Transaction on Energy, Biotechnology, Planning and Environment
ISSN: 2229-8711 Online Publication, June 2012
www.pcoglobal.com/gjto.htm
RE-P21/GJTO

Global Journal of Technology & Optimization
Volume 3, 2012

INTEGRATED DESIGN OF RENEWABLE ENERGY DECENTRALIZED POWER PLANT COMPRISING ENERGY STORAGE FOR OFF-GRID ECO VILLAGE

Ho Wai Shin, Haslenda Hashim

Process System Engineering Centre (PROSPECT), Faculty of Chemical Engineering, Johor, Universiti Teknologi Malaysia
Email: howaishin@gmail.comm, haslenda@cheme.utm.my

Received October 2011, Revised November 2011, Accepted January 2012

Abstract
Decentralized power generation from renewable energy (RE) represents a significant transformation of the electricity industry especially to remote locations where grid connected is not viable. Out of the various RE, solar and wind had been identified to be the most promising RE to meet for future demands. However, due to the intermittency of these resources, back-up from other non-variable RE such as hydro and biomass or energy storage is essential to mainly the reliability of the system. This study is carried out to optimize the RE integrated electricity generation structure comprising of intermittent RE, non-variable RE and energy storage through the development of a MILP model. The technology selected for this study is solar power plant, biomass power plant, and bulk NaS battery system respectively. The model is then implemented in GAMS where the capacity of selected technologies, choice of RE for electricity generation, and scheduling of the designed system over a period of 24 hours was decided. The results shows that the required capacity of solar power plant is 1047 kW, biomass power plant is 403 kW and NaS battery of 691.94 kW. The total profit from this system over a life period of 25 years is $ 5,081,872.87.

Keywords: Renewable Energy; Solar; Biomass; Energy Storage; Eco Village

I. INTRODUCTION (HEADING 1)

The eco village is an intentional community set with a goal for harmless integration of human activities into the environment in a way that support healthy human development in physical, emotional, mental, and spiritual way, and is able to continue into the indefinite future [1]. In order to meet the energy demand of an eco village without harming the environment while having a self sustaining characteristic is to design an energy system relying 100% on renewable energy (RE). Out of the various sources of RE, solar and wind energy had been identified as the key energy to meet the growing energy demand. Complimentary as it is, both these resources are stochastic in nature. Due to the intermittent characteristics of solar irradiation and wind speed, which greatly influence the resulting production, the major aspects in the design of PV, wind generator and power generation systems are the reliable supply of power to consumers under varying atmospheric conditions and the corresponding cost of the total system [2]. Since solar and wind energy are complementary in nature, [2] and [3] had undergone researches to design and optimize a hybrid system consisting of solar and wind energy with an energy storage system. As a country located in the South East Asia region, Malaysia with its abundant RE resources has the potential to develop an eco village with energy production entirely from RE. However, compare to the previous studies, Malaysia lack wind energy to be considered for a hybrid solar and wind energy system. Instead, with abundant resources from biomass, Malaysia could improvise the previous system by removing the wind generator and replaced it with an electricity generator using biomass, biogas, or municipal solid waste (MSW) as fuel sources.

Effort to promote RE in Malaysia had begun since 2001 under the 8th Malaysian Plan (8 MP), when the fifth fuel strategy was introduced to promote the use of RE as well as to address rising global concern on climate change. In May 2001, the Small Renewable Energy Power (SREP) was launch with a set target of 350 MW of electricity generation RE such as biomass, biogas, MSW, solar and mini-hydro. The notion was persevered under the 9 MP by enhancing the use of RE and biomass resources from oil palm, wood, rice husks residue for the purpose of heat and electricity generation. In addition, the National Biofuel Policy 2006 and the National Green Technology Policy 2009 were launched under the 9 MP. Two RE programmes were also launched during this period, namely Malaysia Building Integrated Photovoltaic (MBIPV) and Centre for Education and Training in Renewable Energy and Energy Efficiency (CETREE). Despite the efforts, only 56.7 MW of RE if contributed to the country's total energy mix [4]. The main contributing factor toward slow RE development is the economical feasibility of RE projects. As a measure to increase the economical feasibility of RE projects, the Malaysian government had launched the National Renewable Energy Policy 2010 and introduced Feed-in Tariff (FiT) into the country under the 10 MP. The new target to achieve is of 985 MW by 2015 contributing to 5.5% of Malaysia's total electricity generation mix [5].

In this study, corresponding to the country's goal and as an effort to promote RE utilization within the country, an integrated electricity system comprising of solar photovoltaic (PV) facility, biomass bubbling fluidized bed (BBFB) power plant using palm kernel shell (PKS) as its fuel source, and bulk energy storage of sodium sulfur (NaS) battery was designed over 5 different weather scenario. The system was then optimized by developing a mixed integer linear programming (MILP) model using General Algebraic Modeling System (GAMS) where the capacity of selected technologies, choice of RE for electricity generation (solar or biomass), and time for charging and discharging of energy storage device over a period of 24 hours was decided.

II. SYSTEM DESCRIPTION AND DATA COLLECTION

A. Integrated Electricity System

The proposed integrated electricity system design consists of two sources for electricity generation, PKS BBFB power plant (alternating current –AC) and solar PV facility (direct current – DC), energy storage device (NaS Battery), and an AC/DC converter as shown in Fig. 1. The main objective of the system is to provide sufficient power to the required load using the two main generators (BBFB and Solar PV). As AC is required, the DC from solar PV had to be converted from DC to AC. In this system, solar PV can only provide electricity during the day time when solar radiation is available which is however, limited to the daily radiation intensity. On the other hand, BBFB power plant would than supply the remaining electricity required. As there is a possibility that the generation from solar PV at an instant would be greater than the required demand, a NaS battery is installed in the system to store the excess energy. The battery is also used as a device for peak curtailment in the system. In order to minimize the total size of BBFB power plant, BBFB power plant could generate electricity during low-peak hour to charge the battery, whereby the battery will then discharge the electricity to meet the demand during peak hour.

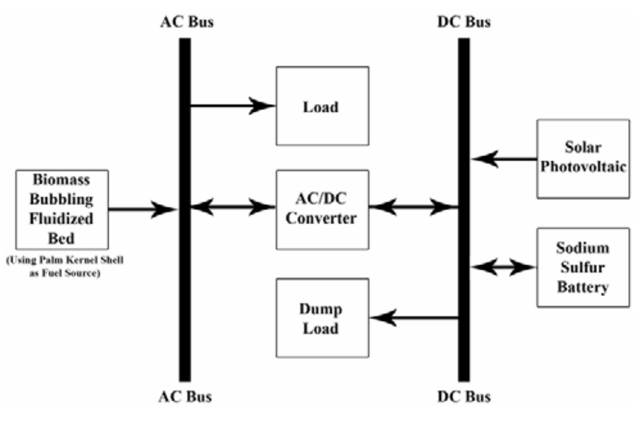

Figure 1.Integrated Electricity System Configuration

B. Solar PV Facility

The PV facility uses several ground-mounted, fixed tilt semiconductor panels in an array to directly convert incident solar radiation in the forms of photon to DC electricity, which can then be converted to AC. Cost analysis for the solar PV facility includes additional balance of plant (BoP) components such as metal racks and foundations to support fixed panels and keep them aligned at the correct angle, a AC/DC converter, AC and DC wiring, combiner boxes where individual strings of panels are connected prior to being fed into the inverter, and a control system to control and monitor output by adjusting the balance of voltage and current to yield maximum power [6]. It is also assumed that the costing of AC/DC converters and control system for the integrated electricity system is included in the cost analysis of solar PV facility. The cost of the facility is as tabulated in Table. 1 [6].

TABLE I. SOLAR PV FACILITY PARAMETERS [6]

Solar PV Facility Parameters [a]	
Capital Cost ($/kW)	6050.00
Fixed Operating and Maintenance (O&M) Cost ($/kW)	26.04
Inverter Efficiency	0.9
Facility Life (yrs)	25

a. Cost analysis for a nominal plant capacity of 7 MW

C. BBFB Power Plant

Initially in the combustion unit of the BBFB power plant, PKS biomass will be combusted to provide heat for the BFB boiler to generate steam. The steam will flow to the steam turbine (ST) for AC electricity generation. The cost specification for a BBFB power plant, heat rate, and PKS fuel price is as tabulated in Table. 2 [6, 7].

TABLE II. BBFB POWER PLANT PARAMETERS [6,7]

BBFB Power Plant Parameters [a]	
Capital Cost ($/kW)	3860.00
Fixed O&M Cost ($/kW)	100.50
Variable O&M Cost ($/MWh)	5.00
Heat Rate (GJ/MWh)	14.24
PKS fuel price ($/GJ)	1.35

a. Cost analysis for a nominal plant capacity of 50 MW

D. Sodium Sulfur (NaS) Battery

NaS battery is a type of molten metal battery constructed from sodium (Na) and sulfur (S). Due to its high operating temperature of 300 to 350^{o}C and highly corrosive nature of the sodium polysulfide, NaS batteries are suitable for large-scale grid energy storage. Additionally, NaS batteries have high energy density, high efficiency of charge/discharge and long cycle life. The cost analysis for a NaS battery system and other parameters are as tabulated in Table. 3 [8].

TABLE III. SODIUM SULFUR BATTERY PARAMETERS [8]

Sodium Sulfur Battery Parameters [a]	
Energy Capacity Related Cost and BoP ($/kWh)	346.00
Power Related Cost ($/kW)	173.00
Fixed O&M Cost ($/MWh)	23
Charging/Discharging Efficiency[b]	0.883
Depth of Discharge (%)	80
Battery Life (yr)	10

a. Cost analysis were developed for 6 hour, 50 MW energy storage scenario
b. DC roundtrip efficiency of 78%

E. *Load Demand*

With Reference from [2], the average daily load profile summarized from 4 different locations in Malaysia, namely Johor, Selangor, Pulau Pinang and Sarawak is as shown in Fig. 2. The daily load profile is then used in this study.

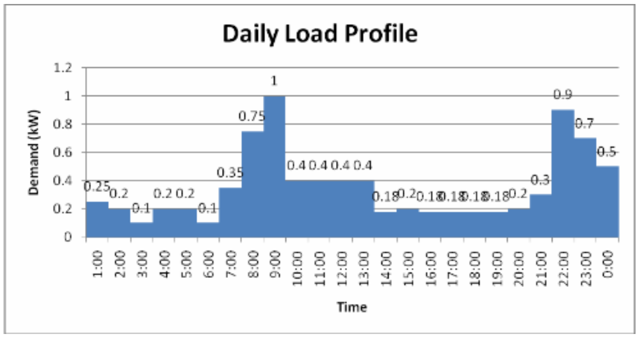

Figure 2. Daily Load Profile

F. *Solar Radiation*

For any installation of solar energy equipment, information on sunshine hour, solar radiation intensity and diurnal variation of global solar radiation is vital for the designer to design and optimize a suitable solar system. In tropical country such as Malaysia where the cloud pattern can be highly variable due to unpredictable weather throughout the year, it is very important that data on the type of weather pattern and the frequency of each pattern is to be obtained before designing for a solar PV system. As a reference from [Rain], 5 weather patterns namely, clear day, cloudy day, rainy day, rain in the afternoon, and solar intensity higher than solar constant are identified. With the analysis based on 1334 days in an observation period of 5 years, the frequency of occurrence of the weather patterns are calculated. The occurrence frequency of clear day is 15.9%, cloudy day is 51%, rainy day 13.7%, rain in the afternoon 16.4%, and solar intensity higher than solar constant 3%. The daily intensity variation of each weather pattern is as shown in Fig. 3 [9].

G. *Feed-in Tariff*

FiT has been implemented in over 40 countries worldwide and thus, proven to be the best mechanism to foster RE rather than other mechanisms such as quotas, direct incentives or voluntary goals. FiT provides guarantee payments per kilowatt-hour for electricity generated from RE over a guaranteed period of typically 15 to 20 years. In Malaysia, FiT covers for RE from solar PV, biomass, biogas, and mini-hydro. Since the renewable energies implemented in this study are both included in the Malaysia FiT, the payments from generating RE are included in the model. Even though FiT rate is different for different generation range, in this study, a single rate is taken for all cases. Rate for solar PV is 0.39 ($/kWh) and biomass is 0.11 ($/kWh) [5].

III. MODEL FORMULATION

In order to design and optimize the system, an objective function is derived to maximize the profit gain, P(w,t) from the integrated electricity system over the entire life of the system as shown by (1).

$$\text{Max } P(w,t) = \sum P_B(w,t) + \sum P_S(w,t) - C_{NaS} \quad (1)$$

where $P_B(w,t)$, net profit from BBFB given by (2):

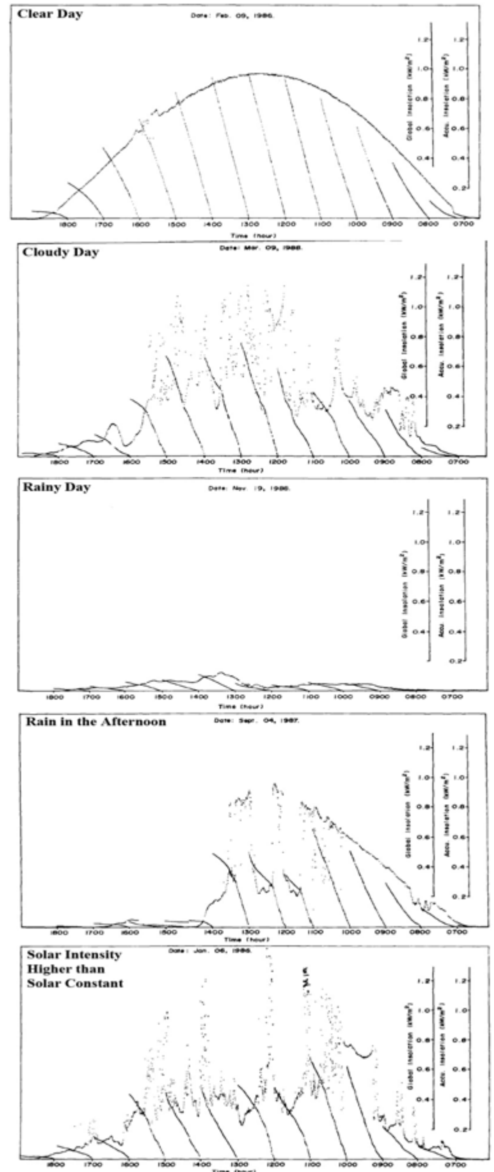

Figure 3. Weather Patterns in Malaysia [9]

$$P_B(w,t) = \sum [[B_{load}(w,t) + [B_{bat}(w,t) \times \eta_D \times \eta_I]] \times D(w) \times [B_{FiT} - B_{var} - (B_F \times B_{HR})]] - B_{size} \times [B_{cap} + (B_{fix} \times L)] \quad (2)$$

where $B_{load}(w,t)$, BBFB generation to meet the load on weather, w (clear, cloudy, rainy, rain in the afternoon, and solar intensity higher than solar constant) at time, t (1-24); $B_{bat}(w,t)$, power from NaS battery originally stored from BBFB; η_D, NaS discharging efficiency; η_I, AC/DC converter efficiency; D(w), amount of days over a year for each weather pattern; B_{FiT}, FiT for biomass electricity generation; B_{var}, BBFB variable O&M cost; B_F, PKS fuel cost; B_{HR}, heat rate of BBFB; B_{size}, BBFB capacity; B_{cap}, BBFB capital cost; B_{fix}, BBFB fixed O&M cost; L, project life; P_S, net profit from solar PV given by (3):

$$P_S(w,t) = \sum [[S_{load}(w,t) + [S_{bat}(w,t) \times \eta_D \times \eta_I]] \times D(w) \times S_{FiT}] - S_{size} \times [S_{cap} + (S_{fix} \times L)] \quad (3)$$

where $S_{load}(w,t)$, solar PV generation to meet load; $S_{bat}(w,t)$, power from NaS battery originally stored from solar PV; S_{FiT}, FiT for solar PV electricity generation; S_{size}, solar PV capacity;

S_{cap}, solar PV capital cost; S_{fix}, solar PV fixed O&M cost; C_{NaS}, cost of NaS battery given by (4):

$$C_{NaS} = [(N_{size} \times N_{EC} \times L_{fac}) / N_D] + N_P \times [N_{PC} + (N_{fix} \times L)] \quad (4)$$

where N_{size}, NaS energy capacity; N_{EC}, NaS energy capacity related cost and BoP; N_D, NaS depth of discharge; N_P, NaS power; N_{PC}, NaS power related cost; N_{fix}, NaS fixed O&M cost; L_{fac}, factor of NaS life to project life given by (5):

$$L_{fac} = L_{NaS} / L \quad (5)$$

where L_{NaS}, NaS life.
Referring to [3], the power generated by PV array, S_P is given by (6):

$$S_p = \eta \, A \, I \quad (6)$$

where η, PV system efficiency; A, total array area (m^2); I, solar radiation intensity (W/m^2). As the capital cost of solar PV facility is based on a standard solar radiation of 1000 W/m^2 [6], the actual power generated for different solar intensity is given by the following correlation:

$$S_{gen}(w,t) = S_p \, (I_T(w,t) / I) \quad (7)$$

where $S_{gen}(w,t)$, total power generation from solar PV; $I_T(w,t)$, solar radiation intensity according to 'w' at 't'.
The energy balance model for BBFB, solar PV, NaS battery, and load is as shown by (8), (9), (10a), (10b), and (11) respectively. For NaS battery energy balance, the equation is split into (10a) and (10b) because of two different sources of RE used for storing. While (10a) is for energy from BBFB, (10b) is for energy from solar PV. However, in reality both BBFB and solar PV share the same NaS battery system.

$$B_{gen}(w,t) = B_{load}(w,t) + B_{NaS}(w,t) \quad (8)$$

$$S_{gen}(w,t) = S_{load}(w,t) + S_{NaS}(w,t) + S_{dump}(w,t) \quad (9)$$

$$N_{bio}(w,t+1) = N_{bio}(w,t) + [B_{NaS}(w,t) \times \eta_C \times \eta_I] - B_{bat}(w,t) \quad (10a)$$

$$N_{PV}(w,t+1) = N_{PV}(w,t) + [S_{NaS}(w,t) \times \eta_C \times \eta_I] - S_{bat}(w,t) \quad (10b)$$

$$L_D(w,t) \times H = B_{load}(w,t) + [S_{load}(w,t) \times \eta_I] + [B_{bat}(w,t) \times \eta_D \times \eta_I] + [S_{bat}(w,t) \times \eta_D \times \eta_I \quad (11)$$

where $B_{gen}(w,t)$, total power generation from BBFB; $B_{NaS}(w,t)$, BBFB generation for storage; $S_{NaS}(w,t)$, solar PV generation for storage; $S_{dump}(w,t)$, dump of excess solar energy; $N_{bio}(w,t)$, accumulated energy from BBFB in NaS battery; $N_{PV}(w,t)$, accumulated energy from solar PV in NaS battery;η_C, NaS charging efficiency; $L_D(w,t)$, load demand; H, unit of houses in the eco village.
Under this configuration, BBFB and solar PV are the two main source of power generation. The power from BBFB, other than is generated to meet the load demand, is also generated for storage. This is mainly for peak curtailing, where the extra power is generated from BBFB during off-peak hour for storage and then used during peak hour. As for solar PV, excess power generated is used, stored in the battery or dumped if not required. As for (10), the formula is derived upon the accumulated energy in the battery. During charging, a small amount of energy would be lost due to the battery charging efficiency. While, to store energy from BBFB, the AC has to be converted to DC with loss of energy due to the converter efficiency. For (11), power from solar PV has to be converted from DC to AC while suffering loss of energy during conversion. To utilize the power from NaS battery, the energy stored in the battery would have to be discharged and converted from DC to AC with energy loss from discharging and conversion. As an extension to (10), to ensure the battery have the same amount of charges accumulated at the beginning of the day when time (t = 1) and at the end of the day, a dummy time (t = 25) is added into the model in order to formulate an equation as shown by (12a) and (12b) for both BBFB and solar PV.

$$N_{bio}(w, t = 25) + N_{bdump}(w) = N_{bio}(w, t = 1) \quad (12a)$$

$$N_{PV}(w, t = 25) + N_{PVdump}(w) = N_{PV}(w, t = 1) \quad (12b)$$

where $N_{bdump}(w)$, dumping of excess energy from NaS battery originally from BBFB; $N_{PVdump}(w)$, dumping of excess energy from NaS battery originally from solar PV.
Several constraints are also derived for the model. Power generation from BBFB cannot be more than the capacity of the power plant.

$$B_{load}(w,t) + B_{NaS}(w,t) \le B_{size} \quad (13)$$

For NaS battery, two constraints are derived indicating the total accumulated energy cannot be more than the maximum energy capacity of the battery, (14) and the discharge rate of the battery cannot be more than the maximum discharge rate, (15) and (16).

$$N_{bio}(w,t) + N_{PV}(w,t) \le N_{size} \quad (14)$$

$$B_{bat}(w,t) + S_{bat}(w,t) \le N_P \quad (15)$$

$$B_{bat}(w,t{=}25) + S_{bat}(w,t{=}25) + N_{bdump}(w) + N_{PVdump}(w) \le N_P \quad (16)$$

The cost of electricity (C_E) is then calculated via (17) and due to the depth of discharge of the battery, (18) is formulated to calculate the actual energy capacity (N_{sizeac}) required for the NaS battery.

$$C_E = [C_B(w,t) + C_S(w,t) + C_{NaS}] / [B_{gen}(w,t) + S_{gen}(w,t)] \quad (17)$$

where $C_B(w,t)$, cost of BBFB; $C_S(w,t)$, cost of solar PV.

$$N_{sizeac} = N_{size} / N_D \quad (18)$$

IV. RESULT AND DISCUSSION

The model for the integrated electricity is applied into GAMS and using CPLEX 12.2.0.0.0 solver, the results revealed that the required capacity of BBFB power plant is 403 kW and solar PV facility is 1047 kW. With size of the power plants, the required NaS battery energy capacity is 1413.62 kWh and power of 691.94 kW. The net profit obtained under this setting over a period of 25 years is \$ 5,081,872.87 with the cost of electricity of 3.56 (\$/kWh).
In order to further understand and describe the system, the energy trend for BBFB and solar PV generation for all 5 weather patterns is analyzed and compared. Fig. 4 shows the energy trend for different weather pattern for BBFB/solar PV generation directly to load, BBFB/solar PV generation to NaS battery for

storage, and stored BBFB/solar PV energy from NaS battery to load.

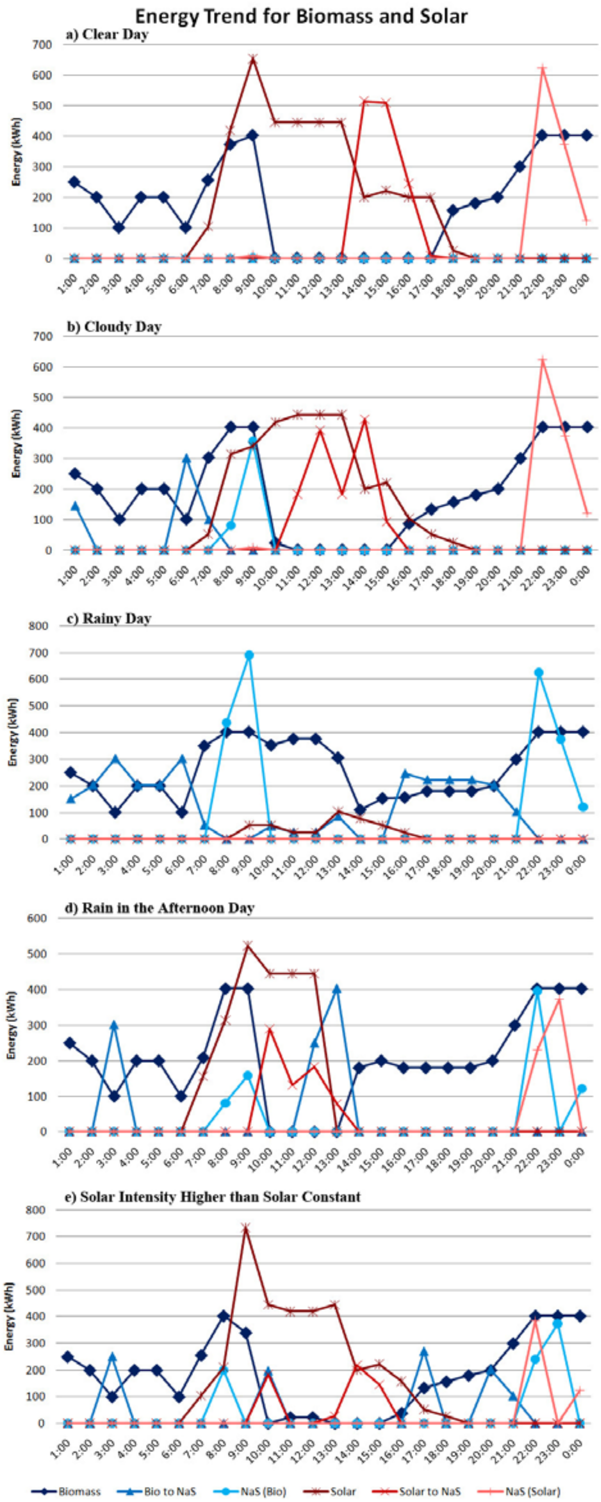

Figure 4. Energy Trend for Different Weather Pattern

Generally, for all cases of weather pattern, it can be seen that, during period when sunshine is not available, biomass energy is mainly used. The period accordingly to this study is from 5 p.m. to 10 a.m. From 10 a.m. to 5 p.m., solar energy is mainly used depending on its availability.

For a clear day, from 1 a.m. to 7 a.m. when sunshine is absent, biomass energy is utilized. Both solar and biomass energy is utilized from 7 a.m. to 10 a.m., when the load peaks. The reason for the increasing demand is because most of the residents has awake from their sleep to prepare for work. Also at this time (7 a.m.), the sun rises providing availability toward solar PV generation. Due to the abundant resource of solar for a clear day, solar energy is solely used to supply for the energy demand from 10 a.m. to 5 p.m. From the graph it can be seen that solar energy is stored from 2 p.m. to 5 p.m. due to excess generation from solar PV. After the sun sets at 7 p.m., biomass energy is utilized to meet the remaining energy demand for the day. According to Fig. 2, there are two peak hour for a residential household at 9 a.m. and 10 p.m. At 10 p.m., due to high peak hour, the stored solar energy is discharged from the energy storage to meet the energy demand.

During a cloudy day, the energy trend is rather unpredictable compare to that of a clear day. From 1 a.m. to 10 a.m., similarly, biomass energy is solely used. Referring to Fig. 4, biomass energy is purposely generated for storage from 6 a.m. to 8 a.m. The stored energy is then discharged from the energy storage to be used from 8 a.m. to 10 a.m. The main reason for this phenomenon is such to prevent the over-sizing of BBFB power plant. The biomass energy is stored at earlier hour for utilization at later hour when the load peaks. From 10 a.m. onward, the energy trend is similar to that of a clear day. For a rainy day when sunshine is rarely available, biomass energy is mainly used throughout the day. For this scenario, the function of energy storage for peak curtailment can be clearly seen. Biomass energy is stored from 1 a.m. to 8 a.m. and 4 p.m. to 10 p.m. is used during peak hour from 8 a.m. to 9 a.m. and 10 p.m. to 12 p.m.

For the remaining two weather pattern, rain in the afternoon and for time when the solar intensity higher than solar constant, the energy trend is similar to that of the previous weather trend accordingly. From the results, it can be concluded that for a RE electricity system, an energy storage is very important for the system optimization in term of sizing and energy usage.

V. Conclusion

In this research, an integrated RE decentralized power plant comprising of energy storage is proposed for an off-grid eco village. Through the energy trend over the 5 weather pattern proves that for different weather pattern, the requirement of the design of this integrated system is different. However, in this case, the proposed sizing of BBFB power plant, solar PV facility, and NaS battery is designed to cater an eco village in Malaysia with different weather patterns. As this study only accommodates for changing weather pattern, but from the results it can also be concluded that, for an eco village with different load trend, the sizing and design of the integrated system would be different as well.

With this model, planning for an eco village in Malaysia is now proven to be economically feasible. This model caters for biomass power generation using PKS as fuel source, assuming that the eco village is built near to a sustainable source of PKS. However, in reality other non-variable renewable energy could be used to replace the current configuration such as MSW power plant, landfill gas, and biogas or even maintain the same BBFB power plant system with different fuel source such as palm oil empty fruit bunch, meso-carp fiber, or rice husks. This integrated system is not limited just for solar PV. A hybrid of different variable renewable energy such as wind could also be implemented and optimized. Similarly, different variety of energy storage system could replace the current selected NaS battery system and with suitable geographical landscape, cheaper and more efficient storage system such as hydro-pump can replaced the current energy storage system to further increase the economical feasibility of the integrated electricity system.

Through the energy trend, it had clearly shown that, energy storage system does not only increase the reliability of variable renewable energy, but it can also function as a device for peak curtailment which would then decrease the total cost of electricity generation. Therefore, this model could be applied not only for an off-grid system, but also for an on-grid electricity network. In conclusion, it is currently not impossible for our world to shift to a more environmental friendly society.

REFERENCES

[1] J. M. Bang, “Ecovillages: A Practical Guide to Sustainable Communities,” New Society Publishers, 2005.

[2] A. M. A. Haidar, P. N. John, and M. Shawal, “Optimal Configuration Assessment of Renewable Energy in Malaysia,” Renewable Energy 36 (2011) 881-888, 2011.

[3] E. S. Sreeraj, K. Chatterjee, and S. Bandyopadhyay, “Design of Isolated Renewable Hybrid Power Systems,” Solar Energy 84 (2010) 1124-1136, 2010.

[4] T. H. Oh, and S. C. Chua, “Review on Malaysia’s National Energy Developments: Key Policies, Agencies, Programmes, and International Involvements,” Renewable and Sustainable Energy Reviews 2010, 14(4): 2916-2925, 2010.

[5] S. C. Chua, T. H. Oh, W. W. Goh, “Feed-in Tariff Outlook in Malaysia,” Renewable and Sustainable Energy Reviews 2011. 15: 705-712, 2011.

[6] U. S. Energy Information Administration, “Updated Capital Cost Estimates for Electricity Generation Plants,” November 2010.

[7] A. Evald, “Renewable Energy Resources,” Integrated Resource Planning, February 2005.

[8] D. Steward, G. Saur, M. Penev, and T. Ramsden, “Lifecycle Cost Analysis of Hydrogen Versus Other Technologies for Energy Electrical Storage,” National Renewable Energy Laboratory, NREL/TP-560-46719, November 2009.

[9] M. Y. H. Othman, K. Sopian, B. Yatim, and M. N. Dalimin, “Diurnal Pattern of Global Solar Radiation in the Tropics: a Case Study in Malaysia,” Renewable Energy Vol. 3, No. 6/7, pp. 741-745, 1993.