Asia-Pacific Journal of Science and Technology: Volume: 29. Issue: 04. Article ID.: APST-29-04-03. Research Article

APST

Asia-Pacific Journal of Science and Technology

https://www.tci-thaijo.org/index.php/APST/index

Published by the Research and Graduate Studies,
Khon Kaen University, Thailand

Evaluation of the PV design based on minimum percentage of energy saving

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Received 24 March 2023
Revised 2 May 2023
Accepted 7 June 2023

Abstract

In Thailand, the use of photovoltaic (PV) energy technology is growing in popularity in the industrial sector to reduce the amount of electricity drawn from the grid. Before the system is installed, the owner must make investment decisions by evaluating the production potential of the PV system. PV sizing is designed using a simplified method under energy-saving circumstances. With the aid of this technique, the engineer can easily design the PV capacity installation and specify PV sizing in the design program. As a case study, power flow assessment was applied to a wastewater treatment system in Sakon Nakhon, Thailand. The results showed that it consumed an average of 3,643 kWh of energy per day and the plant needed to save 10% of this amount of energy annually. Consequently, the optimal capacity for the system was 101 kWp, while the approximate PV sizing was 103.8 kW, depending on factory conditions. The combined energy output of the grid and the PV system was injected into the 950.86 MWh/year electric load. The entire annual energy output from the PV system was 108.24 MWh, with the energy flow from the grid being 842.62 MWh. Based on current (2023) PV market prices, the typical installation cost was THB 27.44/W, with a payback period of 5.3 years. The developed PV system should assist the wastewater treatment plant with predicted yearly energy savings of 11.4%.

Keywords: PV sizing, Grid-tie connection, Daily load curve, Energy saving, Performance ratio

1. Introduction

Since 2011, Thailand's Ministry of Energy has been pursuing a strategy to continuously promote energy through the Alternative Energy Development Plan (AEDP). The government has continuously modified AEDP's aim to reflect changes in the world's energy situation. By 2021, according to Ministry of Energy strategy, 25% of the nation's energy consumption will come from renewable and alternative sources. The goals include solar energy producing 3,000 MW of electricity [1]. Subsequently, the AEDP plan was updated to cover the years 2018–2037, which for example included increasing solar power to 12,139 MW [2].

In rural locations, such as Sakon Nakhon province, medium-sized or small businesses make up the majority of the factories. The factory owners want to install a solar cell system to supply energy to electrical loads and cut back on power from the main grid, with the key being to install solar panels with an affordable initial cost and a 5-7 year payback period. The announced PV system information includes the total installed capacity, the kind of PV modules and inverters, the amount of energy produced each day, month, and year, as well as the decreased monthly energy costs. The factory owner must consider this information while making investment choices.

Currently, PV design software is used to evaluate the potential for power generation in the region where the system will be installed. The software has been developed over time to enable highly efficient estimation in the design phase of PV systems [3]. The PVsyst software is a program used for the design of photovoltaic power generation systems [4,5]. Users may change installation factors, such as inverter size, PV module type, and installation size. The program provides meteorological data related to the field of study from a variety of sources. However, in addition, the PVsyst software allows users to manually enter meteorological information in a specific study location. Errors in predicting the amount of energy generated by the PV system are reduced by accurately specifying its characteristics. In addition, PVsyst offers applications for performing economic evaluations, such as calculating CO^2 emissions or the cost of the energy generated [6,7].

2. Materials and methods

2.1 Methodology

A PV rooftop installation is one of the most effective solutions to cut back on grid energy use. The project designers occasionally must operate under limitations, such as funding or installation space. The primary concern is how the PV system's installed capacity should be adjusted in accord with the available budget. Figure 1 presents the framework for performance evaluation of the PV design approach based on the limitations for any industry.

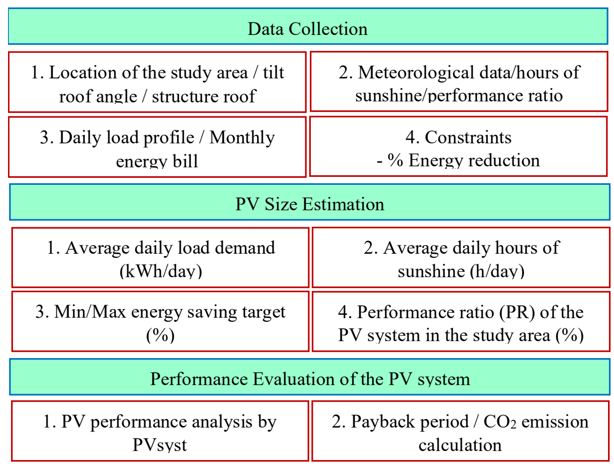

Figure 1 Framework for PV performance evaluation.

To determine the placement of the PV array, data collection at the exact location was taken into account, including taking into account the tiled roof angle and roof structure. The optimum method for obtaining a daily load profile is to measure power at the main distribution board (MDB) of the study region. Typically, the PV size is created to produce energy for all demands. Some factories would like to nominate the energy saving percentage in relation to the PV sizing. The current study first used a simplified method to estimate PV sizing and then the PV design software calculated the parameters for performance evaluation of the PV system. Along with the expected annual energy production, other factors considered included $CO2$ emission savings, investment cost, and payback period.

2.2 Meteorological data

The study area was used primarily for rubber production and processing in Sakon Nakhon province, Thailand (17.3232 N and 104.2301 E), as shown in Figure 2(A). A link in the PVsyst application provides access to meteorological data, such as irradiance, temperature, humidity, and wind speed, depending on where the wastewater treatment plant is located. [8]. There are numerous data sources that can be user-edited or web-sourced. PVGIS is one of the free meteorological databases, offering online meteorological information for any location. The hourly radiation on March 28, a clear day, is shown in Figure 2(B). There is a difference between global and horizontal radiation on any day of the year, with 7 kWh/m^2 being the highest amount of energy produced from horizontal global radiation. However, the direction of the sun at the project site affects the amount of horizontal and global radiation. For optimal power generation, the amount of solar energy entering the study area should be the highest.

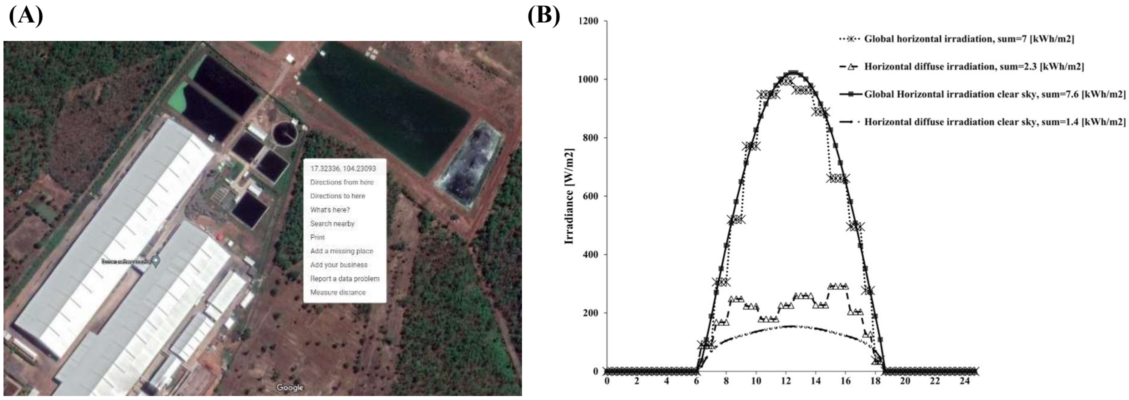

Figure 2 Hourly radiation on a cloud-free day in the project area: (A) Rubber factory and (B) Radiation along the Sun's orbit.

The sun's orbit affects how much radiation falls on a solar panel each day. The azimuth and elevation change along with the sun's orbital angle. Due to the sun's orbit, large structures or trees may block sunlight from reaching the PV modules, affecting the efficiency of PV power generation. Therefore, this factor was used by the simulation program to calculate PV behaviour.

2.3 Daily load profile

The rubber industry's wastewater treatment capacity is typically 700 m^3/day, with electric motors being crucial for the associated power consumption, as they work with auxiliary devices such as air blower pumps or water pumps. Overall, the sewage treatment plant has an installed engine power load of 561 kW. However, since each motor is controlled to perform different functions, they may not all be operational at the same time. The daily load curve is determined for the behavioral analysis of energy consumption by measuring the power flow within the MDB. The procedure for collecting data in the research region is illustrated in Figure 3. The data collection period was at least 7 days. Each daily load curve displays the power flow.

Figure 3 Data collection at wastewater treatment plant.

2.4 Plane tilt and azimuth

An industrial roof is an excellent location for supporting the weight of numerous solar panels while avoiding shade obstacles. Google Earth may be used to determine the azimuth direction. Roof direction is the distance in degrees from north to the roof tilt (the direction where the solar panels should be installed), which is 132 degrees; azimuth is the angle in degrees from south when the PV panel is facing east, which is 48 degrees [9], and the inclination of the PV panel is 10 degrees which corresponds to the roof tilt.

Solar panels are typically aligned south and inclined west. However, the roof tilt determines the panel's angle of inclination. Since the roof is not constantly facing south, it is crucial to pick a roof orientation that provides the most sunshine on average throughout the year.

2.5 Feature PV module and inverter

Meteorological information, solar panels, and inverters were all considered in the evaluation of the PV system's potential for power generation in the research area. Monocrystalline and polycrystalline materials are used to make the majority of commercial solar panels. In the STC compliance test, the efficiency of commercially available monocrystalline PV modules reached up to 21.4%, with an annual average efficiency of 15.46% [10]. The production of large PV modules with capacities exceeding 500 W per module is currently a competitive market for both western and eastern manufacturers. The size and weight of the panel increase with the increased wattage per panel. Consequently, PV designers must consider whether the roof's surface and architecture can sustain all of the modules that will be installed.

Based on the modules available on the Thai market, a 400 W PV power level was used for this investigation. It was decided to use the monocrystalline PV module, which at this time has a high efficacy level of 19–20%. Table 1 lists the mechanical and electrical parameters of the PV module, including the maximum voltage at the maximum power point, the maximum open-circuit voltage, the maximum short-circuit current, and the maximum current at the maximum power point. This information is necessary to ensure that the voltage and current of both series and parallel connections match the inverter input. The effectiveness of power generation, which declines as a PV module's temperature rises, is another aspect to take into account [11, 12]. The temperature coefficient is a metric that shows how much PV power generation falls off for each degree increase in the temperature of a solar cell. Because of this, the PV module's cover material should not heat up or quickly absorb ambient warmth. Thus, a fairly high ambient temperature for the installation area will have an impact on the PV system's energy production.

Table 1 The electrical and physical properties of the PV module and the inverter

PV module		Inverter	
Nominal power	400 Wp	Nominal power	50 kWp
Open circuit volate	42.29 V	Nominal MPP voltage	680 V
Short circuit current	10.70 A	Maximum MPP voltage	1000 V
Module area	20.012 m^2	Maximum PV current	87.5 A
Number cells	72 × 2	Maximum AC current	72.5 A
Temper. Coeff.	-0.36%/°C		

Another essential component of the PV system is the inverter. It transforms the direct current from the PV generator into alternating current under appropriate voltage and current conditions. The purpose of grid-tied inverters with MPPT (maximum power point tracking) capabilities is to convert as much power as feasible, while achieving power quality that has no negative effects on the electrical equipment in the power grid [13]. Currently, inverters can convert energy at a rate of over 95%. Users can choose to manage the operation of the inverter by using variables such as power factor, reactive power, and active power.

The user can choose the appropriate inverter for the desired PV system from a variety of inverter types available in PVsyst. The MPPT function present in commercial inverters currently produces energy with the maximum power output [14]. The MPPT principle uses a microprocessor to monitor the power output of solar modules which constantly adjust the voltage and current values to always get the maximum power according to the received solar intensity. Therefore, commercial inverters use power electronics technology to optimize inverter performance, with examples being central solar inverters, string solar inverters, solar microinverters, and hybrid solar inverters. The choice of inverter depends on the design of the PV system and the budget, as some inverter types cost more than others for the same nominal power.

2.6 Influential affecting the system.

The losses in a PV system are one aspect that affects how much electricity is produced. Environmental losses (shading, ambient temperature, and dust) and device losses (PV modules, inverters, and cabling) are the two categories of system loss. Device losses are due to the characteristics of devices, such as the effectiveness of PV modules and inverters. Line losses occur with long cables and inadequately sized cable wires. Weather and environmental variables are another issue because the ability of a PV module to generate electricity will be diminished by clouds or precipitation. Similarly, the temperature of the PV module will increase in high-temperature locations, resulting in an inevitable decrease in power generation.

PV loss parameters in PVsyst indicate the behaviour of the PV [15]. Field heat loss is influenced by both irradiation on the PV module and the ambient temperature that affect the temperature of the module. The ohmic resistance of the wire circuit affects the ohmic loss. Larger PV systems require larger and longer cables, which increase losses. Estimation of resistive loss is more accurate if the PV designer specifies the size and length of the wiring loop close to the actual installation, with loss being considered for both the AC and DC sections.

2.7 PV Sizing Evaluation

Different techniques for estimating the size of the PV capacity are available, with many methods used based on trial and error. First the number of PV power units is set and then the PV power is calculated. If the owner or project developer wants to change the capacity, the power of the PV system is recalculated. The results are compared, and the best result is selected.

Another option uses the simplified PV size estimation method based on local area data. The first step is to estimate the daily energy of the study area (ED: kWh/day). It can be determined from the daily load curve. The daily hours of sunshine are determined by the specific local climatic conditions. The performance ratio (PR: %) is determined based on all efficiency factors, such as the efficiency of the PV panel, the efficiency of the inverter, the azimuth angle, and losses in the system. Another option determines the PR from an actual PV plant near the study site. Equation 1 shows the PV sizing calculation for the total daily load demand.

$$\mathrm{PVsize} = \frac{\mathrm{ED\ (kWh)}}{\mathrm{sun\ hours\ (h)}} \times \frac{1}{\%\mathrm{PR}}\ (\mathrm{kwp.}) \quad (1)$$

where ED is the average energy demand per day (kWh), Sun hours is the daily period of sunshine in the study area (h), and %PR is the PV performance ratio.

The PV size estimate used in Equation 1 relates the generated energy of the PV system to the total load demand. However, there is a defined value for the energy-saving goal, it can be calculated using Equation 2.

$$\mathrm{PVsize}_{\%\mathrm{ES}} = \frac{\mathrm{ED\ (kWh)}}{\mathrm{sun\ hours\ (h)}} \times \frac{1}{\%\mathrm{PR}} \times \%\mathrm{ES}\ (\mathrm{kwp.}) \quad (2)$$

where %ES is the energy reduction.

If the owner only wants to reduce the monthly or yearly energy by 10%, this step shows the simplified method for estimating the PV size under the constraints. After the PV capacity has been defined, the next step is a more detailed performance assessment of the PV system.

3. Results and discussion

3.1 Daily load curve

The electrical power measurement in a sewage treatment plant was used as a case study to demonstrate the behaviour of power flow in the system. The duration of the current stress measurement was recorded for at least 7 days. The load curve was developed to show the power flow at any time and the level of energy consumption. Figure 4(A) shows the daily load profile of the wastewater treatment plant between September 15 and October 14, 2021. The peak load time was clearly between 06:00 and 15:00 and the course of the load curves was continuously up-down during the day. It is important that not all motors are switched on and off at the same time.

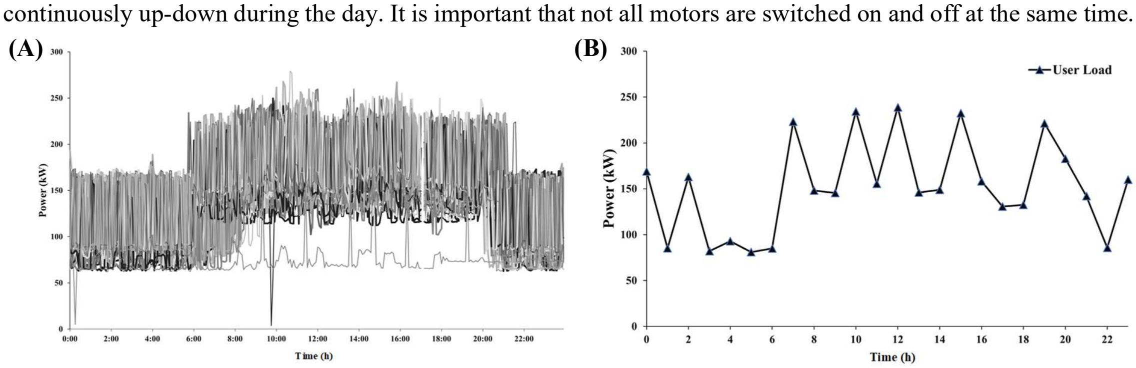

Figure 4 The load curve of the wastewater treatment plant (A) The daily load profile (B) Average daily load profile.

Figure 4 (B) illustrates the daily average load curve and the peak load of 239 kW at 12:00 with reference to Figure 4(A). The load curve shows that there is a high daily electricity demand, making the installation of solar power possible. The size of the PV installation was decided using the information from the load profile. The load curve shows there is 4-5 h of direct sunlight and an average daily energy use of 3,643 kWh. Because the owner wants to apply a 10% annual rate of energy savings, the Sakol Nakhorn PV system's PR shows that its efficiency is in the range 77-82% [12]. Then, the investment costs were calculated, along with the payback period, to determine the PV size, as shown in Equation 3.

$$\mathrm{PVsize}_{\%ES} = \frac{3{,}643}{4.5} \times \frac{1}{0.78} \times 0.1 = 103.8\ (\mathrm{kwp.}) \tag{3}$$

The fundamental idea behind the PV design is to use less energy while maintaining a low budget and a quick return. As a result, the PV system was made up of 14 strings, each of which comprised 18 modules. There were 252 panels in the PV array. The entire area for installing the PV system was 507 m^2, fixed along the roof direction at 10 degrees with the azimuth at -48 degrees, and the PV capacity was approximately 101kW.

A string inverter with a 50 kW and 6 MPPT capability was selected for the PV system. This project used two sets of grid-tie inverters to improve system reliability because one inverter cannot provide electricity if it is malfunctioning. The second one provided power to the wastewater treatment facility. Under the right circumstances, grid-tied inverter technology may automatically turn the PV power flow on and off. The PV system builds up a voltage that is unsuitable for inverter operation when there is minimal solar energy. The circuit connection for the grid-tied PV power generating system is shown in Figure 5, where each inverter is connected to 7 strings, all of which are integrated into one junction box and then wired to the MPPT of the inverter. The MDB of the wastewater treatment plant receives the output electricity of the inverter and feeds it to the busbar.

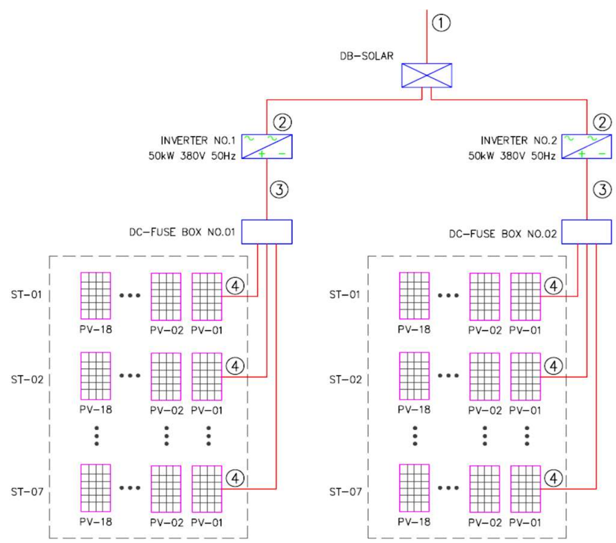

Figure 5 Schematic diagram of grid-tied PV power generation system.

3.2 Energy Generation

The main results of the simulation were based on environmental factors, as shown in Table 2. The total energy generated by the PV array (EArray) was 151.79 MWh per year in the DC power section. For the AC power component, the energy from the PV array supplied to the user load was 108.19 MWh per year (E_Solar), which included the total loss calculation of the entire PV array. Therefore, the energy from the sun (E_Sun) and the energy from the grid (EErGrid) were combined to provide electricity to the user's load (E_User). If E_Solar has a large value, the energy from the grid will be reduced which will also reduce electricity costs.

Table 2 Output of grid-tie simulation for wastewater treatment plant

List	Output	Unit
Produced Energy	149.7	MWh/year
Specific production	1,485	kWh/kWp/year
Performance ratio (PR)	77.76	%
Solar faction (SF)	11.38	%
Effective energy at the output of the array (EArray)	151.79	MWh/year
Energy from the sun (E_Solar)	108.24	MWh/year
Energy from the grid (EFrGrid)	842.61	MWh/year
Energy supplied to the user (E_User)	950.86	MWh/year

The performance ratio (PR), as a PV system quality indicator, is the potential of a PV system in the study area to convert solar energy into electrical energy to supply the user load. The PR formula is the Yf-to-Yr ratio [11, 12], where Yf is the delivered energy to the grid and Yr is the reference yield energy, according to the STC standard. For the current case study, actual performance versus expected performance and possible energy yields was 77.76%. The main key is the orientation of the tilt of the PV module and the azimuth of the incident radiation, which affects energy production. As shown in Figure 6, the energy production or the final system yield for each month was more than 4 kWh/kWp/day on average. June, July, and August (the rainy season) had mostly low energy yield values, while the highest energy yield values occurred in February, March, and April (winter season when solar radiation was high).

Collective loss (Lc) refers to the array losses composed of thermal, wiring, module quality, mismatch, array incidence loss (IAM), shading, pollution losses, and other types that affect the power production of PV modules. In the current study, Lc generated about 1.11 kWh/kWp/day, which was greater than Ls (the system loss including inverter loss). Normally, manufacturers build an inverter with high efficiency (more than 95%). Hence the value of Ls is always low. A tall water tank was close to the PV field yet lower than the PV panel, as shown in Figure 7. The water tank was one surrounding object in the PV field, as shown in Figure 7(A). The nearest shading parameter for shading analysis was 0%. The iso-shading diagram displays zero value in comparison to Figure 7(B). Thus, irradiation shading did not influence the PV loss.

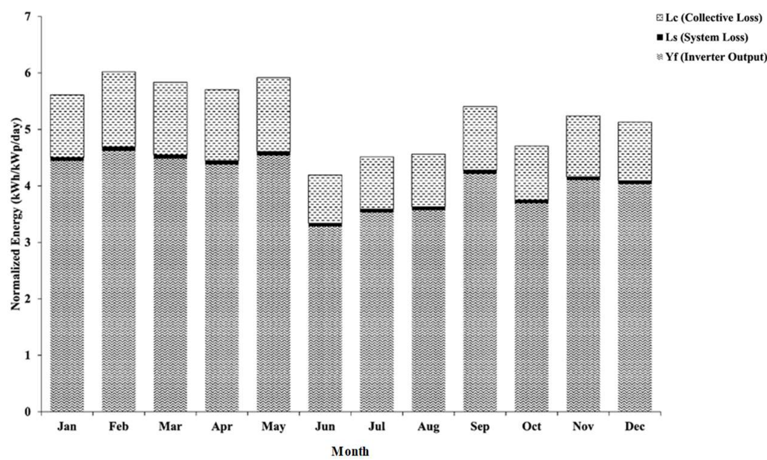

Figure 6 Normalized production results for 101 kWp installation.

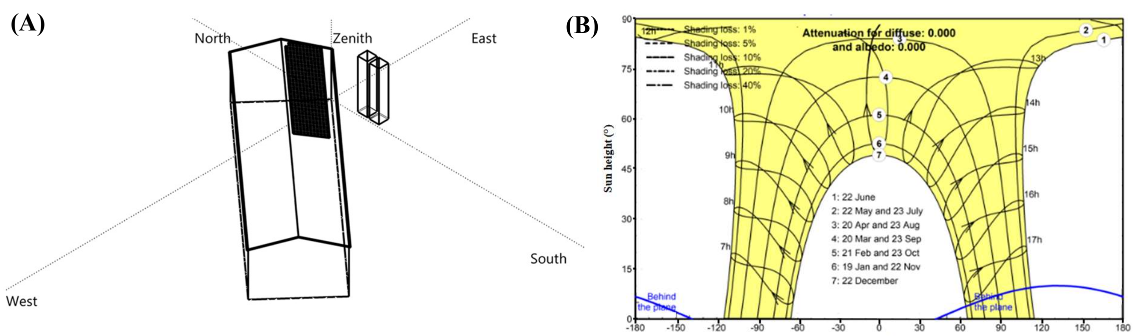

Figure 7 Near shading 3D scene of study area (A) Perspective of PV layout (B) Iso shading diagram.

E_Solar and E_User for the defined user load is shown in Table 3, where E_User is the energy consumed by the user load and E_Solar is the energy production of the PV system that is supplied to the consumer load (E_User). EFrGrid is the energy drawn from the grid. Therefore, E_Solar in combination with EFrGrid supplies electricity to E_User. The energy supplied by E_Solar was 108.24 MWh/year while the user load was 950.86 MWh/year. Thus, the PV system would reduce energy consumption from the grid by 11.4% per year. This result was a main objective of this project.

The PVsyst displays the daily load curve of grid power (blue line), the available solar energy (green line), and the power supplied to the customer (red line) if the load curve is defined, as illustrated in Figure 8. Three daily load curves were compared. At night, the PV system did not produce energy, so the grid was the main energy source for user load. During the day, the user load could draw energy from both solar energy and the grid. The available solar power curve is displayed from 6:00 a.m. to 5:30 p.m. when the PV system reduces peak loads and energy from the grid. Figure 8(A) shows that PV production was high due to the clear sky, reducing the need to supply energy from the grid to feed the user load. Figure 8(B) shows that power generation from the PV array was low during the rainy season, resulting in a greater load being supplied from the grid to meet user demand. Accordingly, the energy from the PV system was 108.243 MWh and the total footprint of the PV module was 507 m^2, so the energy density was 213.5 kWh/m^2.

Table 3 Monthly energy of each part of PV system.

Month	EArray (kWh)	E_User (kWh)	E_Solar (kWh)	E_Grid (kWh)	EFrGrid (kWh)
January	4077	83792	10159	3717	73633
February	13240	72863	9263	3777	63599
March	14231	80149	10202	3809	69947
April	13454	76506	9513	3735	66993
May	14403	83792	10501	3682	73291
June	10082	76506	7049	2860	69457
July	11218	80149	8221	2812	71928
August	11352	83792	8242	2924	75550
September	12929	72863	8572	4159	64290
October	11715	83792	8737	2799	75055
November	12596	80149	9201	3211	70948
December	12790	76506	8582	4020	67924
Year	152087	950860	108243	41505	842617

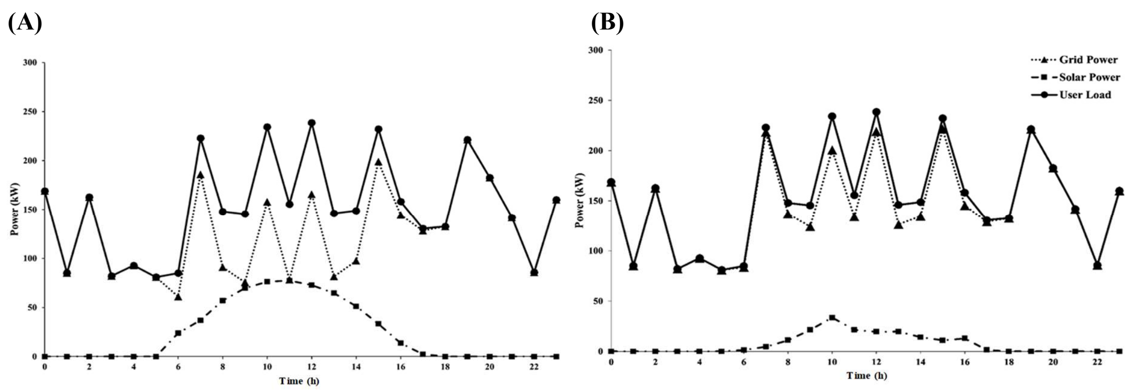

Figure 8 Daily load curve of PV array, grid, and user load (A) Power curve on April 18th (B) Power curve on July 6th.

The investment calculation for the installation of a solar cell system only considers the costs for equipment, installation, and connection to the grid. The investment for 101kWp was THB 27.44 /W. Based on the average energy cost of the wastewater treatment plant in 2022 of THB 4.82/kWh and the estimated annual energy from the PV system was 108,243 kWh, the payback period would be about 5.3 years. Currently, the average investment price for the PV market is THB 25-35/W. The cost investment is cheaper than 5-10 years ago, so the payback period is exceptionally short. The unit price of each unit depends on the type of solar panel and inverter, as well as the quantity. The number of manufacturers of the two major devices around the world has increased, which has led to less price competition. However, when choosing equipment, the performance of the equipment must also be considered.

Various PV design programs have been developed either by manufacturers or by government departments [16]. All factors affecting the investment should be considered and based on good forecasting. In fact, most of the models use meteorological data from various sources, such as weather observation stations and weather satellites, while some data have been projected onto a specific area. However, meteorological data in the study areas can be edited by the user. Finally, by using meteorological data specific to the study area, the forecast results are closer to the truth.

4. Conclusion

This study illustrated how to define PV sizing in accordance with the quantity of energy savings. The wastewater treatment plant in Sakon Nakhon province that was used as the case study needed 3,643 kWh of energy per day and a 10% yearly reduction in energy use. To meet these constraints, the PV installation should be 101 kWp in size, according to the PV sizing calculation, which predicted 103.8 kW. The PV performance was evaluated using the PVsyst software. The azimuth angle from the factory roof to the east was 48 degrees and the PV plane tile was 10 degrees. Two sets of 50 kW inverters and a 400 W PV panel were recommended. The modelled outputs for energy production from the PV array, power flow from the grid, and user load were 108.24, 842.62, and 950.86 MWh per year, respectively. The performance ratio of the PV grid connection was 77.76%. The energy-saving from the main grid was 11.4% per year, which is in line with the objective of the study. The average installation and grid connection costs were THB 27.44/W, and the payback period was 5.3 years. The CO2 emission saving was 1,632 tCO2 for the lifetime of the PV system (25 years) with annual deterioration of 1%.

An advantage of the simulation model was that the PV system designer could investigate the impacts of various estimated values in the system. The proper choice of device characteristics in the PV system is also involved in evaluating PV system performance. Losses in the system are caused by equipment and environmental factors such as choosing a smaller cable that results in a voltage drop. Dust on the PV module reduces the efficiency of energy generation. Consequently, regular cleaning of the PV modules is one way to maintain the efficiency of PV power generation. Therefore, a simulation model for estimating the expected energy from a PV system is another choice that can support consumers when making investment decisions.

5. Acknowledgments

The authors thank the Faculty of Science and Engineering, Kasetsart University, Chalermphrakiat Sakon Nakhon Province Campus (CSC), Thailand for the research support budget and thank Sri Trang Agro-Industry Public Company Limited, Sakon Nakhon Branch for the study area. The aim of our Energy and Environment research group is to study the application of clean energy technologies and process improvement techniques for various industrial processes to reduce energy consumption and improve the appropriate methodology to reduce environmental impact.

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