Engineering Journal issn: 0125-8281

Article

Low Cost Solar Power System with Open Loop Tracking for Rural and Developing Areas

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Abstract: Solar energy continues to enjoy interest and is becoming one of the important elements in the world's future energy consumption and economic growth. One way to increase the use of solar power systems, particularly in rural and developing areas, is through the employment of low cost, power efficient systems. This paper presents a possible low cost solution where an open loop tracking system is implemented with a small size 50 Watt (W) Monocrystalline Photovoltaic (PV) panel. The system's performance is monitored at different tropical weather conditions. In addition, the output power is measured and compared between a static solar panel and one that includes the proposed tracking system. The measurements over the course of 6 months in Pathum Thani, north of Bangkok (Thailand), showed that the output energy with tracking system, on average, is 18 % higher than with static panel (45 Watt hour (Wh) compared to 36.5 Wh). The overall generated energy in 7 hours in a day are 315 Watt hour per day (Wh/day) and 255 Wh/day for tracking and static panel respectively. On rainy days, the average measured output power is reduced to 25% of that on the sunny days. The experimental results have been compared to those of a deduced first order simulation output and this over a period of five months. The experiment shows similarity in the trend between experimental and simulation results. Finally, multiple sensors were added to the solar unit, and measured environmental data sent obtained by these sensors were over a low bandwidth communication link, and recorded/processed on a remote server.

Keywords: Solar energy, solar tracking, developing rural areas, micro controlling, Internet of thing (IoT).

ENGINEERING JOURNAL Volume 24 Issue 5
Received 26 May 2020
Accepted 26 August 2020
Published 30 September 2020
Online at https://engj.org/
DOI:10.4186/ej.2020.24.5.65

DOI:10.4186/ej.2020.24.5.65

1. Introduction

Electrical energy is one of the most important elements of modern life and is increasingly consumed all around the globe. It is almost impossible to achieve sustainable development without affluent energy resources [1]. In addition, world energy challenges such as the increase in energy demand and global warming are critical issues, especially in light of the rapid depletion of coal, oil and natural gases [2]. Renewable energy sources seem to be able to provide a valid solution to the needed energy supply [3, 4]. One of the most promising renewable energy sources is solar power. A PVpanel directly converts light intensity into electrical current [5]. It was estimated that covering 0.16% of the earth's surface with 10% conversion efficient solar panels could provide nearly double the world's consumption of fossil fuel energy [6]. In most developing countries, especially in rural areas, many people do not have access to electricity to light their homes, and irrigate their agricultural fields [3]. Thus, installing a small solar power station in rural areas can supply the basic energy necessity for families or small communities as a sustainable and permanent source [7].

Solar energy generation is based on three factors: the number of layers in the silicon crystal, the efficiency of the crystal in terms of converting solar energy, and the amount of solar radiation that is received on the PV-panel [5]. Solar light intensity is maximized when the panel is normal to the sun's direction [8]. To fulfil that condition at all times requires a tracking mechanism as the earth moves around its orbit in a complex motion. This motion includes daily and seasonal movements. The daily movement causes the sun to move from east to west, while the seasonal motion causes a tilt from south to north and vice versa [9]. Therefore, to keep the PV-panel normal to the sun rays, it is necessary to consider the sun's position in terms of two angles: azimuth (tracking the sun's position in daily motion) and elevation (tracking the sun's position in seasonal motion) [9].

Generally, there are two types of solar tracking controller systems [6], namely closed-loop (feedback) tracking and open-loop tracking. Closed-loop tracking uses one or two light sensors to detect the solar position in a near real-time fashion. It gives feedback to the controller to turn the PV-panel into a position that yields highest incoming light intensity [9]. Although closed-loop tracking provides high accuracy, the system can be affected by weather conditions, e.g. tracking errors may occur during cloudy times. Another disadvantage is that closed-loop systems can be costly [10]. The closed loop system cost can be reduced by utilizing Arduino platform [12], however the feedback complicity remains.

Open-loop tracking systems using a microcontroller programmed with precalculated sun locations are an efficient mechanism to perform solar tracking in a low-speed fashion and with minimum motor power consumption [11]. The sun vector describes the sun's azimuth and elevation angles from the perspective of a specific Global Positioning System (GPS) orientation on earth in a real-time. In this form, the tracking system can be implemented using common microcontroller boards such as Arduino. Moreover, open-loop solar tracking systems are able to track the sun's location and maximize the output energy on both sunny and cloudy days. Using open-loop system in pre-programmed tracking frequency according to the solar velocity shows efficient solar tracking with minimal movement frequency [13]. The major drawback of open-loop tracking systems is the sole dependency on astronomical parameters with no feedback for error correction [14]. In-spite of the fact closed-loop solar tracking demonstrate experimental improvement (18% reported) over open-loop tracking [15], the simplicity of the open-loop implementation makes it a favourable choice in this work.

In this work, an open-loop solar tracking system is implemented using low power motors to design and construct a simple dual axis solar tracker. Tracking is done through pre-calculated sun orientation based on the geographical location, time and date. A Real time clock is used to get the time and date. Though the developed system includes a light intensity sensor, it does not use it for tracking. The light sensors are used mainly to monitor the environment and indicate different weather conditions in combination with humidity and temperature sensors. The study as well focuses on minimizing the motor operations, hence limiting the power used by the tracking system and maximizing the generation of usable energy. This is to ensure the enhancement of the output power in the tracking system compared to static. Additionally, the target of this study is to serve regions with continuous electricity shortage due to life system problems particularly in Afghanistan. Thailand is located at 15.8700⁰ North (N) and 100.9925⁰ East (E). The average annual solar radiation is estimated to be 5.06 kWh/m^{2}day, and, on average, there are 2623 hours of sun in a year [16]. Afghanistan is located at 35.9391⁰ N and 67.7100⁰ E. The annual solar radiation is 5 kWh/m^{2}day with 300 sunny days per year accounting for approximately 3,000 sunny hours per year [17]. Hence, both countries have a very suitable condition to use solar energy as one of the main sources of electrical power supply in rural areas, especially for home lighting, irrigation, and environment monitoring [18].

It is worth mentioning that the main contribution this work presents is a possible low cost solution based on open source technology and commonly available Arduino platform. The demonstrated platform targets regions of urgent need to life basics such as lighting and providing environment monitoring capabilities. The paper does not intend to provide new technology but a solution to practical problem with focus on using off-shelf components and affordable technology that can possibly help improving living condition in unfortunate placed. In addition, the proposed tracking system can be mainly useful in rural areas which are located far from the equator. For example, in Afghanistan the sun radiation makes 32° angle to horizontal on 21 December and the winter days are short. Thus, using a tracking system is more beneficial than a static panel. In the developed system, several sensors are added to the solar panel to observe ambient temperature, humidity, light intensity as well as the produced current and voltage. These data are transmitted over narrow band communication links and are recorded in a remote server for data analysis.

2. Simulation of the Solar Power Output System

This section describes the mathematical model used to calculate the change of the sun's position versus time. The model is used to control the motors as well as to estimate the total output power. In general, the sun's speed in relation to the earth can be considered constant during every day [19]. However, its trajectory changes daily. This trajectory can be described by the equations as following [9]:

1. Declination angle

$$\delta = 23.45\frac{\pi}{180}\sin\left[2\times\left(\frac{284+n}{36.25}\right)\right] \quad (1)$$

where, δ is declination angle (radian), n is the day number, such that n=1 on the first of January.

2. cThe hour angle

$$sin\omega = -\frac{\sin\alpha+sin\delta sin\theta}{cos\delta} = \frac{sin\alpha-sin\delta\, sin\theta}{cos\delta\, cos\theta} \quad (2)$$

where; ω is the hour angle, α is the altitude angle, Az is solar Azimuth angle, ϕ observer's latitude.

3. The Altitude angle

$$sin\alpha = sin\delta sin\theta + cos\delta cos\varphi cos\emptyset \quad (3)$$

4. The Azimuth angle at the sunrise (A_{SZ}) can be calculated from

$$\sin A = -\sin\omega\cos\delta \quad (4)$$

Where: A is the azimuth angle at the sunrise time.

Assuming normal incidence, the output power of the solar panel is simulated by employing PV-Syst, a software package used to simulate and design renewable energy systems [20]. However, it needs to be pointed out that this software does not support small solar panels such as the one used in this paper. Therefore, a scaling factor is used as in order to account for the actual panel area. As the PV-syst implementation time is based on real time, and in practical systems the time was always constant, it caused the result to show a different trend, Fig. 10.

Finally, it needs to be observed that the system consumes energy during running and sleeping modes. A sleeping mode is the state where the motors are not running to rotate the panel. The consumed energy in 24 hours can be estimated by calculating the consumed energy in each operation cycle (motor moving + sleeping), E_{cons} and is defined as:

$$E_{con} = V_R\times I_R\times T_R + V_S\times I_S\times T_S \quad (5)$$

where V, I and T denote voltage drops, electrical currents and mode times The suffixes R and S symbolize running and sleeping modes, respectively. In the system developed, the running time, T_R is set to 1 second while the sleeping time T_S is set to 15 minutes. Subsequently the total consumed energy in one day, then can be estimated as:

$$E_{ssytem}/_{day} = E_{cons}\times\left[{}^{24hour}/_{(T_S+T_R)}\right] or$$

$$120\times E_{Cons} \quad (6)$$

$E_{cons}\times(24\ \text{hours}/(T_S+T_R))$ or $120\times P_{cons}$ for the proposed system. The net stored energy in one day is the one calculated from PV-syst software subtracting the consumed energy.

3. Design and Implementation

The main focus of this work is to develop a simple, low-cost, easy to build, efficient open-loop solar tracking system with additional environmental monitoring capability to determine the panel's efficiency. High humidity and low light intensity mostly indicates rainy periods while high brightness and temperature indicates clear sunny days. These information are important for system study and possible optimization. This as well suits the implementation in places with frequent electricity outages such as rural areas and devastated regions. The tracking system can be easily built and programmed with low-cost equipment that is readily available from the local market. The system was designed to minimize its operation power, and has been accomplished by dividing the task into two parts, namely a mechanical design and electrical circuit design, which are described in Sections 3.1 and 3.2, respectively.

3.1. Mechanical Design

The demonstrated solar tracking system utilizes two motors, one for azimuth tracking (DC - motor for East-West motion), and one for elevation tracking (stepper motor for North-South motion). The mechanical design and implementation is divided into three parts: panel carrier, panel carrier rotator and linear actuator as depicted in Fig. 1. The panel carrier comprises an aluminum rectangular frame to support a 50 Watt solar panel, a 3D-printed circular joint and a post. The 3D-printed joint is connected to the panel frame with two bearings to facilitate the elevation motion. The post is used to connect the solar panel to the rotator by means of a 3D-printed large gear with a diameter of 144 mm and 150 teeth, which is mounted at the rear end of the post. The panel carrier rotator comprises of a small gear with a diameter of 32 mm and 33 teeth, which is coupled to a direct current motor (DC-motor) motor that is mounted to an aluminum base in order to support an azimuth rotation between 0^{o} and 180^{o}. The large gear completes one complete cycle every 4.5 rounds of the small gear. The linear actuator converts circular movement to linear vertical motion, which ensures panel elevation to accommodate for the seasonal angle change of the sun. It comprises of a threaded rod, a nut connected to the panel through a rod, bearings and screws. The threaded rod is directly connected to a stepper motor. Motor rotation turns the rod causing the nut to move linearly up or down. The rod connected between the nut and the end of the panel causes elevation motion as shown in Fig. 1c.

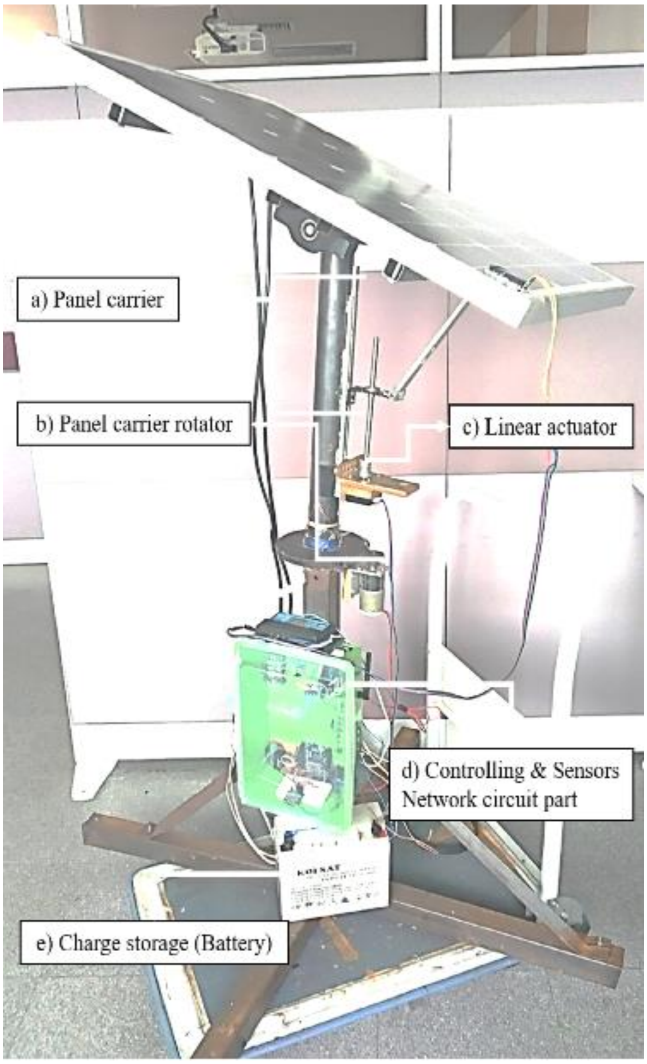

Fig. 1. The developed solar panel system with open-loop solar tracking with the different units (a) Panel and panel carrier (b) Panel carrier rotator (c) Linear actuator (d) controlling and sensor network circuit (e) battery.

3.2. Electrical Circuit Design

The present open-loop tracker uses the commonly available Arduino UNO for system implementation. There are two distinct electrical circuits, namely one that drives the motors and one that connects to the various sensors. The electric circuitry that drives the motors is divided into two units: a movement unit and a controlling unit. The movement unit consists of two 12 V motors, namely a stepper motor and a DC-motor. The stepper motor moves the PV-panel along the vertical axis whereas the DC-motor rotates the solar panel around the azimuth axis. Two motor drivers, type L298N [21], are installed in the controller unit. Both motor drivers include a real time clock and their movements are pre-calculated and stored in the Arduino UNO board that controls the motor drivers. The entire electric circuit that drives the motors is powered by a 12 V battery that is powered by the solar panel. The diagram of the electrical circuit design is shown in Fig. 2.

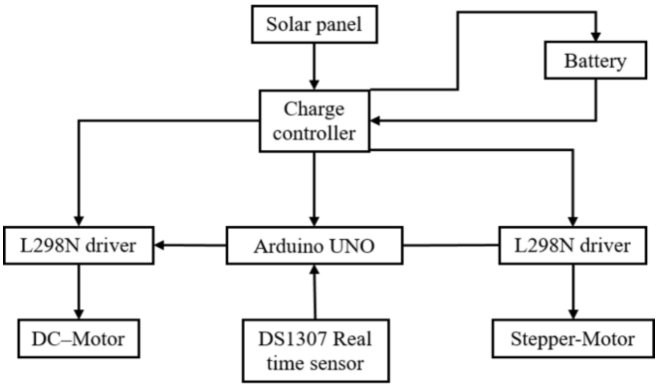

Fig. 2. Block diagram of the electrical circuit design of solar tracker.

In addition to its powering application, several sensors are added to the solar unit in order to monitor its performance as well as to sense environmental conditions. The following sensors have been included:

- A light intensity sensor, type (BHT-1750)[22]
- A humidity and temperature sensor, type (DHT-11) [23],
- AC and DC current and 25VDC sensors, type (ACS712-20A)[24]

A Narrow Band Internet of Things (NB-IoT) links connects to an Advanced Info Service Public company limited (AIS) Magellan dashboard to send the sensors' data over the internet [25]. The recorded data on the AIS Magellan website are then requested by Python client software for analysis. All the sensors and transmission units are connected to one Arduino Uno board for data collection, signal processing and data streaming. The sensors design configuration is shown in Fig. 3.

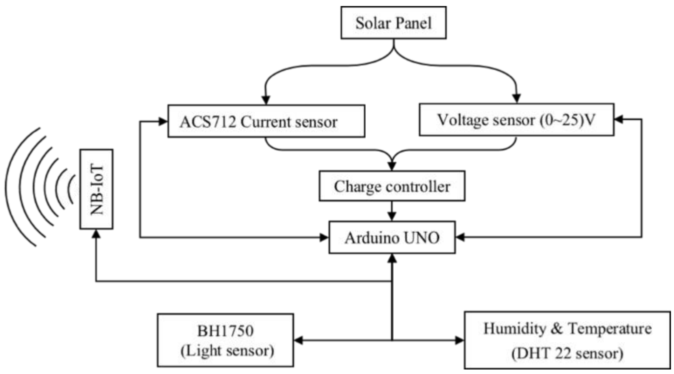

Fig. 3. Block diagram of the sensors, transmission and control board using Arduino Uno and NB- IoT.

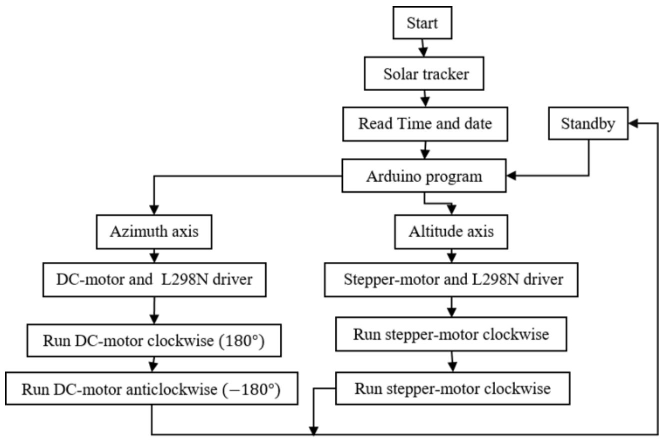

Fig. 4. Block diagram of open loop solar tracking system.

4. Open-Loop Tracking System

Figure 4 shows a dual axis open-loop solar tracking system that is based on real time clocks. Bangkok University's main campus, where the experiments were conducted, is located at 13.986⁰ N and 100.66⁰ E. The entire solar power system, including its tracking control, is programmed by means of an Arduino Uno board and by considering local real time. The system is programmed such that the DC-motor rotates the system clockwise from east to west during the day in order to track the sun's position according to the local time zone. In the evening, the motor rotates the system anticlockwise back to its initial position, and this in a single step. The motor then enters into sleeping mode during the whole night. Whilst carrying out the experiment, it was found that since the location of the installed solar system is close to the equator, tracking along the elevation-axis can be complex during different seasons. For instance, the stepper motor that controls the elevation motion needs to rotate twice a day morning and afternoon in the period from 21st March to 21st September, whereas one rotation every week is sufficient during the rest of the year.

5. Evaluation of the Solar Tracking System Implementation

The system is designed to operate fully on the energy stored in the battery as shown in Fig. 1e. That includes the power for its entire tracking system as well as the power that is required for environmental monitoring. Hence, minimizing power consumption during normal operation time is required, particularly for motor rotation since that consumes most of the operating power. One way to reduce motor power consumption is through rotation in discrete steps rather than following the continuous movement of the sun. The step time though needs to be selected such that the system sustains output similar to continuous tracking movement. To determine the needed step time delay, the solar panel ratio and the misfit angles, which are explained below, when the motors run stepwise in both elevation and azimuth angles with delay periods varying from 0 to 60 minutes as depicted in Fig. 5. The misfit angle α, is the angle the sun rays make from the normal to the surface of the solar panel. The solar panel ratio is the cosine of the misfit angle. It determines the ratio between the solar coverage area when the panel is tilted and the normal to the sun. As earth rotates once every 24 hours, every hour corresponds to 15^{o} of rotation or 0.25^{o} per minute. The calculations in Fig. 5 show that a step time of up to 15 minutes sustains a solar panel value that is at least 99% of the maximum amount of captured sun rays, which corresponds to a maximum misfit angle of 3°. Hence, in the experiment, a step delay of 15 minutes is implemented.

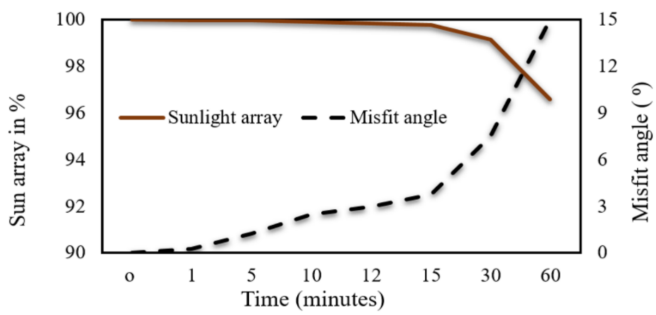

Fig. 5. Calculated the percentage of sun rays for a static panel (sold line) and the misfit angle (dashed line) versus time from noon.

In the presented experiment, the panel is installed at location 13.986⁰ latitude and 100.525028⁰ longitude, which is near to the equator. Here, mono-crystalline panel is used. This is due to its higher reported efficiency compared to the equivalent poly-crystalline. The panel prices have as well reduced to values similar to poly-crystalline ones. The data for both the static panel and a panel with two axis solar tracking were collected over a period of five months. Figure 6a depicts the measured output power for both static and tracking systems over five hours a day. This

DOI:10.4186/ej.2020.24.5.65

study used the same solar panel for both tracker and static system, and the measurements were done on two alternating days, one day for the static case and the other day for the tracking system. The days have similar weather conditions as illustrated in Figs. 6b and 6c for humidity and temperature, respectively. The results indicate that the average PV-panel's output power is 45 Wh for the tracking system and 36.5Wh for the static panel. This corresponds to a total energy generated in 7 hours within one day of 315 Wh/day and 255 Wh/day, respectively. In order to provide a practical comparison, similar calculations were performed for 1kW solar panel. The tracking system and static panel were estimated to generate 6.3 kWh/day by 5.1 kWh/day respectively. The data was measured on 17-18 of September where the sun radiation is received at an angle of 83° in the static panel from the south. With a small misfit angle during this period, the amount of generated energy is almost the same amount of energy in both static panel and tracking system. Hence, the generated energy by the tracking system is 18% more than that of the statics panel. This result includes the consumed energy by tracker and controller. It as well matches the reported improvement when using closed-loop system utilizing Arduino-platform [12]. It is worth noting that, in the tracking system, each motor runs for one second and sleeps for 15 minutes. Using this model of operation and Eq. (5), the power consumed by the motors and the circuits is calculated from the values measured by the current and voltage sensors. In each operation cycle the current raises to I_R = 560 mA during running time and decreases to I_S = 30 mA during sleeping time. During running and sleeping, voltages are set to be equal, i.e. $V_R = V_S$ = 12 V. The total consumed power in one day can be calculated from Eq. (5) by setting T_R and T_S to 0.03 hours and 23.97 hours, respectively, which corresponds to 1 second operation time followed by 15 minutes sleeping time.

$$E_{cons} = (0.56A \times 0.03\ h + 0.03\ 23.97\ h)12V$$

$$= 7.8\ Wh \tag{7}$$

This experience uses a light sensor to show the amount of the sun radiation which falls on the solar panel.

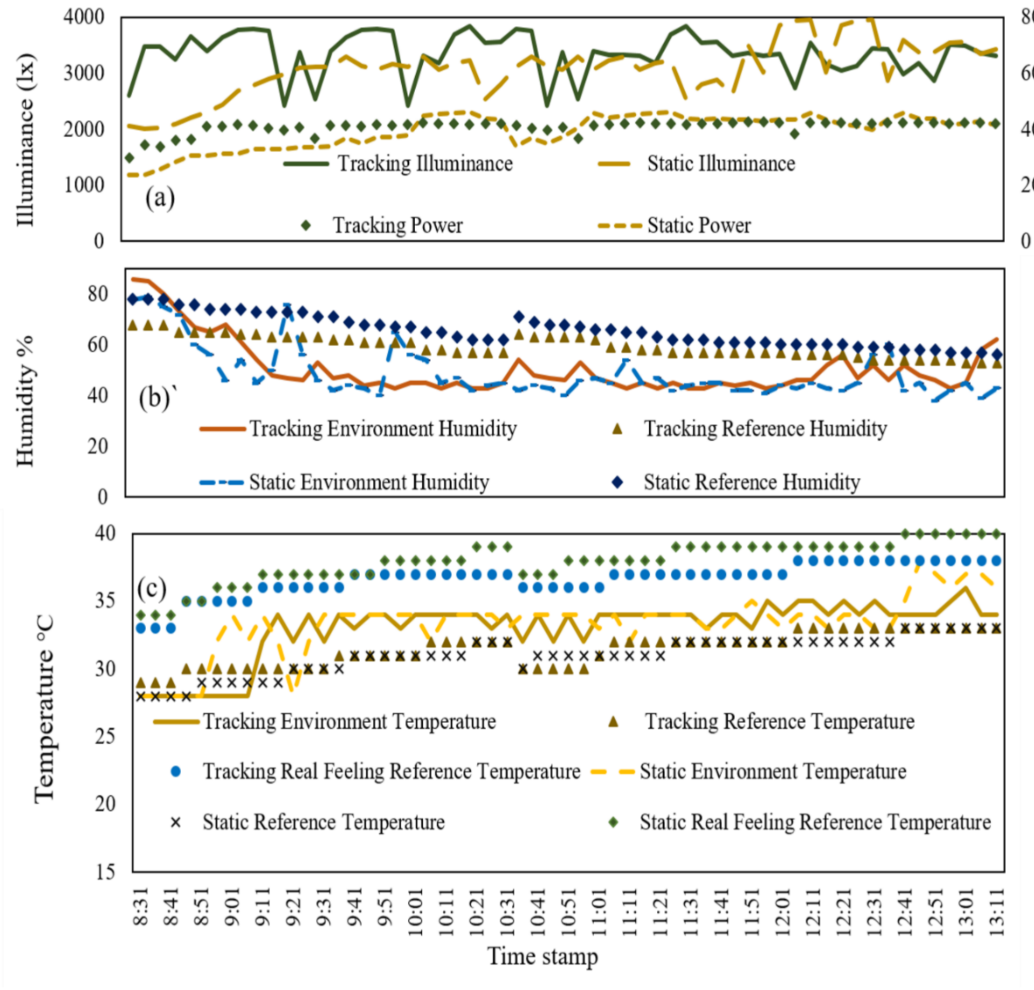

Fig. 6. Solar output power in both statics panel and solar tracking system.

To include the weather effect, several conditions can be considered: sunny, cloudy, partially cloudy and rainy. However, this study focuses on comparing the performance between sunny and rainy days. As shown in

Fig. 7a, the generated power was measured over 7 hours on both sunny and rainy days. The environment's humidity and temperature were measured and compared to the online provided weather information in Figs. 7b and 7c (labelled reference). Using monocrystalline solar cells, a total energy of 293 Wh and 47 Wh were generated on sunny and rainy days, respectively while using the tracking system. Although the light intensity on rainy days is, on average, 25% of that on sunny days, the monocrystalline solar cell panel was able to generate energy that is at least five times higher than that consumed by the motors and the electrical circuitry. As the open-loop solar tracking system is the best option to output a maximum amount of solar power in different weather conditions.

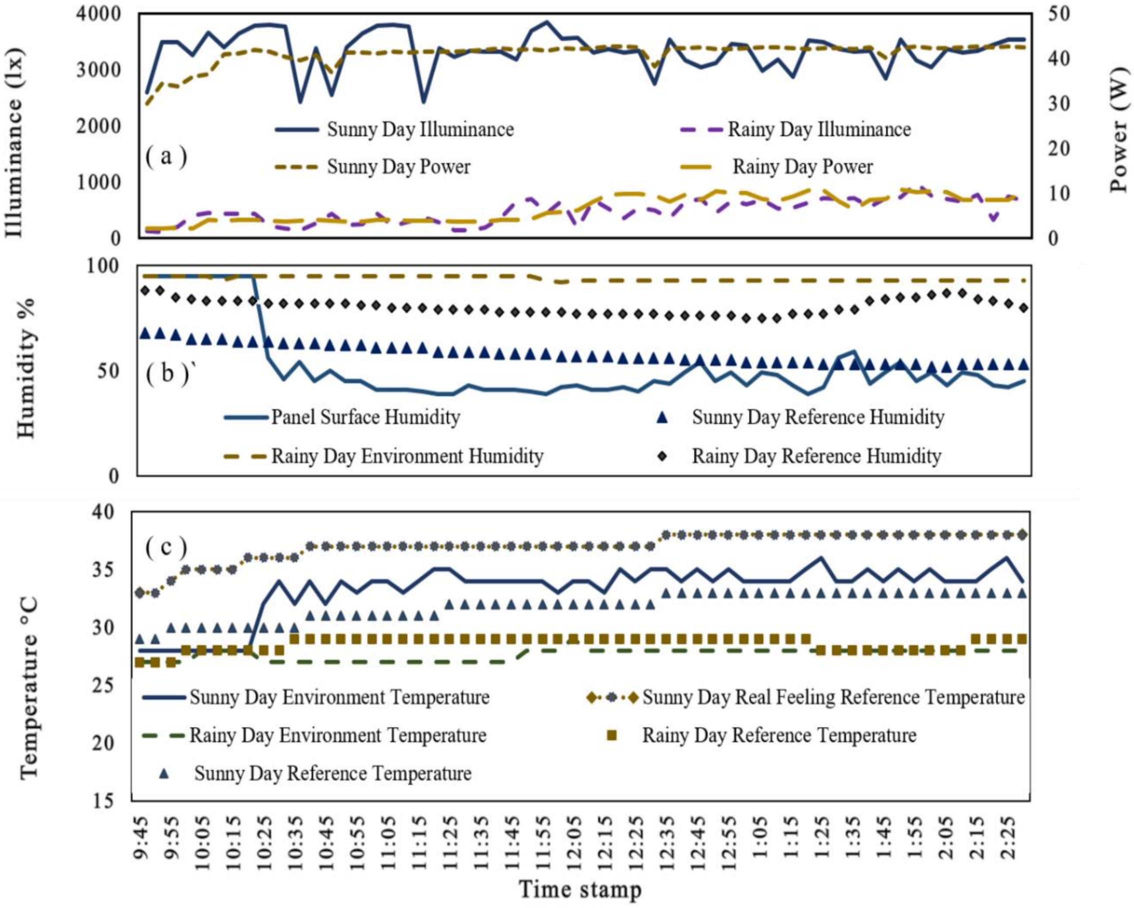

Fig. 7. Comparison of the output Power of the solar panel on Sunny and Rainy days.

One practical factor that can affect the system efficiency is the solar panel's surface temperature. The measured output voltage decreases significantly with increasing temperature [26]. To monitor this effect, two temperature sensors were used, namely one for environment and one for the solar panel itself. Figure 8a shows a noticeable difference in temperature between the environment and the PV-panel area that was measured over a period of 4 hours around noon on a sunny day. The plots show that the panel temperature can reach 17°C higher than the environment. As it noticed in Fig. 8a, high temperature causes a significant drop in the solar panel output voltage. Figure 8b shows however that the PV-panel output current is not affected.

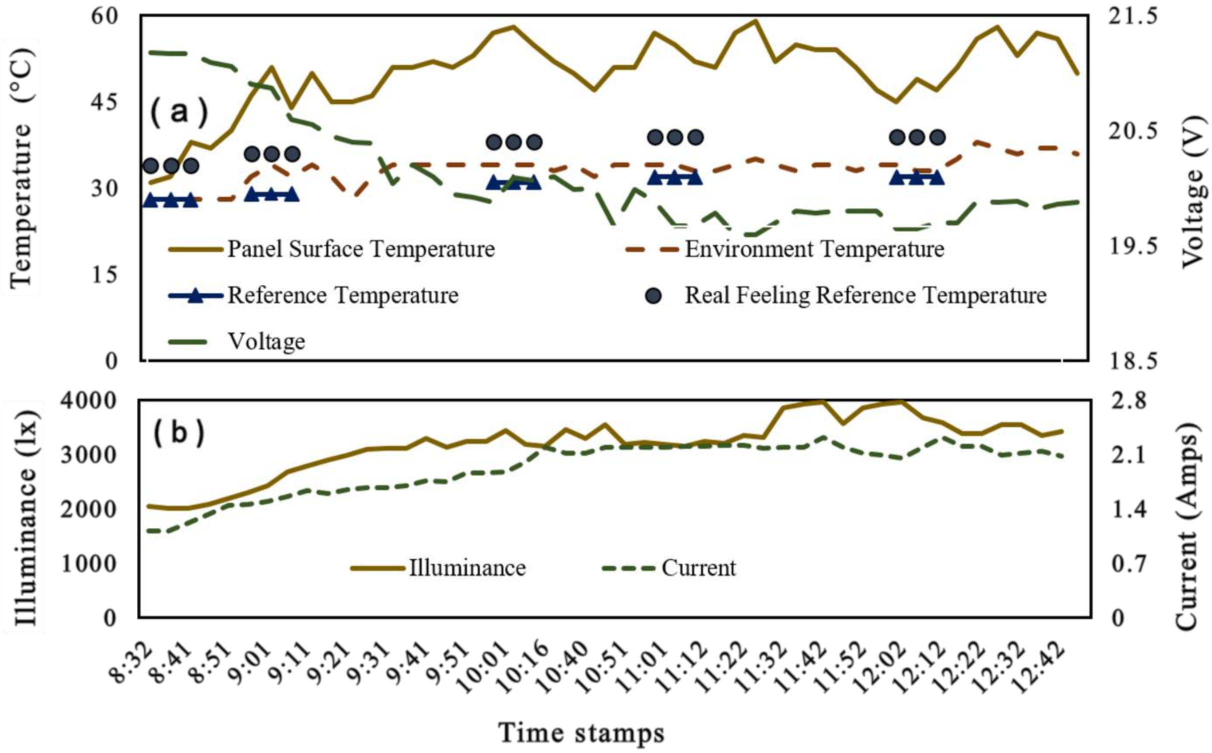

Fig. 8. Comparison temperature effect on solar panel output energy.

In order to test the system over long varying weather conditions, data were stored over five months during April to September 2019. The generated energy is calculated per month and plotted in Fig. 9 in comparison to calculations. Here obtained with PV-Syst software. To acquire the needed calculations, the software requires defining the solar panel location by considering longitude, latitude, albedo, tilt, and time zone time. It also requires setting the amount of demanded solar power in Watt, as well as the number and type of the solar cell with defining dual-axis tracking system. The software output includes produced useful energy, PV-panel loss, and the output power every month of the year as shown in Fig. 9.

It is worth mentioning that, for the experimental graphs in Fig. 9, the output energy was measured over 7 hours daily for 6 months due to the presence of obstacles in the areas. However, Bangkok has at least 11 hours of daily sun during all seasons. To take this into account, the data was interpolated every day to fit the remaining afternoon time. Additionally, the experiment was not performed continuously every day due to weekends and holidays. To estimate the output energy in one month, the average daily energy was calculated as.

$$E_{month} = \frac{\sum_1^n E_N}{N} \times month_{day} \tag{8}$$

where E_{Month} is the total obtain energy per month, and N is the number of the days that the solar energy was collected during one month. $\sum_1^n E_N$ is the total measured energy during the nth day out of the N days over which the experiment was conducted during a particular month. For instance, consider Eq. (7), the total generated energy in September 2019, which was measured on 11 different days of September using the solar tracking system, the following calculation was made.

$$E_{Month} = \frac{2354.624}{11} \times 30 = 6.422 \frac{kWh}{Month}$$

This approximation could be the main reason of the obvious difference between the measurement and simulation in Fig. 9. The difference between experiment and calculations could be mainly due to the fact that PV-Syst is based on real time. However, in the practical system the measurements were done over several time intervals. With this notable difference, the calculations provided a means of indicating the range of the produced energy by the panel over the operation period.

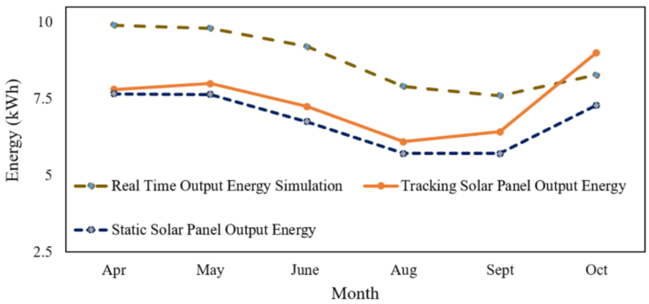

Fig. 9. Comparison of the generated energy per month over a period of five months.

Finally, Fig. 10 depicts the produced energy by the tracking system and the static panel, and this in different weather conditions and different seasons of the year. The figure clearly indicates that the obtained energy using a tracking system is higher than that of a static panel on sunny days. On rainy days, however, the outcome is comparable. On cloudy days, the condition changes along the day from sunny to cloudy and vice versa in case, especially in the case of partly cloudy conditions. Also, light scattering by the clouds sustains some sort of directionality. Hence the tracker increases the solar panel efficiency. According to the results, the static system seems to perform slightly better than tracking system. Hence, one possible improvement of the system is through stopping tracking during the rainy day, where humidity reading is high and brightness is low during the day time.

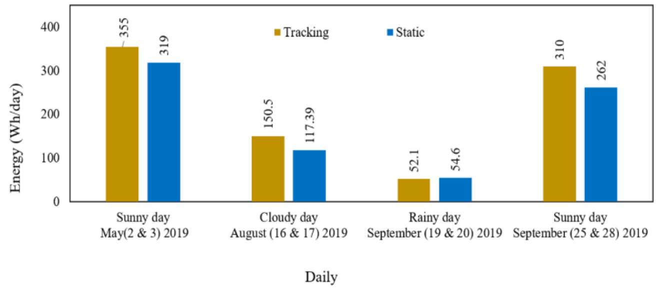

Fig. 10. Comparison Output energy in both tracking system and statics panel in different weather conditions.

In order to evaluate the cost effectiveness of this system, a breakdown of the components cost is compared to one commercially available sun tracker vendor [27]. The results are scaled in order to consider the developed solar power plant size. In this calculation, minor extra tools are not taken in consideration as their cost is negligible. Table 1 shows the solar tracker tools cost in both the commercial vendor and presented system.

Table 1. Comparison of solar tracker tools in manufactories and the this experience.

Solar tracker cost for commercial vendor			Solar tracker cost for the developed system		
Item	Unit	Price per unit $	Item	Unit	Price per unit $
Linear actuator 12V motor Dual-Axis solar tracker Dual-Axis slewing drive bearing RS232 Ethernet server converter DC motor azimuth tracker Clamp assembly SM3 Solar panel monocrystalline 50W Battery , 12V~24hMD Charger controller PWM	1 1 1 1 1 1 1 1 1	40 100 100 40 12 45 35 65 11	Stepper motor ,12V IMS bearing Screw and rod DC motor, 12V PWM Charge controller Solar panel monocrystalline 50W Battery , 12V~24hMD Arduino UNO L298 motor driver DS1307 Real Time Clock	1 3 1 1 1 1 1 1 2 1	
Total		$448			$193

DOI:10.4186/ej.2020.24.5.65

6. Conclusions

This paper presented a dual axis, open-loop tracking solar system using a 50 Watt monocrystalline solar panel and two motors, namely DC and stepper motor. The motors are controlled by a single Arduino board programmed for the real time tracking of the sun's position. Multiple sensors were used to collect environment data, which were transmitted using a narrow band wireless communication link in order to monitor the system's performance as well as the environment. Experimental data were collected in both a solar tracking system and a static PV-panel, and this in different weather conditions. The results over a five months experiment period showed that the panel with the open-loop tracking system produced 18% more energy than the static panel (i.e on average 6.422.kWh/month, compared to 4.89 kWh/month). The results seem to follow the calculated power based on PV-Syst software with the difference attributed to the interpolation of the data during the non-operation period.

Acknowledgement

The authors would like thank Bangkok University, Thailand, for the BUTA scholarship.

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DOI:10.4186/ej.2020.24.5.65

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