Design of Photovoltaic-Thermoelectric Generator (PV-TEG) Hybrid System for Precision Agriculture

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***Abstract*—Precision agriculture is gaining more interest amongst farmers and entrepreneurs as an alternative way to growing plants. Current trend shows the implementation of precision agriculture system to be used in indoor farming, thus allowing crops to be harvested throughout the year regardless of seasonal changes. However, the main challenge with implementing this system is the high energy consumption of the technologies used in the system. Therefore, this paper presents proof of concept solution to manage the energy consumption of the precision agriculture system by designing a hybrid photovoltaic-thermoelectric generator (PV-TEG) system as a power supply. The hybrid system power output is to be compared to a stand-alone solar photovoltaic system. A simple mathematical modelling using Matlab/Simulink is done to estimate the hybrid systems feasibility to provide sufficient power to run the precision agriculture system electrical load for a set period of time. An experimental approach will be done to validate the hybrid systems ability to provide power in real time.**

***Index Terms*—Solar power, Photovoltaic (PV), Thermoelectric Generator (TEG), Hybrid system, Precision agriculture, Indoor farming**

I. Introduction

Internet of Things (IoT) is a network infrastructure which connects all of Internet-enabled physical devices to the web, therefore enabling data collection and monitoring of these devices using the Internet [1]. Machine-to-machine (M2M) communications is an essential part of IoT where a cooperative network of both wired and wireless machines communications is established [2]. The application of IoT varies widely in all fields and is currenty explored in the agricultural field partiularly for precision agriculture. Precision agriculture is a crop management system which enables higher yield production as compared to conventional agriculture through the use of new information technologies such as IoT, cloud computing and Big Data. Precision agriculture has been implemented in farms growing several types of crop and has shown the ability of to produce higher crop output [3]. However, a major challenge that exists for precision agriculture is the high electricity consumption to run the system [4]. There are several technologies used in precision agriculture that required high power consumption, such as lighting, fertigation, water pump, electric motors and robotics. Most power stations around the world uses fossil fuels, such as coal and natural gas as the major power source to generate electricity. This implies that the existing precision agriculture system is being run by non-renewable energy sources, thus diminishing the sustainability aspect of agriculture. Furthermore, with the need of high electricity consumption, the precision agriculture system is not able to be built in rural areas where lack of power sources is an issue. Thus, as a solution, solar energy technology is introduced as a power source to run the system.

Solar photovoltaic (PV) technology is a matured solar energy harvesting technology and has been used in a wide range of application [5]. Solar PV cells harvest solar energy by directly converting light photon to electricity. There are many advantages in using solar PV technology such as zero operations cost, zero greenhouse gas emission during operation and low maintenance cost [6]. In spite of that, there are several drawbacks of using this technology for electricity production. First, the commercially available PV module efficiency is quite low, ranging from 17 % - 22 % depending on the material of solar cells used and the temperature of solar cells during operation as reviewed by B. Parida et al [5]. Furthermore, solar PV has a high initial cost due to the high cost of solar PV panels and high installation cost. The electricity production is also unreliable due to weather constrains where during cloudy and rainy days, the electricity production is less than on sunny days and there are no electricity production at night time. Therefore, to add reliability to the existing PV technology, thermoelectric generator (TEG) can be integrated to a stand alone PV system. TEG is made up of semiconductor material which is able to produce electricity with temperature difference between the junctions also known as the Seebeck effect [7]. During the operation of solar PV, the module will experience a temperature rise at certain time of the day, which in turn decreases the efficiency of the PV module. The waste heat from the PV panel can instead be used by the TEG to further convert it into electricity.

Several studies have shown that there is an increase in efficiency of the system when TEG is added to a stand-alone solar PV [8]–[11]. Van sark [10] investigated on the feasibility of PV-TEG hybrid modules where a model of the hybrid system is designed and simulated. The author found that the hybrid system produced an increase in efficiency by 8 % - 23 % according to the type of module integration. Kossyvakis et al. [11] examined the performance of a tandem PV-TEG hybrid system through experimental analysis. The authors found a prominent performance enhancement when the hybrid system were subjected under elevated temperature. Park et al. [9] results are align with the findings of previous authors where the hybrid system produces an improved performance compared to a stand alone PV. Past researches have mainly focused on the characteristic and performance of PV-TEG hybrid system simulated in lab conditions. Hence, a system consisting of solar PV-TEG hybrid with added battery storage is proposed as the energy source for precision agriculture application. A simulation of solar PV and TEG model using Matlab/Simulink is made to predict the outcome of the system based on actual weather conditions as the input.

The rest of the paper is organized as follows. Section II focuses on the hybrid system design based on the load requirement. Section III provides the mathematical formulas of both PV and TEG adopted from various authors. Section IV discussed on the hybrid model simulation results and findings. The summary of this paper is given in section V and future works are mentioned in section VI.

II. System Design

A. Load Requirement

There are two commonly used lighting options for indoor agriculture which are light emitting diode (LED) and high pressure sodium (HPS). LED lights were chosen for this study due to its higher efficiency compared to HPS [12]. In order to calculate the load power requirement, total length of the LED to be used and the hour of usage should be determined. Lighting hour of usage for optimal plant growth largely varies based on the species of plant to be cultivated in the area. The hour of light usage is estimated to be used for 18 hour/day as been done by previous work [13]. Fig. 1 shows the space used for implementation of the precision agriculture system as well as the LED arrangement in the space.

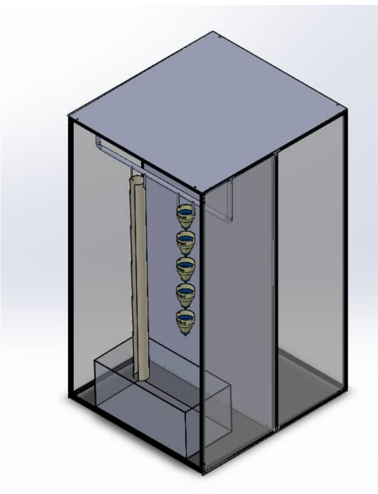

Fig. 1. Space used for implementation of precision agriculture system

Fig. 2 shows the LED lighting arrangement and the dimensions of the space where the total length of LED lights used is 4.2 m. Based on the datasheet of LED light provided from manufacturer, the power requirement for LED light is 14.4 W/m.

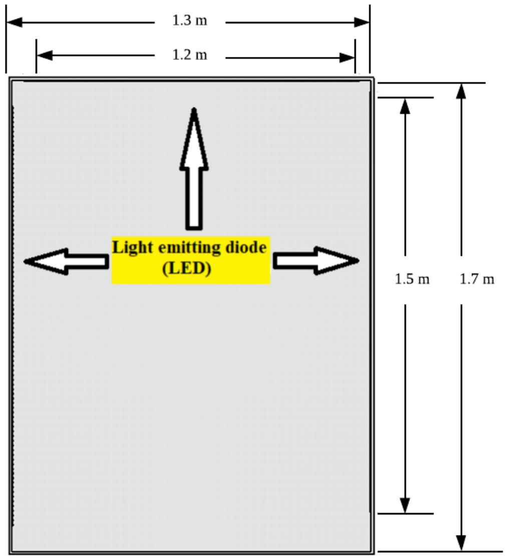

Fig. 2. Diagram of LED lighting arrangement in the growth space

TABLE I
Load Power Requirement of LED

Load power requirement	Value
Length of LED (m)	4.2
Power (W/m)	14.4
Operation hours (hr)	18
Safety factor	1.3
Total energy required, E_T (Whr)	1415.23

B. System Sizing

1) Solar PV panel and TEG: The solar PV panel chosen for this study is ALD100-12V. The panel specification is as shown in Table II.

TABLE II
PV Module Specification

Solar PV Module Model	ADL100-12V
Maximum power at standard testing condition (W_p)	100 W
Optimum operating voltage (V_{mp})	18 V
Optimum operating current (I_{mp})	5.4 A
Open circuit voltage (V_{oc})	22.45 V
Short circuit current (I_{sc})	5.99 A
Dimension (mm)	1200 x 540 x 30

The estimated annual average daily solar irradiation (Irr) for Malaysia ranged from 4.21 kWh/m^2 to 5.56 kWh/m^2 [14]. The solar irradiation value of 4.21 kWh/m^2 is chosen for this calculation for an added safety factor. The standard testing conditions solar irradiation (Irr_{STC})for a solar PV panel is 1000 W/m^2. The panel generation factor (ϵ_{gen}) is determined by:

$$\epsilon_{gen} = \frac{Irr}{Irr_{STC}} = \frac{4210}{1000} = 4.21 \quad (1)$$

To obtain the Watt peak rating (W_p) for the PV module is:

$$W_p = \frac{E_T}{\epsilon_{gen}} = \frac{1415.23}{4.21} = 336.16\, W_p \quad (2)$$

Thus, the number of PV modules required are:

$$No.of modules = \frac{336.16}{100} = 3.36 \approx 4\, panels \quad (3)$$

Since the TEG is to be attached directly to the battery, the number of thermoelectric generators to be used depends on the nominal voltage of the battery which is 12 V. The TEG model used in this study is SP1848-27145 with a dimension of 40 mm x 40 mm x 3.4 mm. The TEG has an open circuit voltage (V_{oc}) of 1.5 V at 35 °C temperature difference. The TEG will be connected in series to obtain a total voltage which matches the battery. Thus, the number of TEG required is:

$$No.ofTEG = \frac{V_{nom}}{V_{oc}} = \frac{12}{1.5} = 8\,TEG \tag{4}$$

2) Battery Sizing: The battery used for this study is lead acid battery PGEL 100-12 with the specifications as shown in Table III.

TABLE III
BATTERY SPECIFICATION

Battery Model	**PGEL 100-12**
Battery Type	Lead Acid
Nominal voltage (V_{nom})	12 V
Nominal capacity (C_{nom})	100 Ah
Battery efficiency (η)	85%
Depth of Discharge (DOD)	0.4

Assuming the days of autonomy (N) to be one, the required battery capacity (C) is:

$$C = \frac{E_T \times N}{V_{nom} \times \eta \times (1 - DOD)} = \frac{1415.23 \times 1}{12 \times 0.85 \times 0.6} = 231.25\,Ah \tag{5}$$

Thus, the number of battery required are:

$$No.ofbattery = \frac{C}{C_{nom}} = \frac{231.25}{100} = 2.31 \approx 3\,battery \tag{6}$$

3) Hybrid PV-TEG System Design: The proposed design for this hybrid system is that the TEGs are mounted behind the solar PV panel as shown in Fig. 3 and 4. The PV panels will be connected in parallel. The TEGs will have a series connection and is connected directly to the battery to provide constant power to the battery bank regardless of the batterys state of charge. The block diagram of the hybrid system is as shown in Fig. 5.

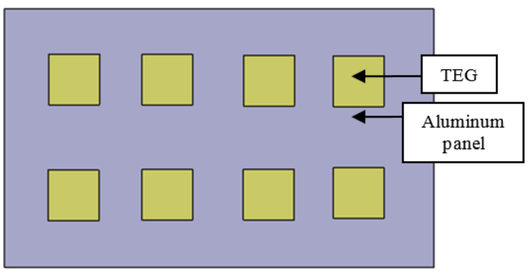

Fig. 3. Back view of PV panel with TEG attached

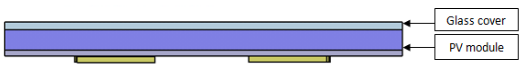

Fig. 4. Side view of PV panel with TEG attached

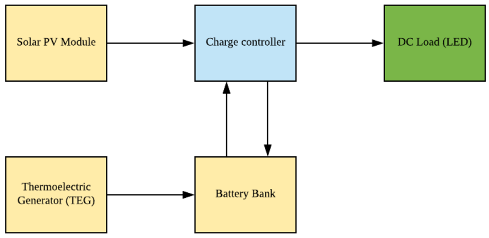

Fig. 5. PV-TEG hybrid system block diagram

III. Mathematical Modeling

A. Solar Photovoltaic Cell

Photovoltaic solar cell are the main building blocks of a photovoltaic module. PV cells are made of semiconductors that exhibit a photovoltaic effect where it converts light from solar energy to electricity. Fig. 6 shows the commonly used form of

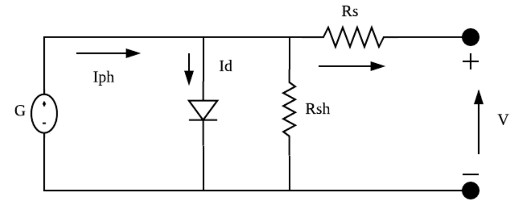

Fig. 6. Equivalent circuit for photovoltaic cell

PV cell equivalent circuit with only one diode adopted from J. Ramos-Hernanz et al. [15]. PV cell mathematical equations for modelling derived by authors [15]–[17] is based on the equivalent circuit shown in Fig. 6:

$$I = I_{ph} - I_d - I_{sh} \tag{7}$$

$$I = \frac{G}{G_{ref}}[I_{sc} + \mu_{sc}(T_{op} - T_{ref})] \tag{8}$$

$$I_d = I_o N_p [e^{\frac{(V+IR_s)}{AN_sV_T}-1} - 1] \tag{9}$$

$$V_T = \frac{kT_{op}}{q} \tag{10}$$

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{11}$$

$$I_o = I_{oref}(\frac{T_{op}}{T_{ref}})^3(\frac{1}{T_{ref}}\frac{1}{T_{op}})(e^{\frac{\varepsilon q}{Ak}}) \tag{12}$$

$$I_{oref} = I_{sc}[e^{\frac{V_{oc}q}{T_{op}AkN_s}} - 1]^{-1} \tag{13}$$

Where:

N_p = Number of PV cells in parallel
N_s = Number of PV cells in series
G = Irradiance
G_{ref} = 1000 W/m^2 (Irradiance at STC)
I_{sc} = Short circuit current
μ_{sc} = Coefficient temperature of I_{sc}
T_{op} = Operating temperature
T_{ref} = 25 °C
I_o = Reverse saturation current
V_T = Thermal voltage
q = 1.602 10−19 C (Electron charge)

k = 1.381 x $10^{-}23$ J/K (Boltzman constant)
ε = Energy gap
A = Ideality factor

Based on (7) - (13) a model of PV cell subsystem can be created in Matlab/Simulink. Sample data for irradiation in Kuala Lumpur is used as the input parameter. The PV cell characteristics are based on the PV panel model ALD100-12V used in this study in order to achieve an accurate result.

B. Thermoelectric Generator (TEG)

TEG cells are made of multiple thermoelectric couples consisting of thermoelements p-type and n-type junctions of the same thickness. According to H. L Tsai et al. [18], there are four main energy processes involved in the thermoelectric elements which are the Peltier effect, Joule heating, Seebeck effect and thermal conduction. These thermoelectric couples are sandwiched in between two ceramic plates and are connected in parallel thermally for decreased thermal resistance and in series electrically for an increased in operating voltage to produce a practically working TEG as noted by the authors. Assuming that the ceramic plates contribution is neglected, the following equations can be derived for TEG model:

$$S = \frac{2V_m}{\triangle T} \tag{14}$$

$$V = S\triangle T - IR \tag{15}$$

$$m_{opt} = \sqrt{(1 + \frac{S^2 T_{avg}}{RK_{TH}})} \tag{16}$$

$$\dot{Q} = \frac{\triangle T}{K_{TH}} \tag{17}$$

$$\eta_{th} = \frac{I^2 R}{\dot{Q}} \tag{18}$$

$$I = \frac{S\triangle T}{(1+m)R} \tag{19}$$

Where:

S = Seebeck Coefficient
V_m = V_R (the load voltage at matched load)
K_{TH} = Thermal conductivity
$\triangle T$ = T_h - T_c (Temperature difference)
m = Resistance ratio

The input parameter values are based on the manufacturers data sheet for TEG model SP1848-27145.

IV. PV-TEG Hybrid Model

The complete system block is as shown in Fig. 7 where it includes the main components of the hybrid system which are the PV module, TEG, battery and LED load as well as an additional component which is the solar charger. Fig. 8 and Fig. 9 shows the simulation result of the solar PV module output characteristic at standard testing condition (STC) of 1000 W/m^2. Based on the manufacturers datasheet of the solar PV panel ADL100-12V characteristic, the PV module modelled shows the same characteristic where it produces almost 100 W output with a current of 6 A and voltage of 22.5 V. This shows that the PV module has been correctly modeled.

Fig. 10 is the sample hourly solar irradiation data taken in Kuala Lumpur where the data was measured using a pyranometer. It shows that there is availability of sunlight in the area from 0800 to 2000 for the solar PV to produce a power output. However, the is no solar irradiation from 2000 to 0800 which means that the solar PV cannot be used as a power source during this period of time. Thus the battery bank included in this hybrid system will be fully utilized during this period of time. Fig. 11 shows the solar PV power output for one solar panel based on the irradiation input in Fig. 10. The maximum power output achievable for one panel is 40 W, thus giving a total maximum power of 160 W for four solar panel.

Fig. 12 shows the power output of TEG based on real ambient temperature and solar PV module temperature data in Fig. 13. The sample data was taken in Kuala Lumpur where the temperature was measured using thermocouples for a duration of 24 hours. This study found that the maximum power output able to be achieved for one TEG is 0.2 W. The hybrid system

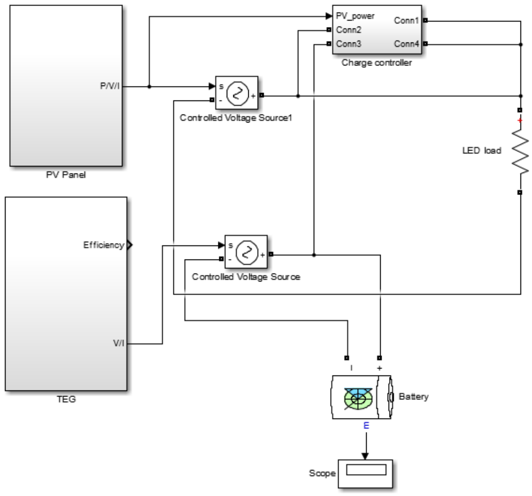

Fig. 7. PV-TEG hybrid model

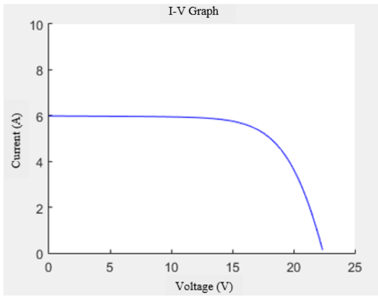

Fig. 8. I-V Graph of solar PV module

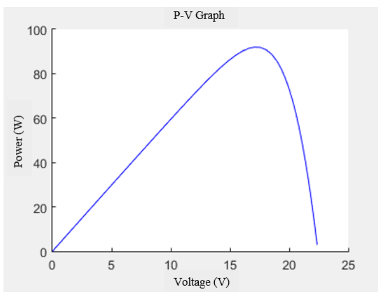

Fig. 9. P-V Graph of solar PV module

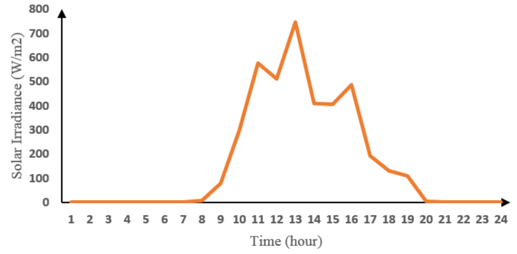

Fig. 10. Sample of daily irradiance in Kuala Lumpur

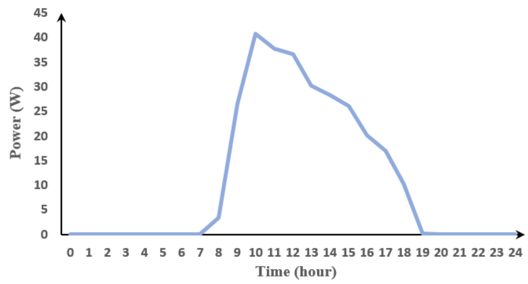

Fig. 11. Power output of PV for 24 hour

design uses eight TEG, hence producing an maximum power output of 1.6 W from the TEGs. As shown in Fig 12, the TEG is able to produce a consistent power output throughout the whole day. This therefore makes it a suitable alternative power source to be used at night time in addition to the battery bank used.

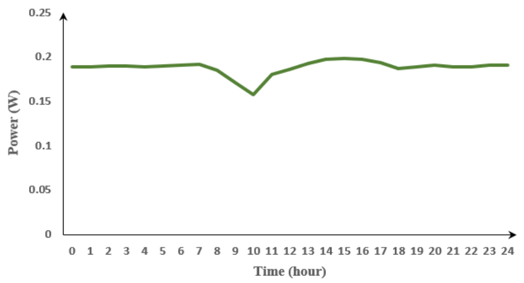

Fig. 12. Power output of TEG for 24 hour

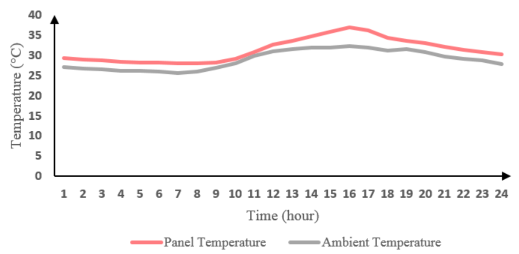

Fig. 13. Sample data for temperature

The overall output for TEGs and solar panels in 24 hours are 37.6 Whr and 1110.88 Whr respectively. This study found that the TEGs are providing an additional 3.4 % power production as compared to using stand alone solar panel.

Comparison of the finding with other authors confirm that the power output of TEGs are small and varies according to the temperature difference between solar panel and ambient temperature. An increase in temperature difference will result in a rise in power production of the TEG as reported by van Sark [10]. Furthermore, Park et al. [9] predicts that a scale-up of the device with larger temperature difference may result in further improvement on the total power output of the hybrid system.

V. Conclusion

In conclusion, the solar PV-TEG hybrid system designed shows a promising outcome on the amount of energy produced to power the LED lighting system for precision agriculture approach. The systems ability to produce required output under selected testing conditions demonstrates its reliability through the modelling simulation results. However, further experimental approach is required to prove the ability of the system to provide sufficient power in actual weather conditions. Several parameters such as ambient temperature and solar irradiation varies according to the weather changes throughout the year which may produce a different output than simulated results. Through the integration of TEG with solar PV, it is expected that the systems total efficiency will improve as opposed to stand-alone solar PV. The system will also be able to provide continuous power output as needed to ensure the growth of plants using the precision agriculture approach. Overall, this study will contribute to the existing solar power technology in the precision agriculture applications.

VI. Future Work

Further evaluation is needed in order to provide verification on the modeled hybrid system. A more detailed analysis on the hybrid system model is required to explore on other parts of the system such as the battery state of charge and switching time between the devices through simulation. Furthermore, an experimental approach should be conducted where testing condition are based on the actual weather conditions within a selected time frame.

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