Realization and Analysis of a Triple Hybrid Power System Consisting of Biomass, Wind and Solar Generators

[1,2]Zulati Litifu, [1]Yasuyuki Nemoto, [1]Izumi Ushiyama and [3]Ken Nagasaka
[1]Department of Mechanical Engineering, Synthetic Research Center,
Ashikaga Institute of Technology, Japan
[2]Department of Statistics and Information, Xinjiang Institute of Finance and Economics, Japan
[3]Department of Electrical and Electronics, Tokyo University of Agriculture and Technology, Japan

Abstract: This study presents a realization process of a hybrid system consisting of biomass and wind as well as solar power generation on the ground of Ashikaga Intitute of Technology located in Ashikaga City of Tochiki Prefecture. The installation principle and procedure are introduced based on the conditions of natural energy such as wind speed and solar rediation degree. The output characteristics from 20 kW biomass generator is explained and analyzed in according to cooperational possibility with the wind power and solar power system. The operation characteristics of 40 kW wind power turbine is provided based on the practical operation data collected within three years and the simulated results obtained from the software calculation. The operation conditions of 20.6kW solar power system is also anaylzed based on the solar irrediance desity in the located site. The general efficiency of this triple hybrid power system in ecomomic and environment aspects is also studied by using and comparing the simulation methodology and the data in practical operation.

Key words: Hybrid system, operation analysis, environment and economical analysis

INTRODUCTION

As an experience of application of renewable energy, a micro-grid consisting of triple generators such as wind power turbine and solar panel as well as biomass unit is used for the university power supply. This application aims at the future development of renewable energy in the suburb and urban district. Since the wind speed in the location site is not high enough with an average wind speed about 4.2 ms^{-1}, the SUBARU 15/40 type wind power turbine that made by Fuji Heavy Industries Company has been used as a wind power system. In wind power generator, the shifting generator with the capacity of 15kW makes it possible to start providing electric power under wind speed of 2ms^{-1}. When the wind speed goes up to certain degree, the large generator with the rated capacity of 40 kW is shifted in the operation. Considering the location site is in a residential area, the silent type of wind power turbine is selected. In brief, this wind power turbine is optimal one that matches for local conditions. In solar power system, the HIP-190B2 type solar panels made by Sanyo Electric Company are applied. The maximum power output from per solar panel is 190W, 108 solar panels are used to make up large array of solar power system with a maximum output of 20.6 kW and formed solar system has a conversion efficiency of 18.5%, which is the relative high efficiency in the world. With this efficiency the required generation can be realized by lower cost and smaller solar system. In the biomass power system, the gasification system is developed by collaborative research group of Fuji Electric Systems Company, which has the capacity of 20kW. In engine system, the Fixed Bed and Down-draft as well as Centered Air-intake typed system is used. Biomass fuels such as wood and charcoal is changed to flammable gas in high temperature conditions with the gas-in-taking system. The gas is combined with air in the mixer and fanned to the engine cylinder. Electricity of about 20kW is obtained from the output terminal of generator connected to the engine. Differing from the wind power turbine and solar PV systems, the biomass power system used in this hybrid system is with commercial availability, it operate with following particularities:

- Biomass fuel is gasified by partial combustion.
- The generated gas is a flammable mixture of CO, H2 and the other air elements.
- The gas is combined with air and sent to the engine cylinder.
- Electricity is produced by a generator connected to the engine terminal.

Corresponding Author: Zulati Litifu, Department of Mechanical Engineering,Synthetic Research Center, Ashikaga Institute of Technology, Japan

The characteristic of biomass gasification is denoted from two aspects:

- High efficiency in the ratio of input and output.
- Compact combustion system.

Driving by the natural wind and solar energy, the power sources only consisted by wind power turbine and solar system is unstable. Therefore, in advance of the system design, the expected energy production from each system was simulated; the expected power productions from the wind power turbine and the solar PV systems were estimated. Simulation result shows that there is relative weak and unstable power generation under measured wind speed and solar irradiance. In this hybrid system, the role of the biomass power system is expected to compensate for the lack of the electric energy produced from the wind power turbine and the solar PV systems on the days that has low wind speed or little sunlight. In according to calculation, if keep expected power generation from hybrid system, the compensating amount from biomass unit for the wind and solar power system should be with 5000 kWh per month throughout one year.

In the view of the micro-grid, this triple hybrid system may form a micro-grid for the main-grid of traditional power system and the control system of this micro-grid provides the perfect performance for wholly co-operation between the micro-grid and power system. It is also expected that the future co-operation between the micro-grid that possible established near this hybrid system. The control system of this hybrid system is, respectively fixed, although this way may results relative high cost, it may keep the hybrid system operating with high reliability and stability, the independent biomass power source may efficiently function to keep entire renewable system has good sustainable and steady power supply.

Monthly efficiency in economy and environment is proved by the general generation from hybrid power system regarding and comparing monthly average CO_2 discharge from hybrid system itself and traditional system. The result of this research indicated that the development of natural energy by using hybrid system of wind and solar power system can be compensated by the biomass generation and this kind micro-grid can be applied in the small scaled power system that widely distributed in suburb and urban region.

POWER GENERATION FROM THE HYBRID SYSTEM

Figure 1 shows the principle diagram of triple hybrid system (Mukund, 2005). As denoted in this figure, the
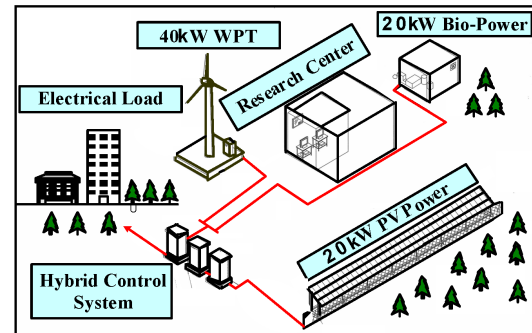

Fig. 1: Location of triple hybrid power system consisting of wind, solar and biomass power unites

wind power turbine is with capacity of 40 kW, which connected to the system load through control equipment. Biomass is with the capacity of 20kW and directly connected to the system connection control panel. Solar PV system is with the capacity of 20.6 kW and fixed near by the wind power turbine and biomass generator room, it is connected to the system connection panel through transformer and converter system. This three generation devices are used for educational load.

Power generation from wind power units: The actual power extracted from kinetic energy in air is just the different between upstream and downstream of the wind flow; it can be expressed by Eq. 1 with the unit of watts (Yasuyuki *et al.*, 2006):

$$P_r = \frac{1}{2}(\text{mass flow per second})\{V^2 - V_0^2\} \qquad (1)$$

Where
P_r : Mechanical power extracted by the rotor.
V : Upstream wind speed at the entrance of rotor blade.
V_0 : Downstream wind speed at the exit of the rotor blades.

The rate of air mass flow can be obtained by considering the air density and average wind speed; supposing air density is $\rho[\text{kg m}^{-3}]$ and area swept by the rotor blades is A [m²], it therefore, can be expressed by the Eq. 2:

$$\text{Mass flow rate} = \rho A \frac{V + V_0}{2} \qquad (2)$$

By the other form, the extracted power on the rotor can be also expressed by the following equation:

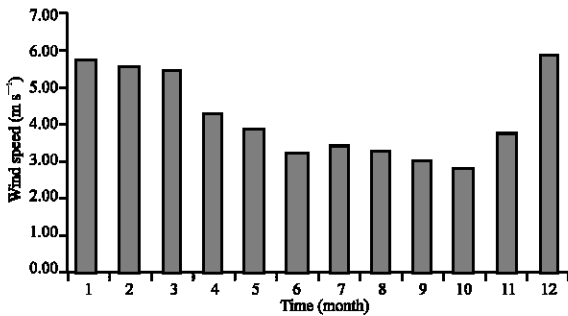$$P = \frac{1}{2}[\rho A \frac{V + V_0}{2}](V^2 - V_0^2) \qquad (3)$$

Fig. 2: Monthly wind speed derived from three year in installation site of wind power turbine

Define C_p as the fraction of power coefficient and λ is Tip-speed Ratio, P_0 and P_A are, respectively stand for the extracted power by rotor and caught power by blades area, C_M is torque coefficient on the rotor, C_p therefore, can be expressed by (4):

$$Cp = \frac{P_0}{P_A} = \lambda CM = \frac{1}{2}(1 + \frac{V_0}{V})[1 - (\frac{V_0}{V})^2] \qquad (4)$$

In practical application, the C_p and area A can be determined by the mechanical characteristics of wind power turbine, they are therefore can be expressed by a constant k and then the obtained power on rotor and the most appropriate wind speed can be expressed as:

$$P = \frac{k}{2}\rho V_3 \quad \text{and} \quad V = \sqrt{\frac{2}{3\rho k}} \qquad (5)$$

The capacity of wind power turbine to be installed can be determined by referring Eq. 5. Supposing power containing in each square meter is calculated based on measured wind speed, β is wished fraction of wind power turbine with unit of $kW\ m^{-2}$, A_{WT} is wished area swept by wind blades and then the capacity of wind power turbine can be expressed as:

$$P_{WT} = \text{ß} \times A_{WT}(kW) \qquad (6)$$

Wind speed in target site is studied based on the measured wind speed data within three years, it is shown that wind condition in this region may drives middle scaled wind power turbine, but it does not match for large scaled wind power turbine, Fig. 2 shows the monthly average wind speed derived from the measured records (Ushiyama Laboratory, 2004-2006):

Based on the wind condition shown in Fig. 2, wind power turbine with the capacity of 40 kW is selected for installation in target site. Table 1 indicates the specification of selected wind power turbine:

Table 1: The specification of wind power turbine selected for target region

Type of wind turbine	Rated power	Hub hight	Rated wind speed	Cut-in wind speed
Subaru 15/40	40kW	21m	11[m s^{-1}]	2[m s^{-1}]
Cut-out wind speed	Rotational velocity	Grid PCS	Frequency	voltage
25[m s^{-1}]	87[rpm]	Int. type	50Hz	200V

Table 2: The power generation obtained based on the wind speed and output characteristic curve

Simulated annualy generation of wind power turbine [kW]			
January	13.1071	July	6.1200
February	12.6272	August	6.0300
March	12.4049	September	5.6800
April	7.2500	October	4.9500
May	6.4800	November	6.3500
June	5.8200	December	13.3716

The monthly generation from proposed wind power turbine is denoted in Table 2. Here, the output is obtained from the simulation based on the Output and Wind Speed Curve under different wind speed. Since for one wind speed only one average power generation is considered, the generation that is widely distributed is represented by a calculated middle value.

It is known from Table 2, wind power turbine provides the most power in December in these three years.

Power generation from solar power unit: The contribution generated from the solar unit is possible to be determined by considering the solar irradiance measured in installed site, here the effect of direction to the sunlight should be regarded and (7) denotes the total amount of solar irradiance:

$$R_{gen} = R_{dir} + R_{sca} = R_{hor}\gamma_{gp} + R_{sca} \qquad (7)$$

R_{gen} : Total amount of irradiation on solar panel;
R_{dir} : Direct irradiance on solar panel;
R_{sca} : Scattered irradiance on horizontal solar panel;
R_{hor} : Direct irradiance for horizontal solar panel;
γ_{gp} : Geometric parameter of solar panel

Defining beta and alpha as the related parameter to shape of solar irradiance and then the probability density function of solar irradiance can be expressed by Eq. 8:

$$F(R) = \frac{1}{B(\alpha,\beta)}\left[\frac{(R - R_{min})^{\alpha-1}(R_{max} - R)^{\beta-1}}{(R_{max} - R_{min})^{\alpha+\beta-1}}\right]$$
$$= \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left[\frac{R}{R_{max}}\right]^{\alpha-1}\left[1 - \frac{R}{R_{max}}\right]^{\beta-1} \qquad (8)$$

Where, alpha and beta are parameters related irradiance characteristic, R_{max} and R are maximum and total
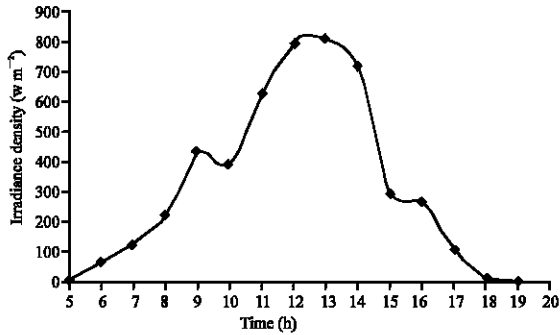
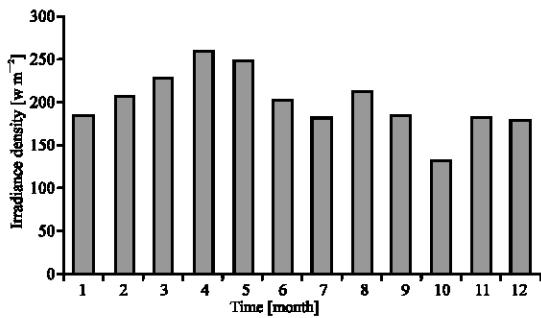Fig. 3: The average daily density of solar irradiance in April 2005

Fig. 4: The monthly average irradiance density from morning 5 to afternoon 19 o'clock

amount of irradiance on the solar panels. Regarding R is the solar irradiance on the panel with efficientη, temperature factor K_T and area A and then the output generation will be $P = AR\eta K_T$, by using generation distribution function, the possible power generation from solar panels can be also determined by the Eq. 9:

$$F(P)=\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\left[\frac{R}{R_{max}}\right]^{\alpha-1}\left[1-\frac{R}{R_{max}}\right]^{\beta-1} \qquad (9)$$

The average daily density of solar irradiance in the target site on the sunlight available days in April 2005 is derived and shown in Fig. 3.

It is known that the distribution of monthly irradiance has much different during one year; and even the daily distribution is with much difference due to near sea weather, Fig.4 shows the average monthly solar irradiance density derived from 2004-2006.

The monthly average generation from the solar panel can be obtained from the monthly solar irradiance shown in Fig. 4; monthly average power generation from solar array is denoted by Table 3.

Power generation from biomass unit: The power generation from a biomass machine can be expressed by Eq. 10:

Table 3: Power generation from solar power unit derived from the simulation

Monthly average generation from solar power unit derived from simulation

January	3591	July	3231.9
February	4003	August	3704
March	4296	September	3282
April	4694	October	2439
May	4535	November	3607
June	3671	December	3591

Table 4: The characteristics of biomass power unit used in the hybrid system

Model of engin	13B
Type of generator	Rotary (2 rotor)
Cooling type	Water cooling
Displacement	654[cc]×2
Compression	9.7
Air fuel ratio	1:01
Charcoal consumption	6.4-14.5[kg h^{-1}]
Wood consumption	6.9-15.7[kg h^{-1}]
Generator structure	2 pole/3Φ200V
Power frequency	50[Hz]
Terminal voltage	3Φ200V

$$P_{bio} = KM + kP_N \qquad (10)$$

Where, P_{bio} is power output from the biomass machine; M is consumption amount related to rated power generation; K is converting ratio of fuel for biomass machine; k is an experiment fraction related to the fuel quality and environment influence, k may be positive or negative in according to the actual application environment, P_N is rated output power of biomass machine. The available power generation from biomass machine and specification of machine and generator are difficult to express by precision numeral method, the historical experiment from actual operation is important. Table 4 shows the characteristic of biomass power unit, two kinds of fuels can be used in this biomass machine, the total power generation is about 20kW under the rated fuel input. Biomass machine uses fixed bed with down draft and centered air-intake typed gas-feeder. Biomass fuel of charcoal and wood is first converted into flammable gas in high temperature conditions in the gas-feeder. Gas combines with the air in the mixer and then fans to the engine cylinder. At the terminal of generator, the power capacity of 20kW is produced from the generator connected to the engine.

It is expected to use the operational characteristics of biomass power unit to compensate for wind and solar power generation, in this simulation, 18.4kW that is available generation of biomass unit is used. Due to the initially application, the biomass power unit and related accessory devices are still under developing. Figure 5 shows the mechanical inter-connection of biomass machine used for this hybrid system.
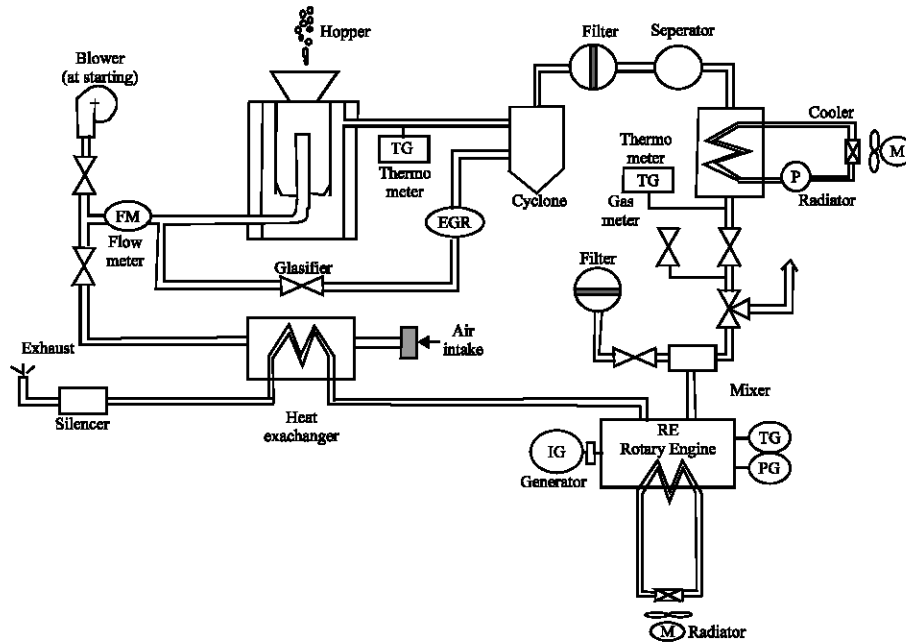
Fig. 5: Inter-mechanical connection of biomass machine established for the hybrid system

SYSTEM OPERATIONAL ANALYSIS

Two alternative loads that have the power load particularity of educational user are connected to the hybrid system. System itself has no any battery to store and regulate the electric power generated from entire hybrid system; this condition makes hybrid system distributing its generated power directly (Ferando and Hernan, 2006). Figure 6 shows the inter-connection of triple hybrid system to main system grid and 2 AC load. Power load of entire system has no direct current load. Wind power and solar power as well as the biomass system have their converting and regulating system as shown in figure. Wind power system has double current converting system from alternative current into direct current and from direct current into alternative current, solar power system has current inverter from direct current into alternative current.
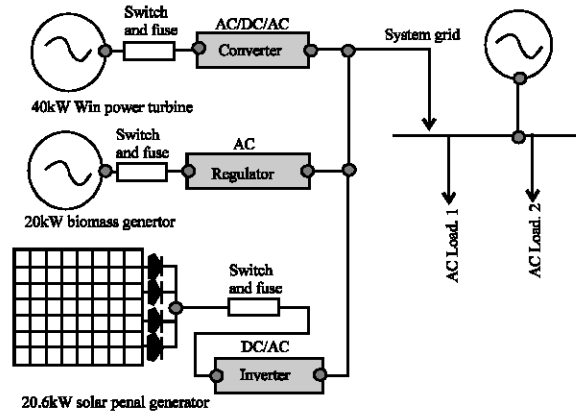
Electrical characteristic of the AC load: Define P_{Li} is the hourly power demand of AC Load.1 and AC Load.2 from hour t_j to t_{j+1}. P_{iab} is power demand from laboratory in university from hour t_j to t_{j+1}. P_{off} is power demand from office electric device from hour t_j to t_{j+1}. P_{add} is additional power demand mainly and averagely consumed by accessory equipments of hybrid system from hour t_j to t_{j+1}. Then the hourly power demand of the power load can be expressed by Eq. 11:

$$P_{L,i} = \int_{t_j}^{t_{j+1}} P_{lad} + \int_{t_j}^{t_{j+1}} P_{off} + \int_{t_j}^{t_{j+1}} P_{add} \quad (11)$$

Fig. 6: The inter-connection of triple hybrid system to main system grid and AC load

The AC Load.1 in average amount is 800 kW and in maximum and minimum are respective is 1200 and 120 kW, AC Load.2 including the power waste of accessory electric devices is estimated as 80kW in average and in maximum and minimum respectively is 100 and 65 kW, Fig. 7 shows the characteristics of average electric power load connected to hybrid system. The monthly energy demand of power load can be expressed by the following Eq. 12:

$$W_{L,g} = \sum_{n}^{i=1} [\sum_{m}^{j=1} (P_1 t_1 + P_2 t_2 + ... + P_m t_m)] \quad (12)$$
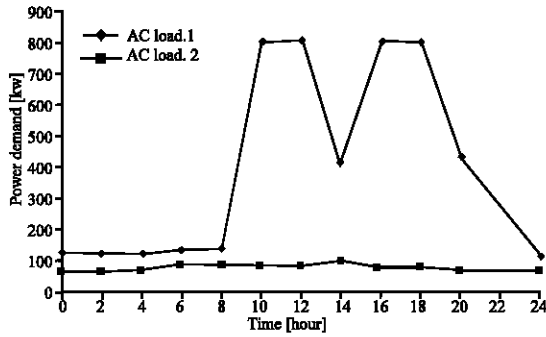
Fig. 7: Characteristics of average electrical load connected to hybrid power system

Where, $W_{L.g}$ is monthly general demanded power energy, P_j is hourly power demand in hour t_j, $j=1,2...24$ and $i=1,2...31$ (or 28 and 30 in according to the different month).

Cooperation of hybrid system with the load: The general contribution of hybrid system is the sum of wind, solar and biomass power unites, it can be expressed by Eq. 13:

$$P_{G.i} = \int_{t_j}^{t_{j+1}} P_{win} + \int_{t_j}^{t_{j+1}} P_{sol} + \int_{t_j}^{t_{j+1}} P_{bio} \qquad (13)$$

Where, $P_{G.i}$ is general power generation from the hybrid power system from hour t_j to t_{j+1}.P_{win} is power generation from wind power turbine from hour t_j to t_{j+1}. P_{soi} is power generation from solar PV panel from hour t_j to t_{j+1}. P_{boi} is power generation from biomass power unit from hour t_j to t_{j+1}. The general monthly-generated electric energy from hybrid system is denoted as:

$$W_{G.g} = \sum_{i=1}^{n} [\sum_{j=1}^{m} (P_{1.win} t_1 + P_{1.sol} t_1 + P_{1.bio} t_1 + \qquad (14)$$
$$... + P_{m.win} t_m + P_{m.win} t_m + P_{m.bio} t_m)]$$

Where, $W_{G.g}$ is monthly general demanded power energy, P_j is hourly power demand in hour t_j, $j=1,2...24$ and $i=1,2...31$ (or 28 and 30 in according to the different month).

Use POCL (Percentage Of Covered Load) to express the degree of covered load percentage to by the hybrid power system. POCL shows the contribution condition of the hybrid system to the connected power load and provides a direct reference for supervising the benefit in different month. POCL may be expressed by (15):

$$POCL = \frac{W_{G.g}}{W_{L.g}} \times 100\% \qquad (15)$$

Table 5: POCL related to AC Load.1 with the different contribution possibility of the hybrid system

WPT = 13.12kW, BMP = 18.4kW, SPV = 3.59kW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	26.27	26.27	26.27	24.14
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	24.93	4.34	4.42	8.64
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	4.34	4.21	7.18	26.27
WPT = 0kW, BMP = 18.4kW, SPV = 3.59KW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	15.33	15.33	15.33	14.42
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	15.21	2.7	2.78	5.45
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	2.7	2.57	4.19	15.33
WPT = 13.12kW, BMP = 18.4kW, SPV = 0kW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	26.27	26.27	26.27	23.35
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	23.35	3.94	3.94	7.67
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	3.94	3.94	7.18	26.27

Table 6: POCL related to AC Load.2 with the different contribution possibility of the hybrid system

WPT = 13.12kW, BMP = 18.4kW, SPV = 3.59kW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	48.49	48.49	48.49	38.71
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	39.96	43.41	44.19	37.40
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	43.41	42.06	48.49	48.49
WPT = 0kW, BMP = 18.4kW, SPV = 3.59KW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	28.31	28.31	28.31	23.12
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	24.38	27.01	27.79	23.59
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	27.01	25.66	28.31	28.31
WPT = 13.12kW, BMP = 18.4kW, SPV = 0kW			
Time interval [h]	0-2	2-4	4-6	6-8
CPOL [%]	48.49	48.49	48.49	37.43
Time interval [h]	8-10	10-12	12-14	14-16
CPOL [%]	37.43	39.40	39.40	33.18
Time interval [h]	16-18	18-20	20-22	22-24
CPOL [%]	3.940	3.940	48.49	48.49

When this hybrid system contributes 0kW, the POCL gives percentage with zero; it is available to present annual POCL for all months. Here, the average POCL in April of three years is considered only. Table 5 and 6 shows POCL related to April in three year.

It is known that the POCL for AC Load.2 is very obvious; it can cover almost the half of the entire load. And also, for AC Load.1, the POCL is not so obvious but still gives the number from about 3.94 to 26.27%. From the entire view, the application of this hybrid system shows very good efficiency, the economic and environment efficiency will be very high in according to the value of POCL shown in above tables.

ECONOMY ANDENVIROMENT EFFICIECY

The economy and environment efficiency is derived based on monthly contribution of hybrid power system.

Economical efficiency of hybrid system: The whole columns in Fig. 8 are the total amount of monthly average power generation obtained from hybris system, which is obtained in accordance to simulated value based on the generation of wind power and solar power as well as the biomass power unit, the operation characteristics of three units are considered in performing total generation.

In this study, the power loss in power transmission line is ignored. The monthly increased power energy makes the power demand in load reduced in the same amount. Hence, the annual reduction in expenditure used for electricity can be derived by converting the generated energy from hybrid system into cost with the ratio of 18 J.Y (Japanese Yen) per kilowatt and then the reduction of expenditure used for the electricity in different month of the year is shown in Table 7 (Izumi, 1999).

Environmental efficiency of MHPP and MWPT: We have much more interest in environment efficiency than financial efficiency. Anyway, it is necessary to indicate the amount of CO_2 discharged from hybrid power system. Define M_M as monthly amount of CO_2 produced from hybrid power system in operation, it may be easily determined by (16):
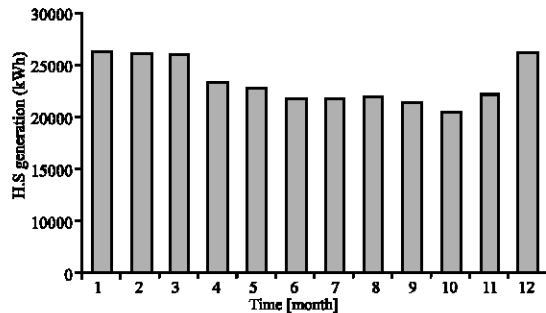

Fig. 8: The monthly generated power energy from the triple hybrid system

Table 7: Reduction of expenditure used for electricity in different month of the year

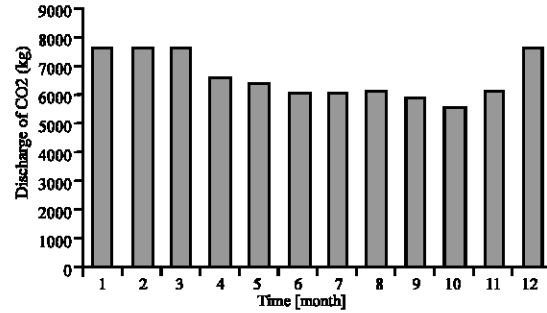| Reduced expenditure with unit [JFT.Y]			
January	454871	July	359665
Februay	453996	August	364617
March	454907	September	354617
April	393253	October	334228
May	381222	November	367506
June	361465	December	458299

Fig. 9: Monthly reduction of CO_2 after applying triple hybrid power system in target site

Table 8: Discharge of CO_2 produced from the hybrid system in different month of the year

Discharge amount of CO2 with unit [kg]			
January	2943.96	July	2796.00
Februay	2936.32	August	2796.84
March	2933.36	September	2787.11
April	2828.01	October	2767.01
May	2811.03	November	2802.96
June	2792.27	December	2949.48

$$M_M = W_{wid}k_{co_2}^w + W_{bio}k_{co_2}^b + W_{sol}k_{co_2}^s \qquad (16)$$

Where, k_{co2}^s (= 8 g kWh^{-1}) and k_{co2}^w (= 29.5 g kWh^{-1}) and k_{co2}^b (= 200 g kWh^{-1}) indicate the CO_2 coefficient of wind, solar and biomass that are corresponding with the monthly power generation and W_{win}, W_{bio} and W_{sol} are respectively indicate the generation from hybrid system. The calculation result is shown in Table 8.

Regarding the thermal power using by user now, it is necessary to introduce the CO_2 coefficient of traditional thermal power that equals to 300 g KWh^{-1}. Regarding to the total generation from triple hybrid system, we can easily obtain the monthly reduction of CO_2 as shown in Fig. 9.

CONCLUSION

The triple hybrid system in this study, provides a good sample of micro-grid established by three kind of dispersed unites. The operation experience shows that the utilization of wind power turbine is still relative low under measured wind speed; it is possible to estimate the capacity of wind power turbine by using the reference obtained from the power generation density on the area swept by wind flow. Anyway, the wind power turbine of 40kW provides annually the power energy in an amount of 73146 [kWh], it is an significant amount in the view of economic and environment aspects. A battery is not established in the solar power system due to the existing of wind and biomass power units. Battery is necessary in dependent operation; the condition without battery makes

this the generation from solar system should be consumed in advance. Biomass unit plays a role of smoothing and compensating the power generation from wind and solar units, the detail characteristics of biomass function in this hybrid system will be the next research of this system. The research result shows that the hybrid system may be able to operate with the main system and provide significant efficiency in economy and environment.

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