Designs and Testing of a 10 kWp Standalone PV Prototype for Future Community Grid Adapted for Remote Area in Thailand

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ABSTARCT

This paper describes the design and testing of a 10 kW_p photovoltaic system and summarizes its performance results after the first eleven months of operation. This system functions as a stand-alone power system that is used to supply electricity for isolated buildings and is designed for integration with a Micro Grid System (MGS), which is the future concept for a renewable energy-based power network system for Thailand. The system is comprised of the following components. An array with three different types of PV modules consisting amorphous thin film 3,672 W, polycrystalline solar cell 3,600 W and hybrid solar cell 2,880 W, making up a total peak power of 10.152 kW. In addition, there are three grid connected inverters (GI) of 3.5 kW each, three bi-directional inverters (BI) of 3.5 kW each and an energy storage system of 100 kWh. After the first eleven months of system operation, it was found that all the components and the overall system had worked effectively. In total, the system had generated about 14,124 kWh and the average electricity production per day was 42.8 kWh. It ranged from 33.08 kWh to 48.73 kWh. The average efficiency of amorphous thin film panel, polycrystalline panel, hybrid solar cell panel and entire photovoltaic panel system was 6.26%, 10.48%, 13.78% and 8.82% respectively. The efficiency of GI1, GI2, GI3 and entire GI ranged from 86-89%, 90-92%, 88-90% and 89-91%. While the average efficiency of BI ranged from 85-90% for charger mode and 87-92% for inverter mode. The final yield (Y_F) ranged from 2.54 h/d to 3.62 h/d and the performance ratio ranged from 0.57 to 0.79. From the analysis of the daily energy production, daily energy consumption and energy storage, the results seem to indicate that there was some mismatching between energy supply and demand in the system. However, this can be overcome by integrating the system to a micro grid network whereby the energy from the system can be diverted to other loads when there is a surplus and additional energy can be drawn from external sources and fed to the system when the internal supply is insufficient.

Keywords : *Design and Testing, Photovoltaic Power System.*

1. INTRODUCTION

The Energy Park project at the School of Renewable Energy Technology (SERT) in Naresuan University, Phitsanulok province, is the first and the biggest renewable energy center in Thailand. One of the project's major aims is to study, research and develop the most applicable and appropriate electricity generating systems that use renewable energy resources. This project was started in 2001 and was financially supported by the Energy Conservation Promotion Fund from the Energy Policy and Planning Office of the Ministry of Energy, Thailand.

The two main tasks of this project are to study and evaluate the various independent renewable energy supply systems that are suitable for stand-alone power generation and to develop these systems eventually for integration to a micro grid system (MGS), which is the future concept for a renewable energy-based power network system for Thailand.

Among the various types of renewable energy resource that can be used to produce electricity, solar energy, biomass and fuel cell are the three most promising ones that are currently being studied as part of the Energy Park project. This is due to the fact that Thailand has a high potential for both biomass and solar, with a yearly average daily global solar insolation of 5 kWh/m^2.day [1], while fuel cell is chosen for its high efficiency and nonpolluting qualities. In the case of electricity generation using biomass or fuel cell technology, output power management is relatively less complicated since the input energy supply is usually known and controllable. This is in contrast to a solar thermal or photovoltaic power generating system where the input supply in the form of solar energy varies with time and meteorological conditions. Hence, there is a need to conduct more studies concerning solar-based power systems in order to better understand the operating characteristics of these systems.

In view of the above, a 10 kW_p stand-alone photovoltaic power system has been installed and operated since June 2005 under the Energy Park project to study the performance and behavior of this type of power system. This system is used to supply electricity to the Testing Building located in the Energy Park which is one example of "isolated building". This system was also designed as a prototype model for supplying power to a micro grid system based on the future concept of a renewable energy-based power network for Thailand. This system is not the same as the usual stand-alone photovoltaic systems in that the PV array has been specially configured to comprise of three different types of solar cell modules. Moreover, it is also the first time that a grid inverter and a bi-directional inverter are used in combination in such a system under the realistic operating conditions of Thailand.

This paper presents the system design, the system components, the system testing and an evaluation of the performance of the system during its first eleven months of operation from June to November 2005. The efficiencies of the system's components such as the PV generator and power conditioning unit were analyzed and the performance of the entire system was also examined.

2. SYSTEM DESIGN AND SYSTEM COMPONENTS

2.1 System design and conditions

The 10 kW_p photovoltaic power system was designed based on two main concepts; (i) as a self-sufficient power station where the input energy supply is dependent only on two built-in sources, namely the photovoltaic panels and battery bank, and (ii) as a prototype model with an appropriate system size for integration to a micro grid system in the future.

Besides it was designed under the sunlight conditions and some other, are as follows;

1. On sunny days, in the daytime, the system will be operated by direct energy from the sun and the surplus energy will be stored in the battery.
2. On semi-cloudy days, in the daytime, the system will be operated by energy supplies, irradiance and battery storage. And in the night period the system operated by energy from the battery.
3. On cloudy days, during daytime and the nighttime, the system is operated by energy from the battery only.
4. All the electrical appliances connected to the system are operated by AC current.

Essentially, this system was designed and installed as a stand-alone photovoltaic power system which has only battery backup. However, its design is not exactly the same as the normal stand-alone photovoltaic system because it uses two different inverters in its system configuration. The first inverter, known as a grid connected inverter (GI), converts DC from the photovoltaic array to AC and supplies directly to the load while the excess energy will be charged to the battery bank via a second inverter [2]. This second inverter, known as a bi-directional inverter (BI), has two functional modes, i.e. charger mode and inverter mode. During charger mode, the inverter converts AC to DC and charges the battery bank. During inverter mode, the inverter converts DC from the battery to supply to the AC load during the night and whenever the irradiance is insufficient in the daytime. The schematic block circuit diagram of the 10 kW_p stand-alone photovoltaic power system is illustrated in Fig.1.

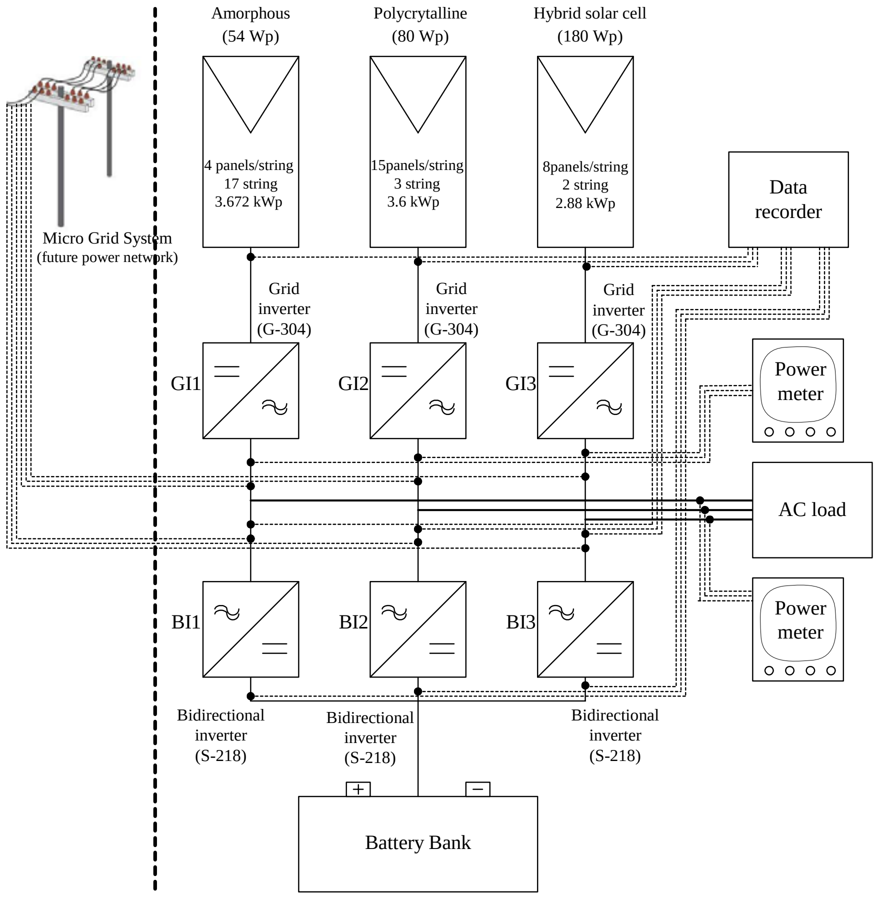

Fig. 1 Schematic block circuit diagram of the PV system.

2.2 System components

The 10 kW_p photovoltaic power system is composed of the following three main components; photovoltaic generator, power conditioning system and the energy storage system. The photovoltaic generator is consisted of three different types of photovoltaic technology. First, amorphous thin film (a-Si) 3,672 W of 54 W x 68 modules are connected into 17 strings, 4 modules each. Second, polycrystalline solar cell (p-Si) 3,600 W of 80 W x 45 modules are connected into 3 strings, 15 modules each and the last is hybrid solar cell (HIT) 2,880 W of 180 W x 16 modules are connected into 2 strings, 8 modules each. The total peak power of this system is 10.152 kW. The power conditioning system is consisted of three grid connected inverters (GI1, GI2 and GI3), 3.5 kW each, Leonics G-304 and three bi-directional inverters (BI1, BI2 and BI3), 3.5 kW each, Leonics S-218C. The energy storage system is 100 kWh battery, Fiamm SGM 2000 (16 OPzV) 2 V 2000 Ah x 24 cell [3].

3. MONITORING SYSTEM

The 10 kW_p PV system is fully monitored to assess the potential of PV technology and performance of the system. The monitoring system was designed to meet guideline of standard IEC 61724 [4] and within the framework of the International Energy Agency Photovoltaic Power System (IEA PVPS) Program task 2 [5,6,7]. For the general data acquisition, a multi-function measuring device measures the parameters are shown in Table 1:

Table 1 System parameters.

Electrical parameters:	Meteorological parameters:
DC, AC voltage of PV array1, 2 and 3	Tilt irradiance (Kipp & Zonen CM11)
DC, AC current of PV array1, 2 and 3	Total irradiance (Kipp & Zonen CM11)
Power of PV array1, 2 and 3	Module temperature PV panel1, 2 and 3
status of GI1, GI2 and GI3	Ambient temperature
fault of GI1, GI2 and GI3	Wind speed
DC voltage battery	
DC current battery	
status of BI1, BI2 and BI3	
fault of BI1, BI2 and BI3	
frequency	
Daily energy	
Monthly energy	
Annual energy	

The parameters for performance evaluation used to assess the PV subsystem and entire PV system are as follow:

- The final yield (Y_F) is the portion of the daily energy of the entire PV system which is delivered to the load per kilowatt peak of installed PV array.
- System losses (L_S) are gained from inverter conversion losses in grid-connected systems and from accumulator storage losses in stand-alone systems.
- Array capture losses (L_C) are due to PV array losses.
- Performance ratio (PR) is the ratio of PV energy actually used to the energy theoretically available.

Some of the equations used to evaluate the system performance are given as follow:

array yield: $Y_A = E_A/P_0$ kWh/kW_p d (1)

final yield: $Y_F = E_{use}/P_0$ kWh/kW_p d (2)

reference yield: $Y_R = \int G_i \, dt / G_{STC}$ kWh/kW_p d (3)

capture losses: $L_C = Y_R - Y_F$ kWh/kW_p d (4)

system losses: $L_S = Y_A - Y_F$ kWh/kW_p d (5)

Performance Ratio: $PR = Y_F/Y_R$ (6)

Where:

E_A array output energy (kWh)
P_0 peak power (kW)
E_{use} energy delivered to load per day
G_i mean daily insolation in array plane (kWh/m^2 d)
G_{STC} reference irradiance at STC (1 kW/m^2)

4. ANALYSIS OF SYSTEM AND SUBSYSTEM PERFORMANCE

4.1 Analysis of PV panel performance

As mentioned earlier, the 10 kW_p photovoltaic generator is consisted of three different types of photovoltaic technology and each of them has unequal watt peak. Thus, this part of the study will analyze and compare the performance of both entire PV generator system and individual PV generator technology. Some example data of the DC output power generated by the entire PV generator was measured at the site on October 2005 and was shown in Fig. 2. The results showed that the output power generated is linearly dependent on the irradiance.

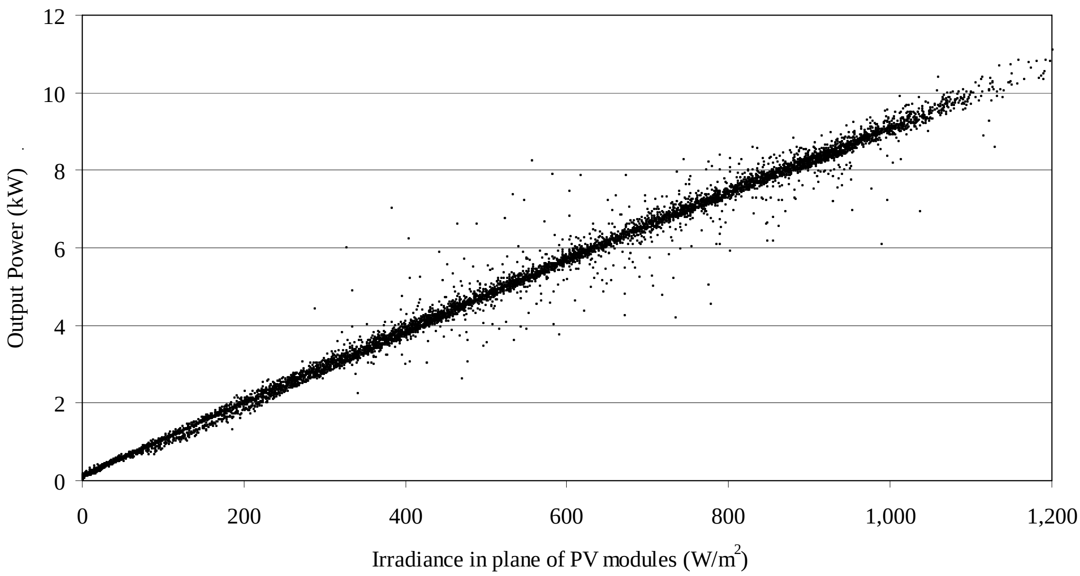

Fig. 2 The output power versus irradiance in Oct 2005.

Fig. 3 shows the comparison of the output power and the efficiency of both the entire PV generator system and individual PV generator technology on 30 October 2005 while Fig. 4 shows the comparison of the individual PV module temperature on the same day.

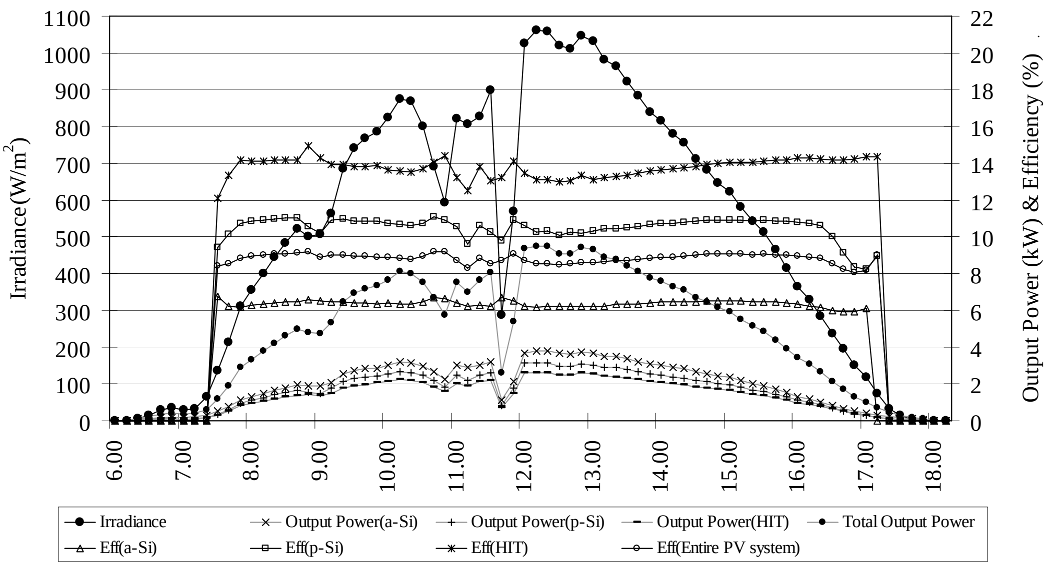

Fig. 3 The output power & PV efficiency versus irradiance on 30 Oct 2005.

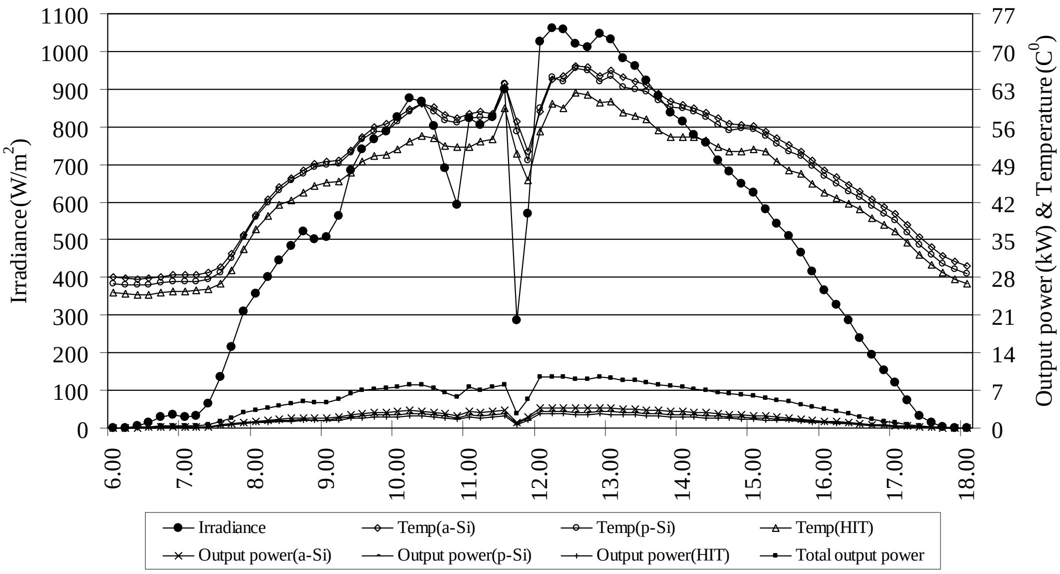

Fig. 4 The output power & module temp. versus irradiance on 30 Oct 2005.

From Fig. 3 and Fig. 4, it was found that the maximum value of the solar irradiance is 1063 W/m^2 at 1210 hrs, while the other measured data such as the PV module temperature and the PV output power generated, and the analyzed data such as the output power generated per watt peak and the individual PV efficiency are shown in Table 2.

Table 2 Photovoltaic panels technology performance comparison.

PV technology	module temperature.(^{0}C)	output power (kW)	output power/Wp (%)	efficiency (%)
a-Si	64.80	3.78	102.94	6.26
p-Si	65.15	3.13	86.94	10.48
HIT	60.20	2.61	90.63	13.78

At the same solar irradiation condition, all module temperature has the same trend and dependent on irradiance and time of day. It is observed that the module temperature of a-Si and p-Si are close but both are higher than HIT, with a range of 3.0-6.7 ^{0}C or an average of about 4.4 ^{0}C. The highest module temperature to the lowest is given by p-Si, a-Si and HIT, is 65.15 ^{0}C, 64.80 ^{0}C and 60.20 ^{0}C respectively. The output power generated by a-Si is the highest at 3.78 kW, next is p-Si at 3.13 kW and HIT is the lowest at 2.61 kW, while the total output power of the entire PV generator system is 9.52 kW. The individual PV output power generated is quite normal when considered in relation with its watt peak; hence these output power values are not used to compare the PV generated performance. Instead, the percentage output power per watt peak to compare the PV generator performance is used [8-10]. The highest output power per watt peak is given by a-Si, followed by HIT and p-Si is the lowest. From table 2, one interesting point to note is the output power per watt peak of a-Si which is observed to be 102.94%. This value occurred because it was a new panel and was produced with a slightly higher peak power than its specifications. With regards to the output power, the highest value is given by a-Si, followed by p-Si, while HIT is the lowest (Fig. 5).

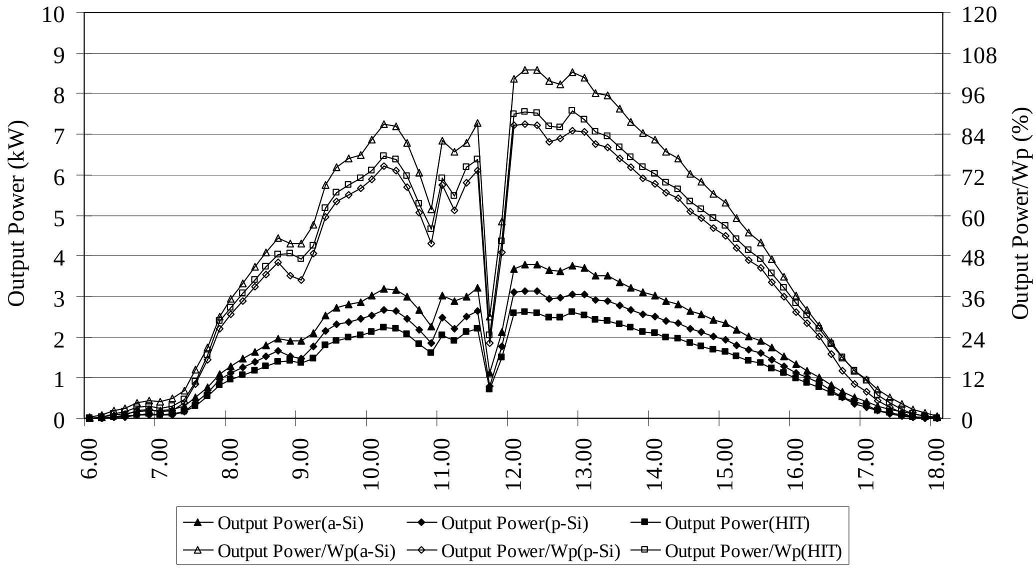

Fig. 5 The output power & the output power per watt peak on 30 Oct 2005.

The average efficiency of a-Si panel, p-Si panel and HIT panel are 6.26%, 10.48% and 13.78% respectively, and the average efficiency of the entire PV generator system is 8.82%. Each PV panel's efficiency is slightly different from the company's specification and this is probably due to the difference between the working temperature at the actual site and the conditions at STC. Also, the accumulation of dirt on the surface of PV modules may affect the output power and the efficiency of the PV generator system.

4.2 Analysis of grid inverter performance

The three grid inverters (GI) used in this system, GI1, GI2 and GI3, were produced by the same company with equal capacity of 3.5 kW each (Leonics G-304). Each inverter was connected in line with a-Si panel (GI1), p-Si panel (GI2) and HIT panel (GI3) respectively. The measured data and evaluated revealed a bit different efficiency range of each GI which is about 86-89% for GI1, 90-92% for GI2 and 88- 90% for GI3. While the efficiency of the entire GI system ranged between 89-91%. All GI efficiency curves model have the same trend as shown in Fig. 6.

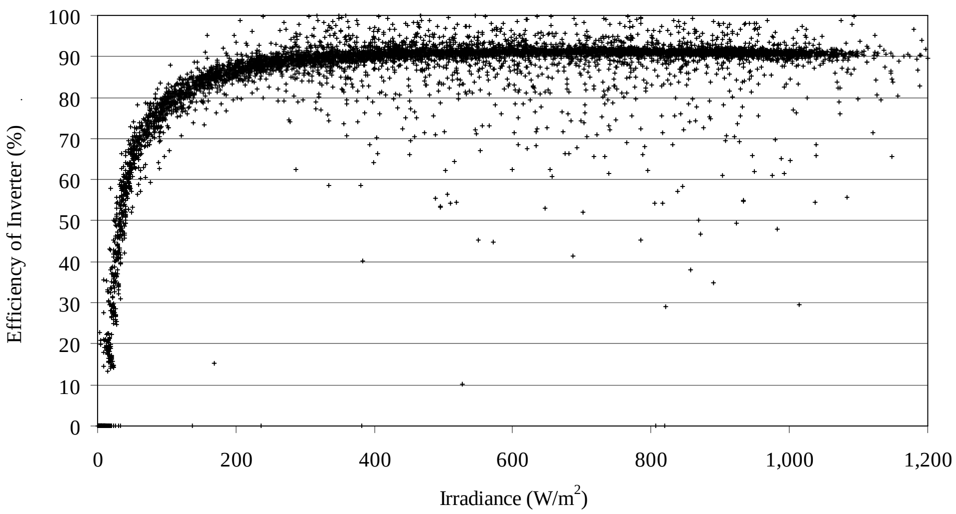

Fig. 6 The GI efficiency curves versus irradiance in Oct 2005.

All GI efficiency curves indicated the same shapes and the GI do not perform well in case of low solar irradiance especially when the solar irradiance is lower than 250 W/m^2. Also, the high scattering of the efficiency values is an indication of the quality of the GI equipment.

4.3 Analysis of bi-directional inverter performance

The three bi-directional inverters (BI) used in this system, BI1, BI2 and BI3, similar to the GI, were produced by the same company and have equal capacity of 3.5 kW each (Leonics S-218C). Each inverter was connected in line as GI1, GI2 and GI3 respectively. At the same time, each was connected as a single phase to AC load. The measured data and evaluated show similar efficiency for both functional modes, i.e. charger mode and inverter mode. For charger mode (above X axis), the average efficiency ranged between 85-90%, and for inverter mode (under X axis), shown as minus values, the average efficiency ranged between 87-92%, see Fig. 7. This means that BI with inverter mode works more effectively than charger mode; this can be due to the different input power of each mode. For charger mode, the input power through BI is the output power from GI which came from the PV panel that depends on the solar irradiation. While in inverter mode, the input power through BI is the output from battery which depends on load demand, is quite constant.

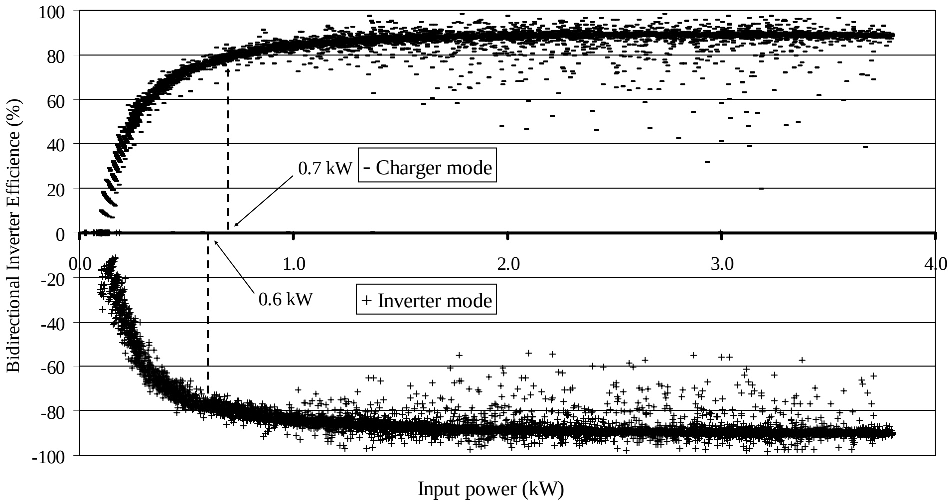

Fig. 7 The BI efficiency curves versus irradiance in Oct 2005.

Also, it was found that there was a slight difference in efficiency between each BI but it was insignificant. From Fig. 7 two interested points were noted; first, the input power needs for BI operated with an acceptable efficiency of 80%, were observed to be about 0.7 kW for the charger mode and about 0.6 kW for the inverter mode. Second, the high scattering of data in the BI efficiency curves indicated that the quality of the BI equipment was similar to that of the GI.

4.4 Analysis of storage system

The battery used in this system is 100 kWh, Fiamm SGM 2000 (16 OPzV) 2 V 2000 Ah x 24 cell. Two main purposes of the battery in this system are, (i) as a backup in case of low solar irradiation in daytime and, (ii) as an energy supply source in nighttime. After the first eleven months of system operation, it was found that the use of energy from the battery storage was quite small, see Fig. 8, where the lowest SOC was 93.9% and the maximum power discharged was 3.86 kW. This can affect both battery life and battery efficiency [11] for long term operation. However, it is not too serious for the present situation. Otherwise, it means that at present, this PV power system may be oversized for the current energy demand. However, as mentioned before, this PV power system is also designed for integration to a micro grid system (the future energy supply network) where it may be connected to other energy supply sources and able to serve a higher load demand.

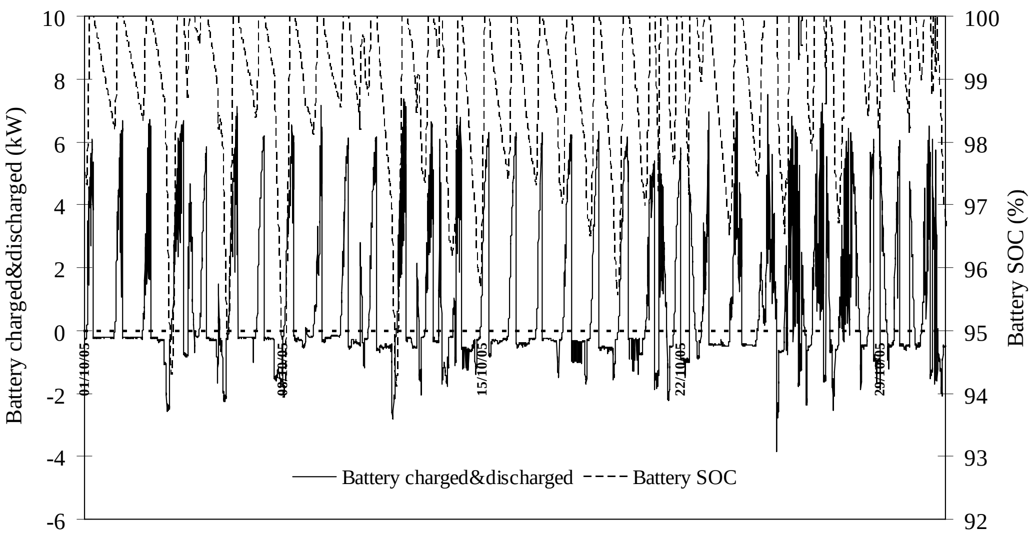

Fig. 8 The status of battery in Oct 2005.

4.5 Analysis of daily energy balance

In this part, the relation of daily energy production and daily energy consumption for three different cases of solar irradiation is considered, determined by the average daily solar irradiation from 6.00 a.m. to 18.00 p.m. Firstly, sunny day means the average daily solar irradiation is higher than 600 W/m^2. Secondly, semi-cloudy day means the average daily solar irradiation is between 400-600 W/m^2 and thirdly, cloudy day means the average daily solar irradiation is lower than 400 W/m^2. For simplicity, an approximated daily energy consumption of 38.9 kWh is used to compare with each daily energy production. Three examples of each case are illustrated in Fig. 9-11.

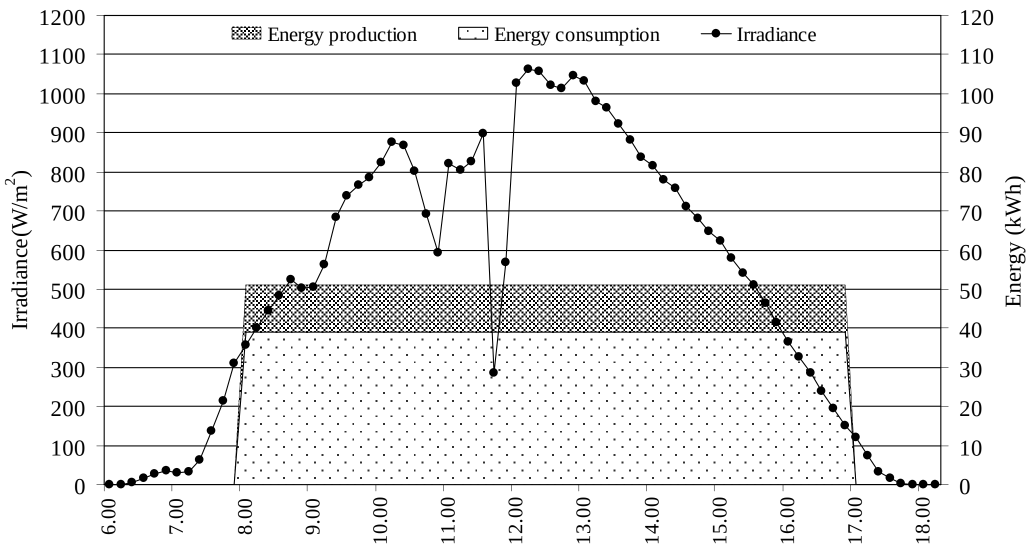

Fig. 9 The energy production versus energy consumption on 30 Oct 2005.

In case of sunny day, for example on the day of 30 October 2005, see Fig. 9, the average solar irradiation was about 612.3 W/m^2 which produced the energy about 51.0 kWh, is higher than the approximated daily energy consumption about 12.1 kWh. Normally this surplus energy will be charged to battery, but in case where the battery is fully charged this surplus energy will be unutilized. These results confirmed the advantage of using this surplus energy to share with the other energy demand sources.

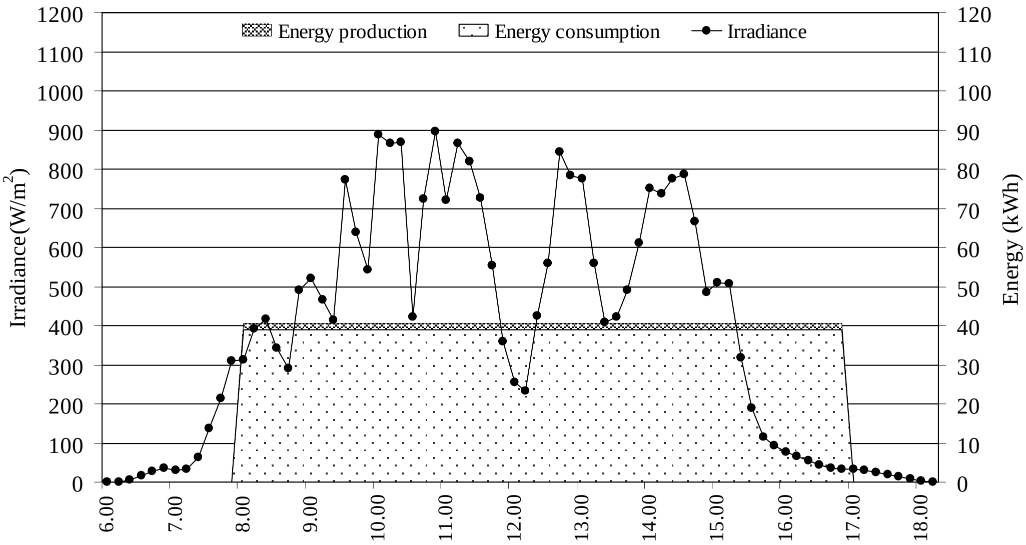

Fig. 10 The energy production versus energy consumption on 3 Oct 2005.

In case of semi cloudy day, for example on the day of 3 October 2005, see Fig. 10, the average solar irradiation was about 479.9 W/m^2 which produced the energy about 40.6 kWh, was slightly higher than the approximated daily energy consumption by about 1.7 kWh. This case is similar to a pure stand-alone system where the input energy is supplied from two sources, PV generator and battery. This is good for battery life which can be charged and discharged with the deep cycle.

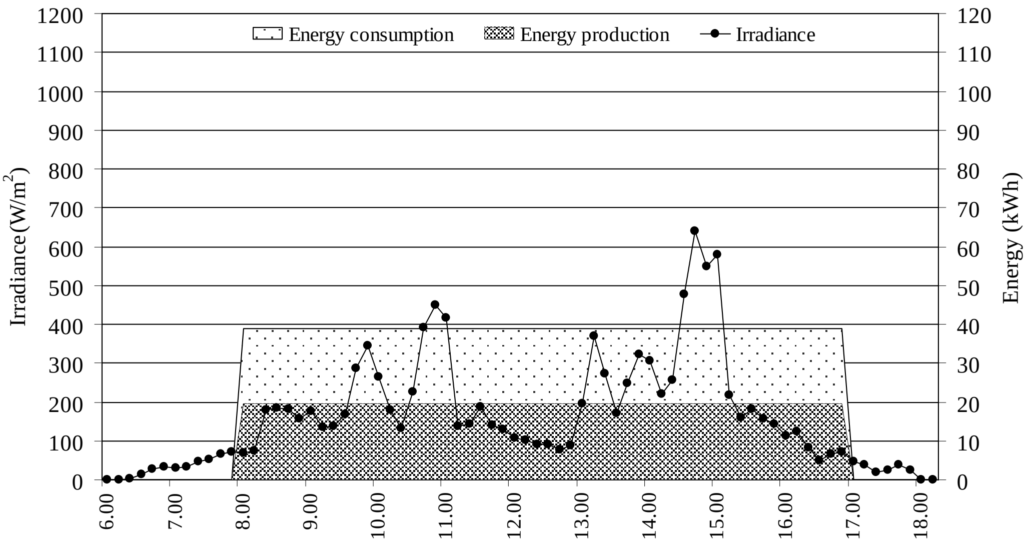

Fig. 11 The energy production versus energy consumption on 14 Sep 2005.

In case of cloudy day, for example on the day of 14 September 2005, see Fig. 11, the average solar irradiation was about 226.4 W/m^2 which produced the energy about 19.5 kWh, is less than the approximated daily energy consumption by about 19.4 kWh. In this case, the PV stand-alone power system may be inadequate because even with battery backup, the power supply system can fail if the weather remains continuously cloudy for many days. However, this situation can be overcome by using energy from the other supply sources. These results also support the energy network as in the first case.

4.6 Analysis of entire PV system performance

During the first eleven month of operation, the 10 kW$_p$ PV system can generate about 14,124 kWh, the average of electricity production per day is 42.8 kWh. It ranged from 33.08 kWh (December 2005) to 48.73 kWh (April 2006). The system performance evaluation is shown in Fig. 12.

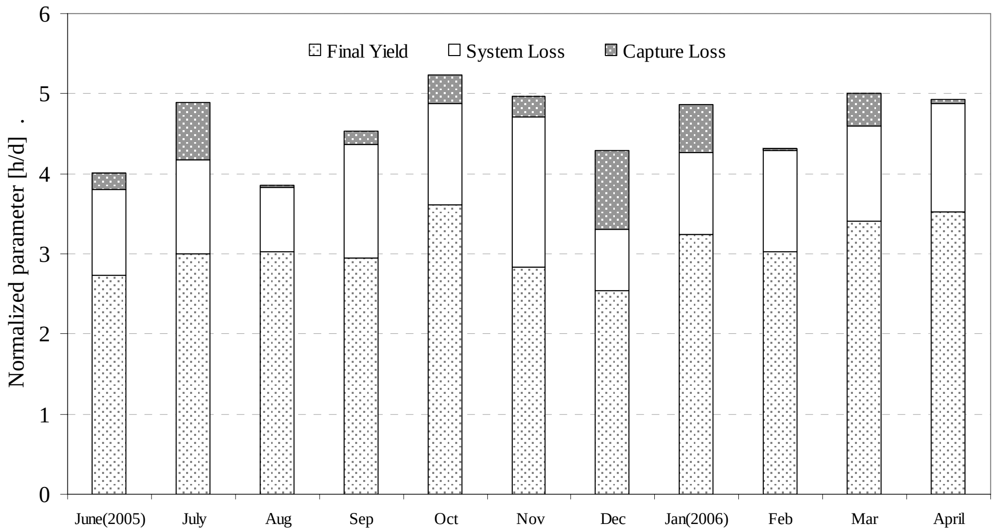

Fig. 12 Normalized Parameters Y_F, L_S and L_C in June 2005 - April 2006.

From Fig. 12, it was found that the evaluation results of each month during June 2005 to April 2006 are as follow. The final yield is ranged from 2.54 h/d (December 2005) to 3.62 h/d (October 2005); the system losses are ranged from 0.77 h/d (December 2005) to 1.88 h/d (November 2005); the array capture losses are ranged from 0.02 h/d (August 2005) to 0.98 h/d (December 2005); and the performance ratio is ranged from 0.57 (November 2005) to 0.79 (August 2005).

In October 2005, a month which has the largest energy production (1510.3 kWh), the Y_F is 3.62 h/d, L_C is 0.37 h/d, L_S is 1.25 h/d and the PR is 0.69. While in December 2005, a month which has the least energy production (1025.48 kWh), the Y_F is 2.54 h/d, L_C is 0.98 h/d, L_S is 0.77 h/d and the PR is 0.59. While Fig. 13 shows the monthly average daily potential PV energy and the average daily energy consumption of this system.

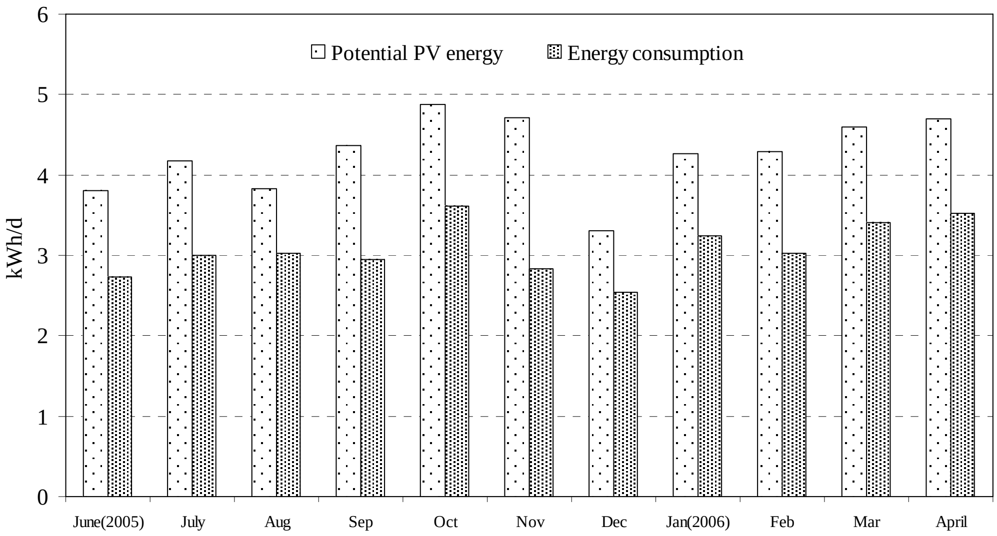

Fig. 13 The potential PV energy versus energy consumption in June 2005 - April 2006.

5. CONCLUSIONS

After the first eleven months of operation, based on the data measured and data analyzed, it was concluded that the 10 kW_p Photovoltaic power system had worked effectively. In part of PV generator, all types of PV technology had generated power that varied linearly with the solar irradiation and the operating efficiency of each technology was lower than the company's specifications. The highest output power per watt peak was generated by the a-Si panel, followed by HIT panel, and the lowest was the p-Si panel. The module temperature of a-Si and p-Si was very close, but both were higher than HIT. In part of inverter, the efficiency of each grid inverter showed little difference and it did not function optimally at low solar irradiation. It was similar for the bi-directional inverter. It had a slight difference in efficiency and it also did not function as well at low input power, both for charger mode and inverter mode. In part of energy storage, it was found that the energy from battery was only a little utilized in relation to the daily energy demand, implying that the battery bank has sufficient capacity to support an even higher load demand. Overall, the results from this study have shown that the 10 kW_p Photovoltaic system is adequate to function as a standalone power system. Moreover, this system can also be integrated to a community micro grid where the surplus energy produced can be channeled to other loads while any energy shortages can be compensated by other energy sources that are connected to the micro grid.

Acknowledgements

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