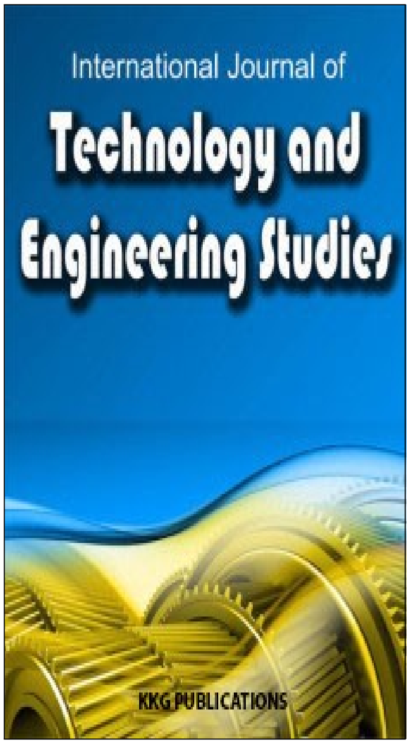

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DESIGN OF STAND-ALONE IRRIGATION SYSTEM ON STRAWBERRY CULTIVATION POWERED BY WIND TURBINE AND PHOTOVOLTAICS

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Abstract. The stand-alone irrigation system had been designed using drip irrigation (DI) method and powered by hybrid renewable energy systems (wind turbine and photovoltaics). The system was implemented on the area of a strawberry plantation in Garut, Indonesia. The drip irrigation system was designed using a pumping system where water flow rate to the plant was controlled around 1.5 l/day with operating planting time of 1.58 hours/day. Based on the calculation of irrigation piping system, pressure in the system must be maintained at the set point 1.2 bars to produce the desired flow rate. Proportional Controller (Kp) was used for controlling the opening of control valve. Based on the response of the controller, the system could reach the set point at 24.95 second, with a maximum overshoot of only 0.0231 bars and has no steady state error. Energy for pumping irrigation system was supplied by a combination of photovoltaics (PV) and wind turbine (WT). Based on the irrigation water demand per day, the total energy demand for this irrigation pumping system was 1743 Wh. The hybrid renewable system was designed by a combination of ten PV cells and a single wind turbine. The energy generated by PV and WT was 8705 Wh/day, therefore the power system was feasible to be implemented because it was still 3.3 times larger than the requirement.

INTRODUCTION

Strawberry (Fragaria x ananassa Duch) is a commercially important fruit commodity, commonly consumed fresh or processed [1]. It is widely cultivated worldwide for its attractive fragrance, sweet taste and high economic value [2]. In particular, strawberry fruits contain a very high amount of phenolic compounds, which are well known for their antioxidant activities [3]. In Indonesia, this plant can only grow in mountain areas with altitude of more than 1000 m above sea level and can be harvested up to five times a year in which the highest production occurred in July and August depending on the circumstances and environment. The data on the number of strawberry production in Indonesia have not been well documented, however according to data from the Indonesian Central Bureau of Statistics, the imported fresh strawberries in Indonesia reached 210 tons ($480,602) in 2011 [4]. It shows that the strawberry consumption needs of the Indonesian people are greater than the amount of production. In order to boost the production, it needs the technology that can improve the quality and quantity of strawberry cultivation in Indonesia.

According to [5] [6], the cultivation of strawberry requires the irrigation. New leaf production, stomatal conductance, and photosynthetic rate were significantly reduced under limited water which could reduce plant growth compared with well-watered plant. Generally, there are 3 types of irrigation methods, i.e. surface, overhead, and drip irrigation. However, based on [7], the illness of strawberry plants can be caused by water used for crop irrigation that is contaminated with indicator and pathogenic microorganisms and may be affected by many parameters such as irrigation methods. From their report, drip irrigation (DI) method can reduce the risk of illness in the strawberry lower than overhead method because it can reduce the persistence of the bacteria. According to [8], DI method can save about 51% of irrigation water and can 19% higher fruit yield as compared with surface irrigation method.

Moreover, by considering water scarcity and increasing competition between different sectors (agriculture, industrial and domestic), it is considered for adopting water saving strategies according to evaporation demand, or plant or soil water status [9]. [10] have been designing precision irrigation systems which controlled in an integrated manner using soil water sensors, smart water meters, programmers, electric valves and weather station. Then [11], proposed agricultural water management system for areas that have limited soil water availability with technologies involving automation, control,

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and Information and Communication Technologies (ICT), thus creating precision system. For rural areas where the availability of electrical energy is limited, these two systems have drawbacks because it requires a source of energy to run the components of the system, but it is not always profitable or convenient to build electrical grid extensions. The use of renewable resources for powering the irrigation system can be the solution that is sustainable, independent, and cleaner than fossil fuels. However, power supply continuity and stability, for example for solar and wind resources, are the challenges to study the feasibility of renewable energy integration for this kind of application [12]. The recent works in the literature [13] [14] [15] 16] [17] have studied about pumping systems powered by renewable energy in rural areas. In this paper, the feasibility study was conducted to demonstrate the technical feasibility of the renewable energy systems for powering drip irrigation facilities on strawberry cultivation. This study was carried out in one of strawberry plantation areas in District Garut, West Java, Indonesia which had an altitude of 1400 meters above sea level where the electric grid was not often available.

DESIGN OF DRIP IRRIGATION SYSTEM

In drip irrigation system, water is supplied to the soil that is very close to the plants at very low flow rates from a plastic pipe fitted with outlets (drip emitters) [25] [26]. Fig. 1 shows the schematic design of drip irrigation system that will be implemented for strawberry plantation in Garut, Indonesia. Energy for pumping irrigation system is supplied by hybrid renewable energy source which is a combination of photovoltaic cells (PV) and wind turbine (WT). The irrigation system was designed using a piping system which was controlled based on the flow required by controlling the opening control valve (CV) in which the pumping start was triggered by soil moisture sensor (SH).

Evaluation of Water Demand

Strawberry plantation in Garut, West Java is the second largest strawberry plantation in Indonesia, i.e. 160 Ha [4]. In this study, drip irrigation system will be implemented on one of private-owned strawberry plantations in Garut which have a total area of 2.400 m2. Strawberry crop is cultivated on 600 polymer bags where each bag contains four strawberry crops. According to [18], flow rate of drip irrigation system is around 1.5 l/day with the operating planting time of 1.58 hours/day, with watering interval of once in every 72 hours. Hence, the total plant that needs to be watered is 9600 plants. With this configuration, the water demand for that plantation is 14,400 liters for each watering period. In this study, due to the watering interval for strawberry crop is once every three days, the irrigation area is divided into 3 sections, so the irrigation would be done simultaneously for one section per day. With this scheme, water demand per day for each section is 4800 liters/day.

Design of Irrigation Pipeline

To distribute the water with constant flow into strawberry crops, the pressure of pipeline needs to be calculated. Based on Bernoulli's law for a closed flow system [20], pressure in the inlet pipeline can be calculated analytically. Parameters to obtain the pressure on the inlet pipe are the total head between the inlet and outlet pipes, and diameter of pipe used which can be calculated based on the following equation:

$$p_1 + \rho g h_1 + 1/2\rho v_1^2 = p_2 + \rho g h_2 + 1/2\rho v_2^2 \tag{1}$$

According to head loss in piping installation, the pressure is needed to be calculated not only from total head and diameter of the pipe but also from the difference of head loss which is divided into major and minor head loss. Major head loss due to flow of a fluid flowing in a pipe is affected by fluid viscosity, speed, roughness, and the geometry of the pipe. While minor head loss is caused by the installation of piping such as a connection pipe, valve reduction, etc. Analytical calculation of inlet pressure that is required on the irrigation pipeline can be explained in the following:

Major head loss due to friction with the pipe wall is:

$$H_L = f\frac{L}{D}\frac{V^2}{2g} \tag{2}$$

where f is friction factor, L is Length of Pipe, V is average fluid velocity, D is Diameter of Pipe, and g is acceleration of gravity.

$$f = \frac{64}{Re} \tag{3}$$

while minor head loss is due to valve and fitting:

$$H_L = K\left(\frac{V^2}{2g}\right) \tag{4}$$

where K is head loss factor. Pressure from the difference in elevation and speed can be calculated by equation:

$$p_1 = p_2 + \rho g(h_2 - h_1) + 1/2\rho(v_2^2 - v_1^2) \tag{5}$$

From the equation (1) to (5), the pressure of the inlet pipeline system p_1 is 111096.2684 Pa, the major head loss H_L is 0.405 m, the pressure drop of the pipeline system is 3954.608 Pa, the minor head loss is 0.095 m, and the pressure drop is 928.370 Pa.

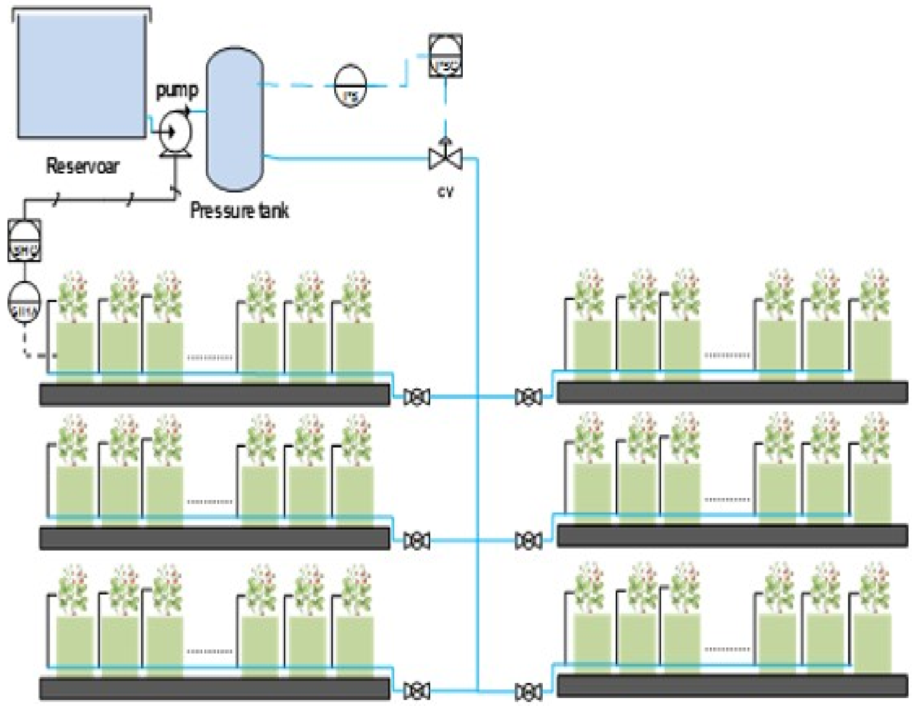

Fig. 1 . Design schematic of drip irrigation system

The total required pressure is the sum of inlet pressure, pressure drop of major head, and pressure drop of minor head which resulted in 115979.246 Pa (1.2 bars). This result was based on the following pipeline specification: The main pipe is DN 40 type with the length of 45 meters and distribution pipe is DN 15 type with the length of 300 meters. The flexible hoses with diameter of 2.5 mm are connected on the distribution pipe as a dripper.

Design of Drip Control System

The irrigation system is designed using a piping system which is controlled based on the flow required by controlling the opening of Control Valve (CV). Based on the results of piping design, the pressure must be maintained at the set point of 1.2 bars. The opening of control valve (controlled variable) depends on the reading of pressure sensor (measured variable) in pressure tank. The traditional way to control a process is to measure the controlled variable and compare its value with the desired value (the set point to the controller) and feed the difference or error into a feedback controller that will change a manipulated variable to drive the controlled variable back to the desired value [19]. The block diagram of drip irrigation system can be shown in Fig. 2.

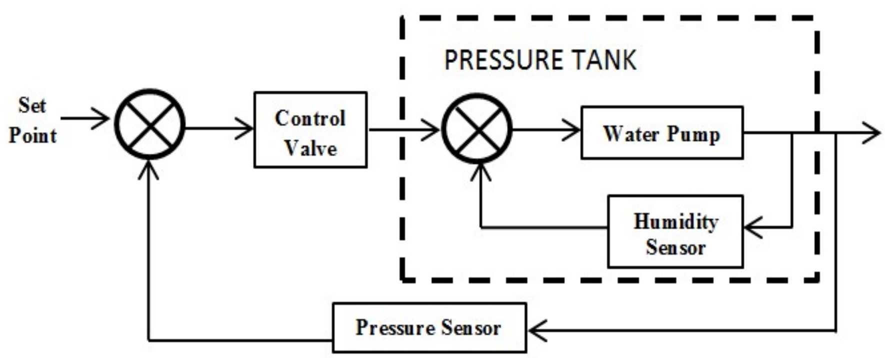

Fig. 2 . Block diagram of drip irrigation system

From the block diagram, the transfer function of each component can be determined by applying the transfer function of each component. The transfer function of drip irrigation system can be written as the following equation:

$$\frac{(44.096s^3 + 11.9059s^2 + 0.90948s + 0.01378)}{(96s^5 + 1305.92s^4 + 3551.5232s^3 + 904.1458s^2 + 68.3157s + 1.0329)} \quad (6)$$

Before applying an appropriate controller on drip irrigation system, it needs to plot the transfer function of the system. The step response of the plant is shown in Fig. 3. From the step response, the system could not reach the set point while the system is already in steady state condition quickly. The pressure of drip irrigation system can only reach 0.014 bars in 1.74 second. The controller is needed as a gain of the system until it reaches the set point of 1.2 bars. Therefore, we chose the proportional controller to increase the gain of the system. By tuning the proportional controller (Kp) on MATLAB, we could obtain the Kp value of 74.95. Fig. 4 shows the response of system plus controller. The system response above shows that the system could reach the set point at 24.95 seconds, with maximum overshoot at only 0.0231 bars and has no steady state error.

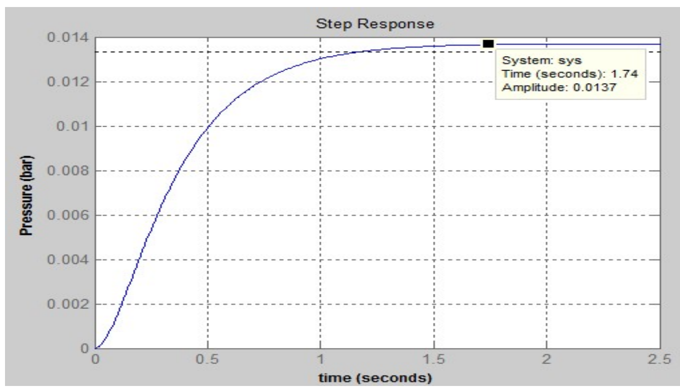

Fig. 3 . Step response of system

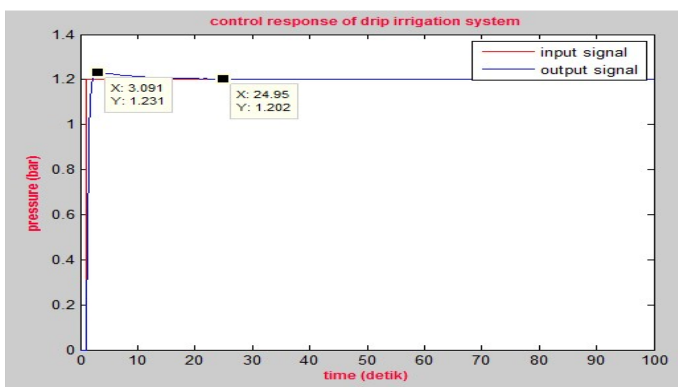

Fig. 4 . Control valve + Kp of drip irrigation system response

DESIGN OF HYBRID ENERGY SYSTEM

Evaluation of Energy Demand

Energy supply system is designed in compliance with water demand for irrigation on each section per day. Increasing of strawberry demand on the market should be offset by the growth of plantation area, and hence the energy supply system should be capable of supplying power three times larger than the current needs. Energy is produced by combining solar cell and wind turbine and is stored in the battery banks via a charge control system. Then direct-current (DC) power from batteries is converted into alternating-current (AC) power by DC-to-AC inverter. These AC power sources are dominantly absorbed by electric pump for irrigation system and only a little portion of them are used for lighting and utility system.

According to the calculation of daily water requirement on previous section, this irrigation system should provide water at least 4800 liters per day. Water distribution to each poly-bag is done by means of electric pump running continuously during the watering period. The pump is using electric pump of 750 W with power factor of 0.8. This pump gets electricity from a pure sine-wave inverter of 3000 W capacity. Omitting excessive (transient) energy during starting period of pump and assuming that inverter's efficiency is 0.85, the energy demand for this irrigation system can be calculated as follows [23].

$$S_{pump} = \frac{P_{pump}}{pf} \tag{7}$$

where S_{pump} is AC apparent power of pump (VA), P_{pump} is AC active power of pump (W), and pf is power factor (dimensionless).

The AC apparent power of 750 W pump is 937.5 VA. Apparent power is actual power consumed by the pump during its operation which is included in power output and power loss in the motor's winding [23]. DC power is consumed by pump and inverter which is obtained by using equations below:

$$P_{DC} = \frac{S_{pump}}{\eta} \tag{8}$$

where P_{DC} is DC power consumed by pump and inverter [Watt], and η is Inverter's efficiency (dimensionless).

Note that the pure sine-wave inverter is a bridge to transfer power from DC into AC and hence, the unit "Watt" is different on these domains. Energy demand for this irrigation system can be calculated by using equation below [23]:

$$E_{irr} = P_{DC} T_{irr} \tag{9}$$

where E_{irr} is energy demand (Wh) and T_{irr} is watering time (h).

The DC Power consumed by pump and inverter (P_{DC}) is 1103 W and watering time (T_{irr}) is 1.58 h, thus the total energy demand for this irrigation system is 1742.74 Wh ($\approx$ 1743 Wh).

Requirement of battery capacity for this irrigation system is calculated by:

$$C_{batt} = \frac{E_{irr}}{V_{DC}} \tag{10}$$

where C_{batt} is a minimum battery capacity (Ah) and VDC is nominal battery voltage (V)

Hence, the minimum battery capacity is 36.3 Ah. To store the energy, we used 12 pieces of battery with current capacity 100Ah and 12 V. By forming 4 batteries into series circuit so that each bus system has a voltage of 48 V, the total capacity of battery could be determined below:

One series of batteries= 12 V 4 100 Ah=4800 Wh.

Total of 3 parallel batteries = 3 4800=14400 Wh=14.4 kWh

Thus, to charge empty battery until full, take time 14.4/8.69 = 1.65 days.

From the calculation above, it can be inferred that a system with energy storage capacity of 100 Ah and voltage of 48 V is large enough to fulfill the energy requirement for drip irrigation system.

Renewable Energy Resources

To evaluate renewable energy resources, sensors for wind speed, wind direction, and solar irradiation are installed in the studied location, i.e. Garut district. The average value of wind and solar radiation was generated in a week (data were taken from 14 June to 21 June). Fig. 5 and Fig. 6 respectively show the generated wind speed and solar radiation in Garut. From the observations, the peak of wind speed is 2.25 m/s, with the average of daily wind speed of 0.7 m/s. While the maximum solar radiation is 807 W/m2 with the average of half-day radiation (starting from 6am until 6pm) of 398.1 W/m^2.

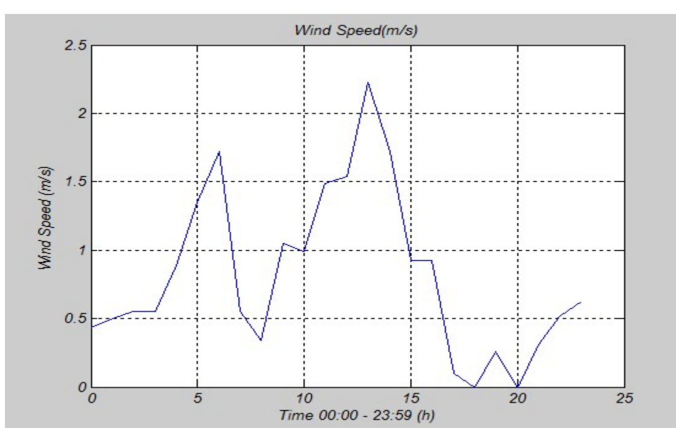

Fig. 5 . The average of wind speed

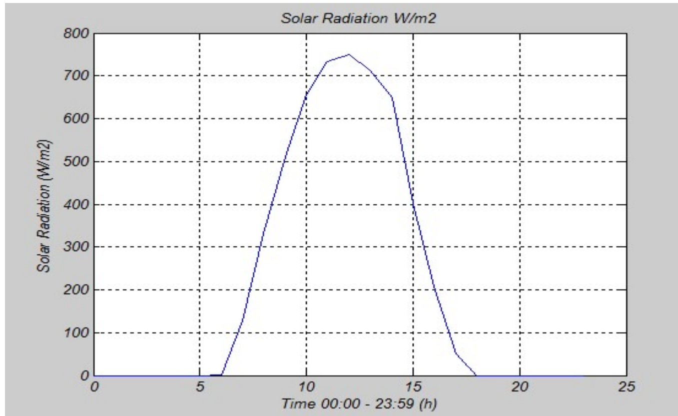

Fig. 6 . The average of solar radiation

Design & Evaluation of Hybrid Energy System

To supply the energy demand for irrigation, ten of PV cells and a single wind turbine were designed using 48V DC bus. Twelve pieces of battery with capacity 12V was used to store the energy production on four series, with each battery having a capacity of 100Ah. Therefore, there are three parallel batteries which use divert type of charger. The benefit of divert type is battery safety, due to unstable power production from wind turbine. Divert type of charger controller bypasses or diverts the incoming power which is higher than set point voltage. Another type of charger controller is MPPT in which the battery is charged by auto convert input voltage to be same with max voltage battery. With unstable wind turbine power production, the using of divert type is better than MPPT type for battery safety.

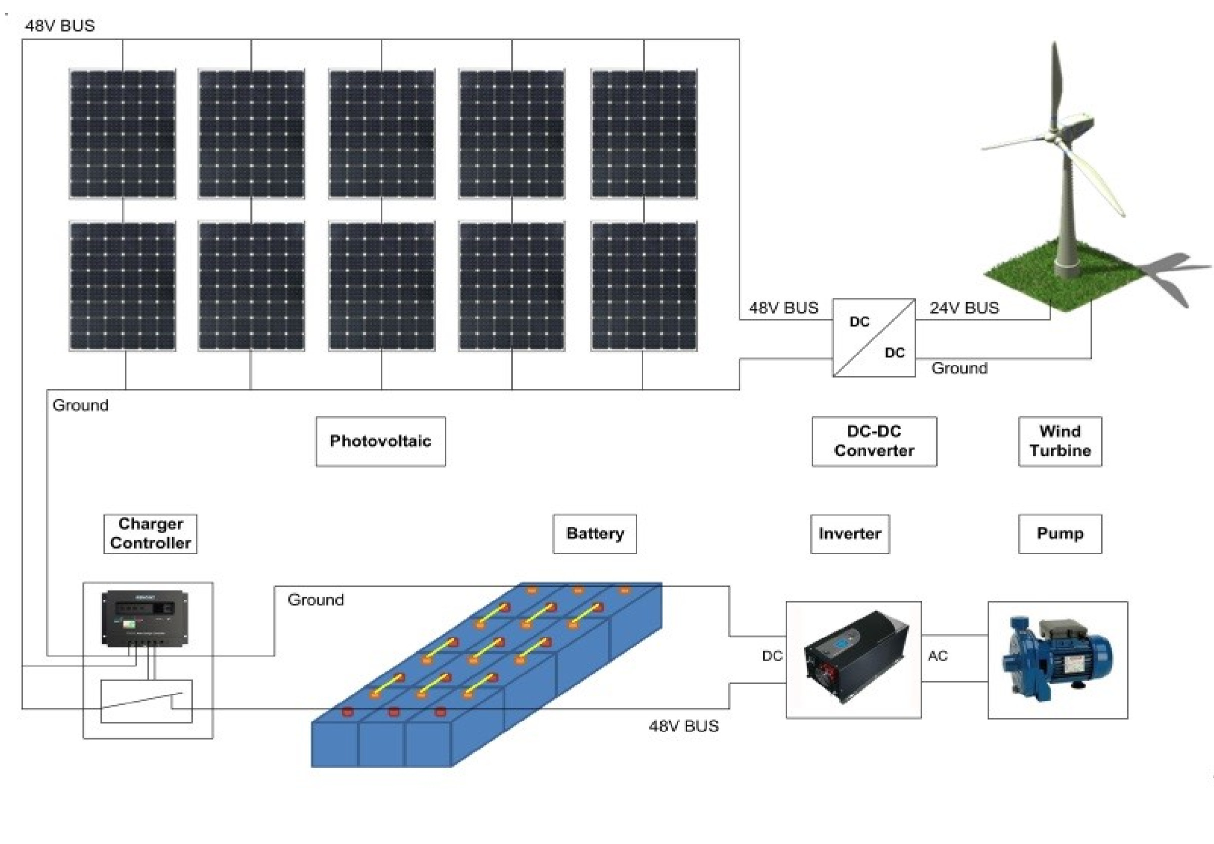

Fig. 7 . The design of hybrid power plant

Pure sine wave inverter is used to convert 48 volt DC in battery for running irrigation pump. The scheme of hybrid energy for irrigation can be shown in Fig. 7.

Correlation of wind speed to energy production could be obtained by using the kinetic energy equation [21].

$$E = \frac{1}{2} Mass V speed^2 \tag{11}$$

By differentiating the energy equation with respect to time, we can obtain power equation of wind speed [21].

$$P = \frac{1}{2} V^2 \frac{dm}{dt} \tag{12}$$

$$\frac{dm}{dt} = \rho A \frac{dx}{dt} \tag{13}$$

$$\frac{dx}{dt} = V \tag{14}$$

$$A = \pi r^2 \tag{15}$$

$$\frac{dm}{dt} = \rho \pi r^2 V \tag{16}$$

By substituting equation (13), (14), (15), and (16) into equation (12), the equation of wind power is:

$$P = \frac{1}{2} \rho \pi r^2 V speed^3 \tag{17}$$

where ρ is density (kg/m3), r is radius (m), and V is speed of wind (m/s). By calculating wind speed into power equation, the graphic could be shown below. Based on wind turbine data sheet [22] [24], starter speed of wind turbine is 1 m/s. Thus on the calculation of design, only more than 1 m/s of wind speed is considered on the calculation. By using equation (17), the maximum power of wind turbine is 5.17 W, while average power of wind turbine is 0.63 W. Thus total power generated by wind turbine is 180.15 W. The comparison between wind speed and energy produced can be seen in Fig. 8. If compared with the pump power demand which is 1743 W in every watering period, generated power of wind turbine is not enough to fulfill the irrigation pump power demand, therefore it must be coupled with PV in hybrid system.

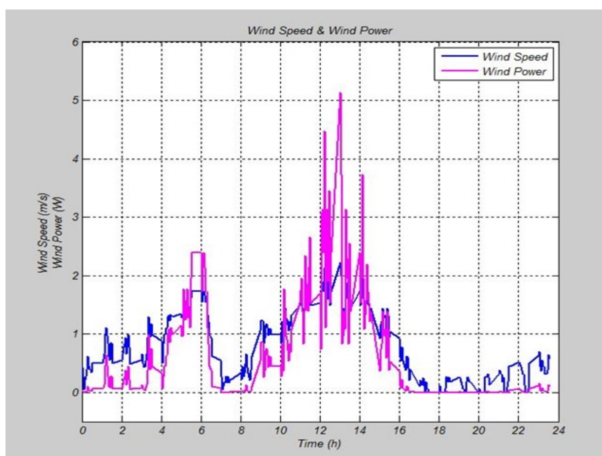

Fig. 8 . The comparison between wind speed and energy produced by wind turbine

Based on PV datasheet, the PV area is 1.18 m2. From weather monitoring data, effective radiation period is 12 hours and average daily generated radiation is 425.69 W/m^2 or equal to 426 W/m^2.

$$\eta_{max} = \frac{P_{max}}{E_{sc} A_c} \tag{18}$$

Where P_{max} is maximum power output, η is maximum PV efficiency, E_{sc} is incident radiation flux, and A_c is area of PV collector. P_{max} can be obtained by using the following equation [22]:

$$P_{max} = \eta_{max} E_{sc} A_c \tag{19}$$

$$P_{PV} = 0.17 E_{sc} \tag{20}$$

By the input average of effective radiation period, generated power per hour is 72.42 W.

Generated daily energy based on effective period every day (12 hours) can be obtained by using the following equation:

$$E_{PV} = P_{PV} t \tag{21}$$

Hence, the generated daily energy is 869.04 and the total generated energy of 10 Photovoltaics every day is 8690.4 Wh. The comparison between solar radiance and energy produced by PV can be seen in Fig. 9.

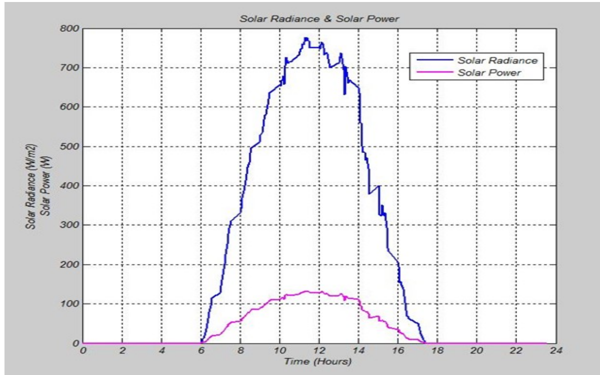

Fig. 9 . The comparison between solar radiance and energy produced by photovoltaics

By using energy equation, E = P x t, the comparison of energy demand and energy consumption for every energy resource can be seen in Fig. 10. Wind turbine can produce power around 180 W/day and every solar cell can produce 10.421 W. Daily energy generated by solar cell and wind turbine is using unit Watt hour (Wh). While on monitoring data, the weather data are taken in every 5 minutes. Thus, it needs to be converted into hour unit, i.e. 1/12 hr. The generated energy of wind turbine can be calculated by 15 Wh. Meanwhile, the generated energy of photovoltaic is 8,690 Wh. By using those data, the generated energy can fulfill the energy demand with the total energy of 8705 Wh/day. The strawberry plantation area needs the total energy of 2614.5 Wh/day for supplying the irrigation system. Therefore, the hybrid power plant can be used to supply the requirement of irrigation energy for 3.3 times of plantation area. Residue of energy capacity is designed to anticipate a rainy season, where photovoltaic as the main energy resource is usually not stable because clouds can block the sun light.

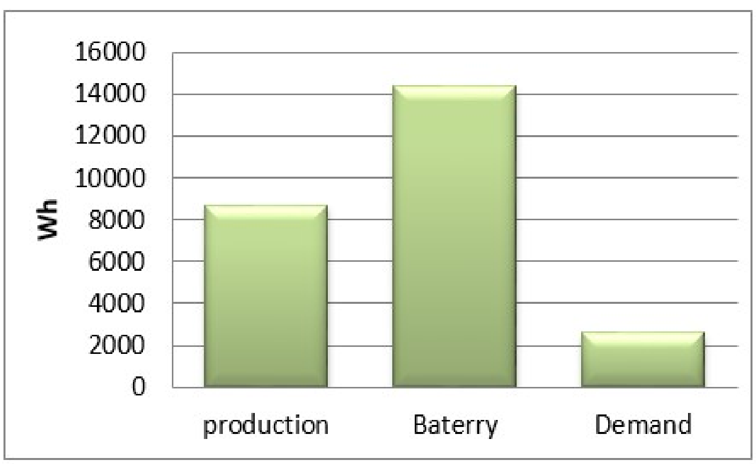

Fig. 10 . The comparison of generated energy, battery capacity, and energy demand

CONCLUSION

Based on the land area and number of plants, the water demand for each section of plantation was calculated at 4800 l/day with a flow rate of drip irrigation system in each plant of 1.5 l/day and operating planting time of 1.58 hours/day. To produce the desired flow rate, water flow was controlled using proportional controller based on a pressure piping system which was maintained at the set point of 1.2 bars. Based on the response from the proportional controller, the system could reach the set point at 24.95 seconds, with maximum overshoot of only 0.0231 bars and had no steady state error. Based on the results of the design of the hybrid energy system, the generated energy could fulfill energy demand. The total average of generated energy every day was 8705 Wh, while the energy demand of the plantation area was 2614.5 Wh for irrigation. Therefore, the hybrid power plant was feasible to be implemented because it was still 3.3 times larger than the requirement.

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— This article does not have any appendix. —