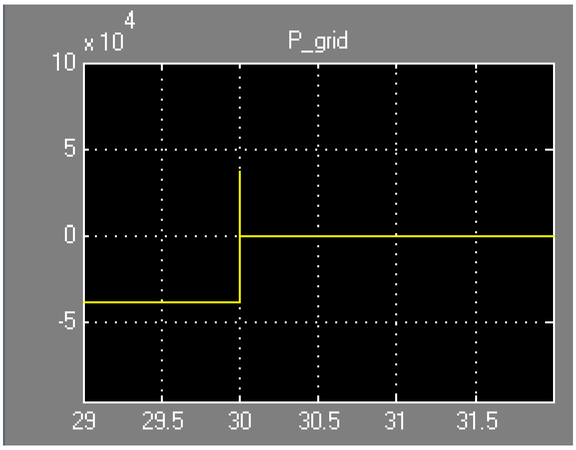
(b) PV Power Output



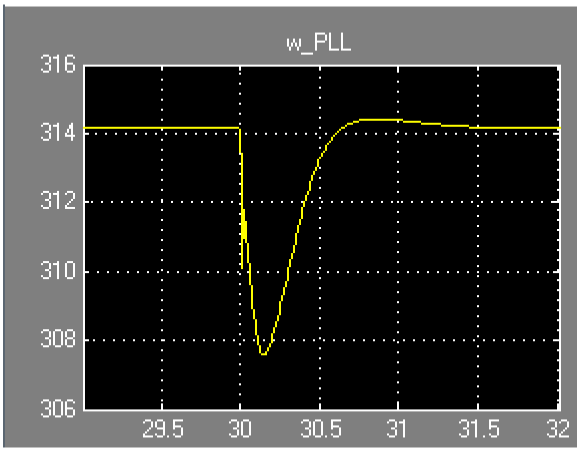
(c) Biomass Power Output



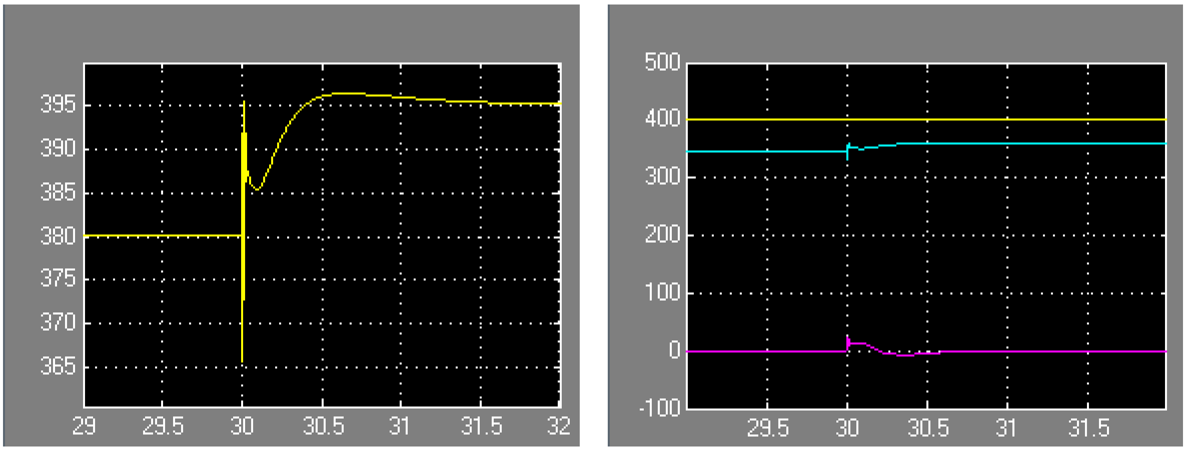
(d) Batteries Power



(d) Grid Power



(e) Grid Frequency (omega)



(f) Grid Voltage (g) DC Voltage

Figure 5.22. dynamic simulation result of scenario 4

## 5.3. Result and Discussion

The highlights of the dynamic simulations for every scenario are shown as follow.

- In general the system works properly for both condition the load stepped-up and the grid-disconnected.
- In scenario 1 and 3, the frequency is constant, the frequency transient happens at 20th second when the load is instantaneously increased. The range of fluctuation is between +0.025% and -0.03% within 100 milliseconds.
- In scenario 1 and 3, the voltage is constant, the voltage transient happens at 20th second when the load is instantaneously increased. The range of fluctuation is between +2.6% and -2.6% within 100 milliseconds.
- In scenario 2 and 4, the frequency is constant, the frequency transient happens at 30th second when grid is disconnected. The frequency is increase around 2.23% within 500 milliseconds.
- In scenario 2 and 4, the voltage increases from 380V to 395V about 3.95%, the voltage transient happens at 30th second when grid is disconnected within 500 milliseconds.

Overall simulation shows that the system is quite stable especially when connected to the grid. But in the real situation the grid is weak so the islanded operation could be the best option for that hybrid renewable energy system.

# 6. Conclusion and recommendation

## 6.1. Conclusion

The objectives of this research are exploring renewable energy resources, designing and evaluating performance of the hybrid renewable energy system. The proposed hybrid renewable energy system for Ikem consists of:

1. PV array:
    a. Type: 24 V; 160 Wp of multi-crystalline silicon cells
    b. Number of modules: 1056
    c. Total maximum power output: 170 kWp
2. Biomass combustion:
    a. Type: 3 x 35 kW Stirling engines
    b. Total maximum power: 105 kW
    c. Biomass resources: husks and straws supplied by the rice milling industry
3. Batteries:
    a. Type: 12 Volt, 33 Ah of valve regulated lead acid battery
    b. Number of batteries: 928
    c. Total maximum capacity: 370 kWh

The continuity supply of renewable energy resources is sufficient and the performance of the whole hybrid renewable energy system is good due to the simulation.

## 6.2. Recommendation

The future recommendation is the further research could be done to investigate the possibility of using hydro-power whether the data of rivers on Ikem is collected. If the hydro-power is feasible to use then the composition of the proposed hybrid renewable energy system could be combined in such a way to achieve the best performance of the hybrid system.

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