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Techno-Economic Assessment of a 1 MW Solar PV Rooftop System at Thaksin University (Phatthalung Campus), Thailand

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Abstract: This study presents a techno-economic assessment of a 1 MW solar photovoltaic (PV) rooftop system at Thaksin University (Phatthalung Campus) in Thailand. A detailed analysis of the solar PV rooftop system is performed with particular attention to the performance of different PV technologies and the effects of different tilt angles and orientations of the PV panels on the annual energy production, the specific production, and the performance ratio. The economic analysis was performed for four scenarios: (1) self-investment and self-consumption scheme, (2) bankable and self-consumption scheme, (3) bankable and feed-in tariff (FiT) scheme, and (4) energy service company (ESCO) scheme. The results show that the amorphous silicon/micro-crystalline silicon (a-Si/μc-Si) technology shows the lowest annual energy production and performance ratio (PR), while the copper indium disulfide (CIS) technology records the largest annual energy production and PR. The largest annual energy production and specific production were obtained with the PV panels installed at a 10° tilt angle and with the PV modules facing South (S), while the lowest annual energy production and specific production were observed with the PV panels installed at a 45° tilt angle and the PV modules facing North (N). The economic analysis results show that the best scenarios are Scenario 3 (bankable and FiT scheme) and Scenario 1 (self-investment and self-consumption scheme). The findings of this research provide valuable information for regional stakeholders and policymakers regarding investments in solar PV rooftop systems.

Keywords: Photovoltaic; Energy Yield; PV Technology; Economic Analysis; Solar PV Rooftop.

1. Introduction

The world is facing key challenges related to environmental protection, energy conservation, and sustainable energy consumption and production. The growing population and industrialization have increased the electricity demand [1-2]. Non-renewable resources such as oil, coal, and natural gas are diminishing over time and are characterized by greenhouse gas emissions. Globally, researchers are investigating alternative energy sources to meet the energy demand in an eco-friendly way [3-4]. The best alternative to non-renewable energy sources is solar and wind energy. In 2021, the global total installed capacity of renewable energy reached 3,064 GW (IRENA) [5], out of which 843 GW was in solar photovoltaic (PV) installed capacity [6].

The International Energy Agency (IEA) has reported that solar PV systems could deliver 22% of the world's electricity by 2050. Worldwide, the potential of solar PV to be installed on a mega-scale has been enhanced by the progress in solar PV technology and rapid cost reductions. Solar PV has the potential to substantially decrease the amount of rising global CO2 emissions from fossil fuels. The carbon emission intensity is high in conventional fossil fuel-based technologies, while it is minimal in the operation of solar PV technology. Hence, solar PV technology can significantly contribute to meeting the worldwide energy demand through low-carbon power generation [7].

The average daily solar radiation is a significant factor in forecasting various applications, mainly the sizing of photovoltaic (PV) systems, building design, agrometeorology, and agriculture [8]. The performance of solar PV technology largely depends on the weather, the regional conditions and the solar cell technology [9-10]. For instance, Quansah et al. [9] studied the outdoor performance of five PV technologies, i.e., polycrystalline (p-Si), monocrystalline (m-Si), copper indium disulfide (CIS) thin-film, amorphous silicon (a-Si), and heterojunction incorporating thin (HIT) films. They evaluated that the p-Si technology is the most appropriate, while the CIS is the least appropriate in the considered site. Ali and Khan [11] conducted a techno-economic assessment of p-Si and CIS technologies. They analyzed that the CIS performs better regarding the performance ratio (PR), and they produce higher annual energy, while the p-Si shows a better-levelized cost of electricity (LCOE) and requires less area. Olarewaju et al. [12] examined fourteen PV modules to determine the best technology. They observed that the Panasonic solar PV showed the best capacity factor and performance ratio performances. Nour-eddine et al. [13] scrutinized the techno-economic performance of three PV technologies, including m-Si, p-Si, and a-Si. They found that the m-Si technology is the most suitable for performance parameters.

The energy produced by solar PV modules mainly depends on several parameters, namely the spatial layout, the tilt, and the azimuth angle [14]. Various studies focused on the optimal configuration of PV and optimal tilt angle for solar PV systems. For instance, Bakirci [15] found that the optimal tilt angle varies between 0° and 65° during the whole year in Turkey. Mamun et al. [16] investigated the effect of the tilt angle on the PV module performance on an experimental basis and confirmed that the optimum tilt angle is 15° in Malaysia. Al Garni et al. [17] analyzed the impact of the tilt and azimuth angle on a PV system in Saudi Arabia. They reported that adjusting the orientation five times per year can increase the energy yield by up to 3.63%.

Techno-economic assessments of solar PV rooftop systems have been performed in many parts of the world. For example, Christiaanse et al. [18] studied a grid-friendly solar PV rooftop system for commercial buildings in British Columbia, Canada. They applied a bi-level optimization framework and determined that the solar PV rooftop installation is profitable at a 50% cost reduction of current prices. Mangiante et al. [19] presented a novel solar PV rooftop approach in Brownsville, Texas, U.S.A. Based on the technical potential, they analyzed that residential buildings could generate up to 11% of the city's energy demand. Imam and Al-Turki [20] studied the feasibility of a 12.25 kWp solar PV system under a typical residential building in Saudi Arabia. They determined that the proposed model could fulfill 87% of the electricity demand of the residential building.

Thailand, situated close to the equator, has a high solar energy potential. Assessing the incident solar radiation over a specified region is significant to obtain the maximum potential of solar energy. The amount of available solar radiation over the earth's surface is important for numerous applications, such as the practical utilization of solar energy for electricity generation, domestic water heating, drying processes, estimation of crop productivity, environmental and agro-meteorological research as well as atmospheric physics research [21]. Thailand mainly invested in installing the utility-scale solar system in the past [22] (Tongsopit, 2015). However, the number of prosumers significantly increased in the industrial and residential sectors due to the cost reductions of solar PV systems. Thus, the role of solar PV rooftop systems in Thailand continues to increase renewable energy production in commercial and residential buildings [23](Yoomak et al., 2019).

This study presents a techno-economic assessment of a 1 MW solar PV rooftop system with an application at Thaksin University (Phatthalung Campus) in Thailand. This work aims to evaluate the performance of different PV technologies and the effects of the tilt angle and orientation on solar PV panels. Furthermore, the solar PV rooftop system is analyzed under four economic scenarios: (1) self-investment and self-consumption scheme, (2) bankable and self-consumption scheme, (3) bankable and feed-in tariff (FiT) scheme, and (4) energy service company (ESCO) scheme, to identify the best scheme with specific application to this public university situated in southern Thailand.

2. Materials and Methods

2.1 Study area

The solar PV rooftop system is installed at 7.81 °N latitudes and 99.94 °E longitudes in the Phatthalung Campus of Thaksin University in southern Thailand. The installed capacity of the project site is 1 MW. This project aims to assess this university's potential for clean energy technologies while encouraging the surrounding communities to consider becoming self-sufficient in energy. The satellite imagery for the location of the proposed 1 MW solar PV rooftop system at the Phatthalung campus of Thaksin University is shown in Figure 1.

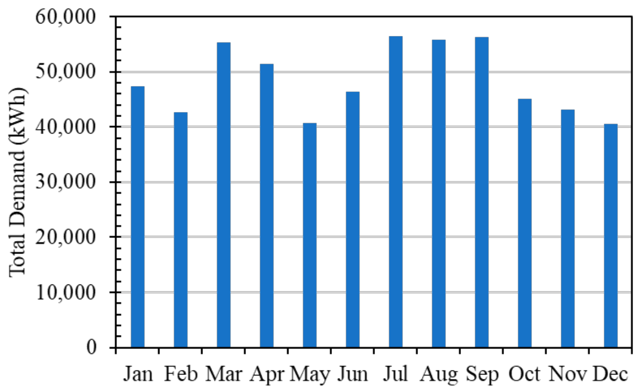
The monthly and daily electrical load demands of the Phatthalung Campus of Thaksin University are displayed in Figure 2 for 2019. It is noticeable from the figure that the campus monthly electrical load demand is highest in March and April, along with in July, August, and September. Also, the daily load profile shows the cyclic variation of the load demand in typical weeks, with high on-peak needs during the week and low off-peak demands during the weekends. Additionally, the highest electrical load demands are observed in the last weeks of March and in September.

2.2 Simulation of the solar PV Rooftop System

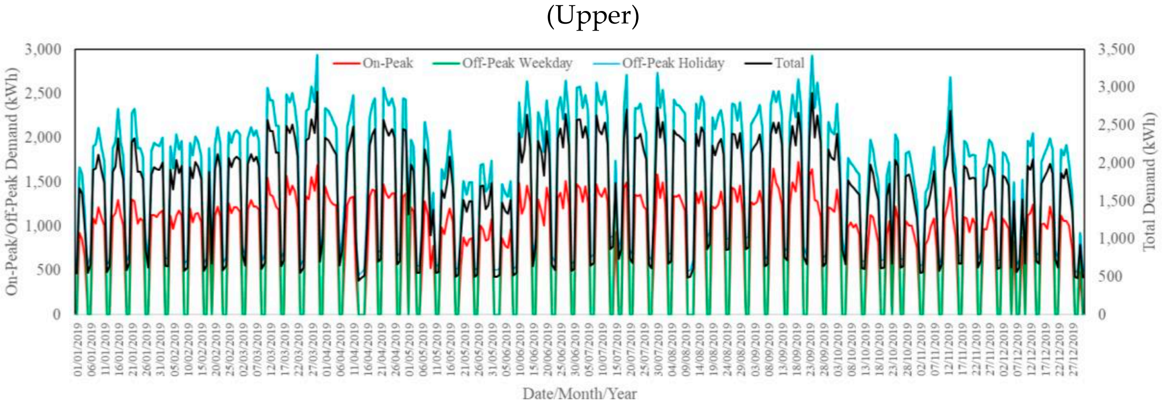
A 1 MW solar PV rooftop power generation system is assessed through the PVsyst simulation tool. This model has emerged as a convenient simulation tool for energy yield assessments and the optimal design of solar power plants [4]. The simulation uses an extensive knowledge of PV technology, meteorological, solar irradiance data, and solar PV system components [24]. PVsyst can import meteorological data from various databases, notably from the National Aeronautics and Space Administration (NASA) and Meteonorm 7.3. It intelligently evaluates the performance of grid-tied, stand-alone, pumping, and DC-grid systems. The model uses detailed hourly data, and it predicts the system output. Furthermore, PVsyst contains an inclusive solar PV system components database for PV modules and inverters [25].

The flow diagram of the PVsyst model is shown in Figure 3. The site location is specified in the first step, and the PV panels' tilt angle and the PV modules' orientation are defined. In the second step, the weather data (global horizontal irradiance (GHI) and air temperature) are accessed through the Meteonorm database and are imported into the PVsyst tool. In the third step, appropriate PV system components (PV modules and inverters) and the electrical load demand of the study area are analyzed. In the next step, the system sizing and optimization process is performed. Finally, after the execution of the simulation, various tables, graphs, and summary reports, such as the annual energy production (AEP), the performance ratio (PR), and the system losses, are generated.

Figure 1. Satellite imagery of the study area shows the location of the proposed 1 MW solar PV rooftop installation.



(Upper)



(lower)

Figure 2. Monthly (upper) and daily (lower) electrical load demand of ThaksinUniversity (Phatthalung Campus) in 2019.

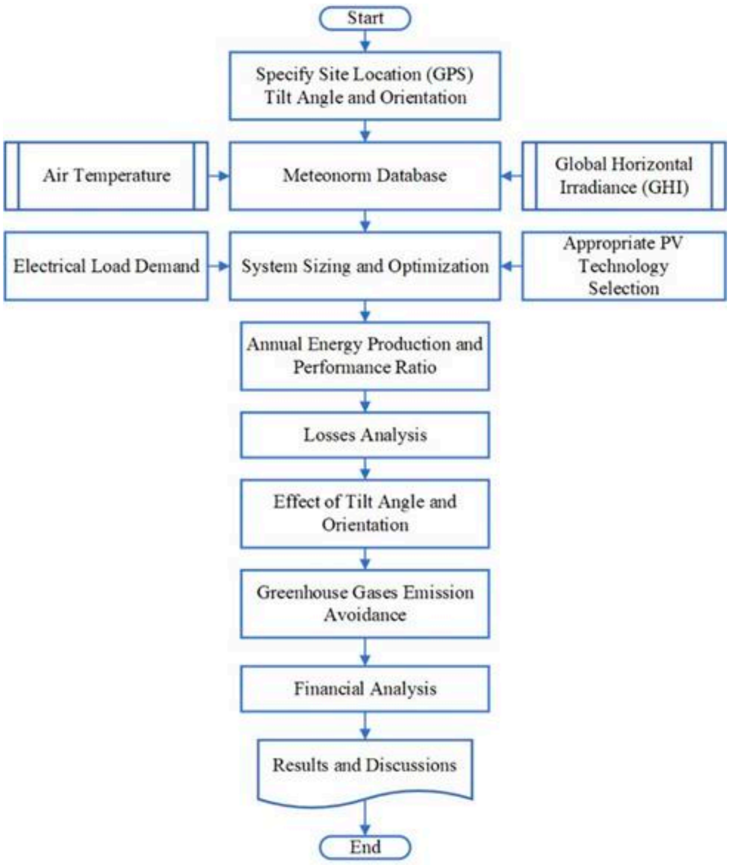


Figure 3. Flow diagram of the PVsyst model.

2.3 Climatic Data of the Study Area

Phatthalung, a province in southern Thailand on the Malay Peninsula, borders the large shallow Songkhla lake in the east. The region's climate is characterized by southwest and northeast monsoons, with hot summers [26-27]. Figure 4 displays the monthly average global horizontal irradiation (GHI) and average ambient temperature of the study area, taken from Meteonorm 7.3. The maximum average GHI is found to be 182.3 kWh/m^2 in March and 184.4 kWh/m^2 in April, while the lowest average GHI is observed in December, with a value of 110.8 kWh/m^2.

The average temperature varies between 26.29 °C and 28.21 °C over one year. The maximum average temperature is noticed from March to May, while the lowest average is observed in November. Furthermore, the solar GHI, global incident irradiation, and GHI clear sky data have been analyzed by the Solar and Wind Energy Research Laboratory (SWERL) at the Research Center in Energy and Environment, Thaksin University (Phatthalung Campus) and are shown in Figure 5. It is noticeable from the figure that the solar GHI, the global incident irradiation, and the GHI clear sky are characterized by two peaks, namely one peak in March-April and another peak in September. It can also be observed that these variables fluctuate greatly daily, which is due to the changing weather patterns throughout one month.

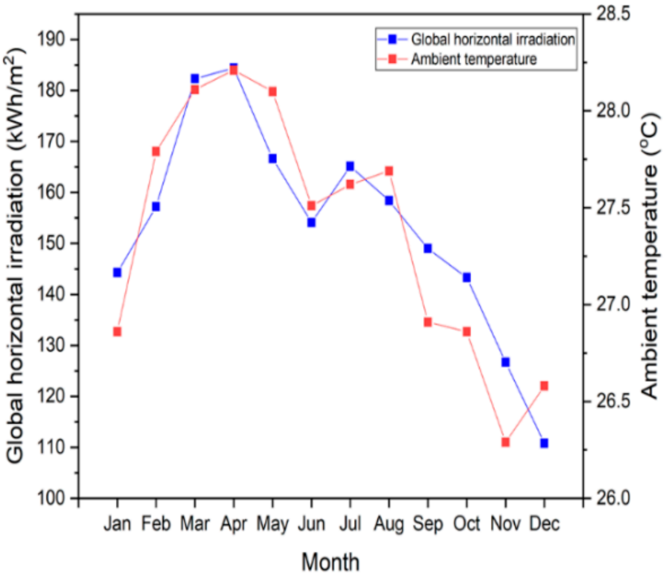


Figure 4. Monthly average global horizontal irradiation and average ambient temperature of the study area.

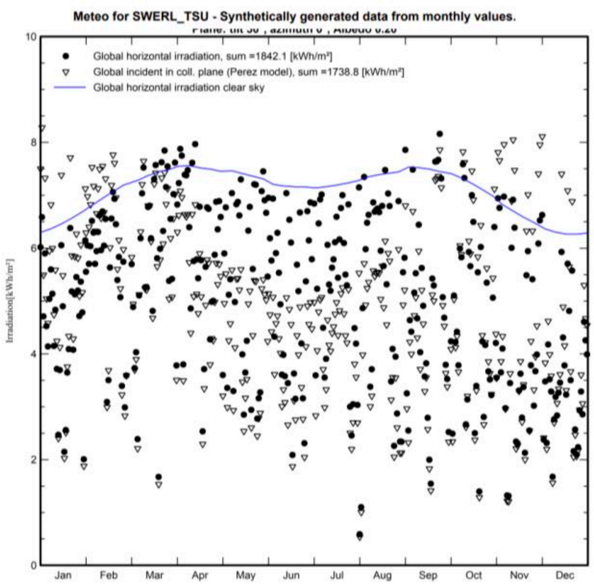


Figure 5. Variation of the solar global horizontal irradiation, global incident, and global horizontal irradiation clear sky throughout the year in the study area.

2.4 Description of the PV Technology

In this study, different PV technologies have been considered to compare and determine the optimal PV technology under the climate conditions of southern Thailand. The proposed 1 MW solar PV rooftop power generation system has the option of a variety of solar PV technologies, consisting of polycrystalline silicon (p-Si), monocrystalline silicon (m-Si), heterojunction incorporating thin (HIT) film, cadmium telluride (CdTe), amorphous silicon/micro-crystalline silicon (a-Si/μc-Si), and copper indium disulfide (CIS). The nominal power of PV modules is 400 Wp, except the cell-type CIS (thin-film) PV module, which has a 360 Wp nominal power. The PV modules would be connected with several strings in series. The technical specifications of each PV module are presented in Table 1.

Table 1. Technical specifications of the potential PV panel modules.

PV modules					
Cell-type	**Model**	**Nominal Power (Wp)**	**Total PV Modules**	**Nominal Power (STC) (Wp)**	**Modules (Strings x Series)**
p-Si	CS3W-440P SE	440	2,280	1,003	120 x 19
m-Si	LG 440 N2T-E6	440	2,280	1,003	121 x 19
HIT	REC440AA 72	440	2,272	1,000	142 x 16
CdTe	FS-6440-PA	440	2,272	1,000	568 x 4
a-Si/μc-Si	F440	440	2,280	1,003	570 x 4
CIS	CIGS-3600A1	360	2,784	1,002	232 x 12

Key: p-Si: polycrystalline silicon, m-Si: monocrystalline silicon, HIT: heterojunction incorporating thin-film, CdTe: cadmium telluride, a-Si:/μc-Si: amorphous silicon/micro-crystalline silicon, CIS: copper indium disulfide.

2.5 PV Inverter

The inverter model selected for this solar PV rooftop power generation system is the PVS800-57, manufactured by ABB. The nominal AC power of the ABB inverter is 1,000 kW, while the DC voltage ranges between 600 and 850 V. The nominal AC output voltage and the AC are 400 V and 1,445 A, respectively. The efficiency of the inverter is 98.8%. Further details of the technical specifications of the PV inverter are given in Table 2.

Table 2. Technical specifications of the PV inverter [28].

Manufacturer	ABB
Model	PVS800-57-1000 kW-C
DC Voltage Range	600-850 V
Max DC Voltage	1,100 V
Max DC Current	1,710 A
No. of DC Inputs	8-20 (+/-)
Efficiency	98.8%
Nominal AC Power (at 50oC)	1,000 kW
Max AC Output Power	1,200 kW
Nominal AC Current	1,445 A
Nominal AC Output Voltage	400 V
Output Frequency	50/60 Hz

2.6 Tilt Angle and Orientation of the PV modules

When exposed perpendicularly to the incoming solar irradiation, the PV modules will work most efficiently in the sunlight. However, the solar irradiance is not necessarily perpendicular to the PV panels. Therefore, the concept of tilt angle originated such that the PV modules could be positioned over the horizontal surface in an inclined manner [29]. A solar PV rooftop system's performance is determined by the PV panels' tilt angle and the azimuth angle of the PV modules [30]. This study analyzed the performance of a solar PV rooftop system at eight different tilt angles and eight different azimuth angles, as shown in Table 3 and Table 4, respectively.

Table 3. Various tilt angles for the solar rooftop PV modules.

Tilt angle	10°	15°	20°	25°	30°	35°	40°	45°

Table 4. Various azimuth angles along with the orientation for the solar rooftop PV modules.

Azimuth Angle	0°	-45°	-90°	-135°	180°	135°	90°	45°
Orientation	S	SE	E	NE	N	NW	W	SW

2.7 Cost-benefit Analysis

A cost-benefit analysis (CBA) is a technique for assessing the strengths and weaknesses of a project, such as those related to the installation or modification of energy projects [31-33]. The benefits of energy projects include positive impacts on the environment, job creation, reduced reliance on fossil fuels, and reduced oil dependence costs. Various studies have highlighted the benefits of energy projects from environmental and social perspectives [34-36]. This study determines the economic impacts from four main perspectives: (1) self-investment and self-consumption, (2) bankable and self-consumption, (3) bankable and feed-in tariffs (FiT), and (4) Energy Service Company (ESCO), with each of these schemes analyzed under the parameters and assumptions provided in Table 5. The four main financial indices are discussed below to determine a project's CBA.

2.7.1. Cost-benefit Analysis

The benefit-cost ratio (BCR) is a useful metric in decision-making to assess the benefits of a specific project. It is the ratio of the project's total benefits relative to its total costs over a specific period. The BCR identifies the rate of return to the investors in terms of net gain or loss. A project is considered economically viable if the BCR exceeds 1 [37]. The formula to calculate the BCR of a project is expressed as [38]:

$$CR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \quad (1)$$

Where B_t = the project benefit in year t; time t = 0 to T years; C_t= the project costs in year t; T = the total number of years of the project life span; and r = the discount rate for the investment.

2.7.2. Net Present Value

The net present value (NPV) determines whether a project is profitable. It is defined as the difference between the present value of the benefits and the costs related to the investment. A positive NPV indicates the financial viability of a project, whereas a negative NPV implies a financial loss. The NPV can be calculated mathematically as:

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (2)$$

2.7.3. Internal Rate of Return

A project's internal rate of return (IRR) is the interest rate that makes the NPV equal to zero. Usually, it evaluates the desirability of projects where a high IRR makes a project more desirable to undertake [39]. The IRR can be calculated as:

$$0 = \sum_{t=0}^{T} \frac{c_t}{(1+r)^t} \quad (3)$$

where c_t denotes the cash flow in the period t and r represents the internal rate of return.

2.7.4. Internal Rate of Return

The payback period (PBP) is defined as the time required to recover the initial investments in the project. Energy projects having shorter PBP are economically viable and sustainable. The payback period is calculated as:

$$PBP = \frac{Investment}{Net\ annual\ cash\ flow} \quad (4)$$

The financial metrics for a proposed 1 MW solar PV rooftop power generation system are determined using various inputs and assumptions, as mentioned in Table 5.

Table 5. Inputs and assumptions used to evaluate the 1 MW solar PV rooftop system.

No.	Parameter	Value	Unit
1	Project Lifetime	25	Year
2	On-Peak Tariff (TOU)	5.1135	THB/kWh
3	Off-Peak Tariff (TOU)	2.6037	THB/kWh
4	On-Peak/Off-Peak Ratio	15/75	%
5	FiT [45]	6.40	THB/kWh
6	Discount Tariff (ESCO)	20	%
7	Exchange Rate	34.47	THB/US$
8	Interest Rate (MRR)	5.97	%
9	Debt Ratio	70	%
10	Amortizing Repayment	7	Year
11	Discount Rate	7	%
12	Inflation Rate	5.73	%
13	Upfront Fee	1	%
14	Power Development Fund	0.01	THB/kWh
15	Salvage	3	%
16	Carbon Credit Trading (T-VER)	200	THB/tonnes CO2eq
17	Gas Emission Factor	0.5986	kWh/g CO2eq
18	Cleaning Cost (2 Time/Year)	4	US$/Panel
19	Basic Inspection for Maintenance	1,100	US$/Year
20	Egrid	1,536	MWh/Year

2.8. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is the selling price of electricity required by the system to break even at the end of its period [40]. It can be measured using the following expression:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{5}$$

where I_t, M_t, F_t and E_t refer to the investment costs in year t, the maintenance costs in year t, the fuel expenditures in year t and the electricity generation in year t, respectively. Here, r is the discount rate, and n shows the lifespan, in years, of the solar PV rooftop system.

3. Results and Discussion

This section presents the technical and economic assessment of the proposed solar PV rooftop system using the PVsyst tool.

3.1. Technical assessment

In this subsection, the performance of six PV technologies, along with their total losses, are analyzed. The effect of the PV panels' tilt angle and the solar PV modules' orientation are studied to determine the optimal tilt angle of the PV modules and the azimuth angle.

3.1.1. Annual energy production and performance ratio

The annual energy production and the performance ratio of six PV technologies are plotted in Figure 6. It is noticeable from the figure that the a-Si/μc-Si technology shows the lowest annual energy production of about 1,370 MWh, with a PR of 78.6%. The m-Si and CdTe induce almost the same annual energy production and PR with a slight dominance of CdTe. The annual energy production and the PR for the p-Si, m-Si, and CdTe technologies are approximately 1,458 MWh and 83.65%, 1,466 MWh and 84.12%, and 1,468 MWh and 84.51%, respectively. The CIS technology has observed the highest annual energy production of 1,537 MWh, with a PR of 88.24%, followed by HIT, with a yearly energy production of 1,501 MWh and a PR of 86.41%.

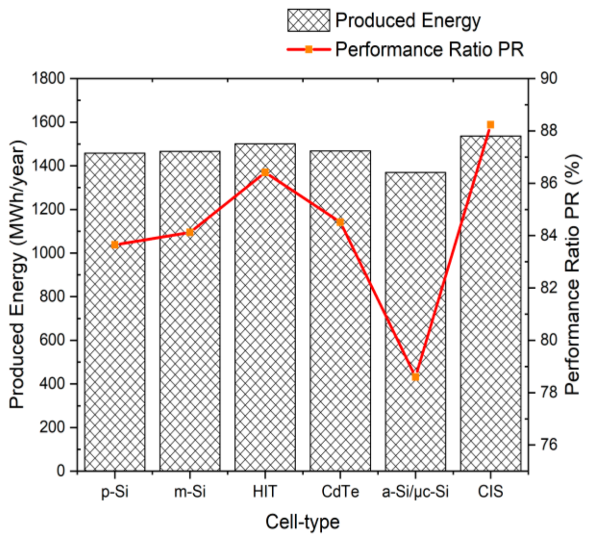


Figure 6. *Annual energy production and performance ratio of different PV technologies.*

The CIS and HIT technologies yield more annual energy output than the other PV technologies in this study. The a-Si/μc-Si technology produces the lowest annual energy output. This might be a consequence of its low conversion efficiency [41]. Similarly, the CIS technology has the highest PR, whereas the a-Si/μc-Si technology has the lowest PR. A PR above 80% is always considered desirable as it accounts for an economic gain [42]. The PR of all PV technologies is above 80%, except for the a-Si/μc-Si technology, which has a 78.6% PR value.

Figure 7 illustrates the monthly energy production of different PV technologies. The results show that all PV technologies attain the highest monthly energy production from January to April. The CIS and HIT achieved the maximum monthly energy production in March, with 156.1 MWh and 152.5 MWh values, respectively. The lowest monthly energy production for all PV technologies was observed in June and December. The a-Si/μc-Si technology has recorded the lowest monthly energy production of 95.1 MWh in June and 98 MWh in December. This implies that these months receive low solar radiation.

Based on the monthly energy production, a comparison has been performed among the six PV technologies. Over the entire period, the CIS and HIT technologies show the best performance compared to other technologies. The monthly energy production during the entire period is almost identical for the CdTe, m-Si, and P-Si. Nevertheless, the a-Si/μc-Si technology has been observed as the least interesting in monthly energy production.

3.1.2. Analysis of the losses in the PV technologies

The difference between the reference yield (Y_r) and the field yield (Y_f) of a PV system is termed as the system's total losses (L_T), which can be expressed as [43]:

$$L_T = Y_r - Y_f \tag{6}$$

The total losses for the six PV technologies considered in this study are presented in Figure 8. It is evident from the figure that the highest total losses, with a value of 4.2 kWh/kWp/day, are observed in the CIS technology, followed by the HIT, with a value of 4.11 kWh/kWp/day. The total losses recorded by the CdTe, m-Si, and p-Si are 4.02 kWh/kWp/day, 4 kWh/kWp/day, and 3.98 kWh/kWp/day, respectively. The a-Si/μc-Si technology has noticed the lowest total losses of 3.74 kWh/kWp/day.

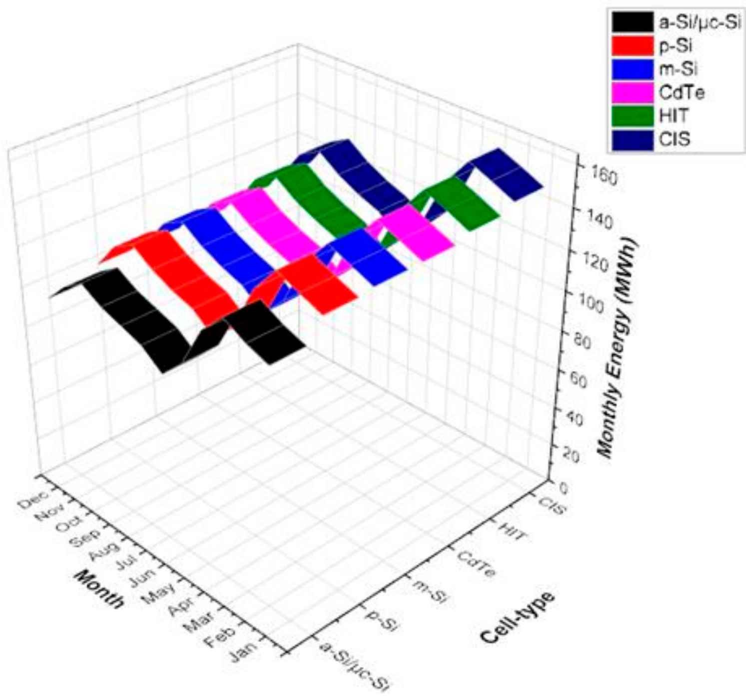


Figure 7. Monthly energy production of different PV technologies.

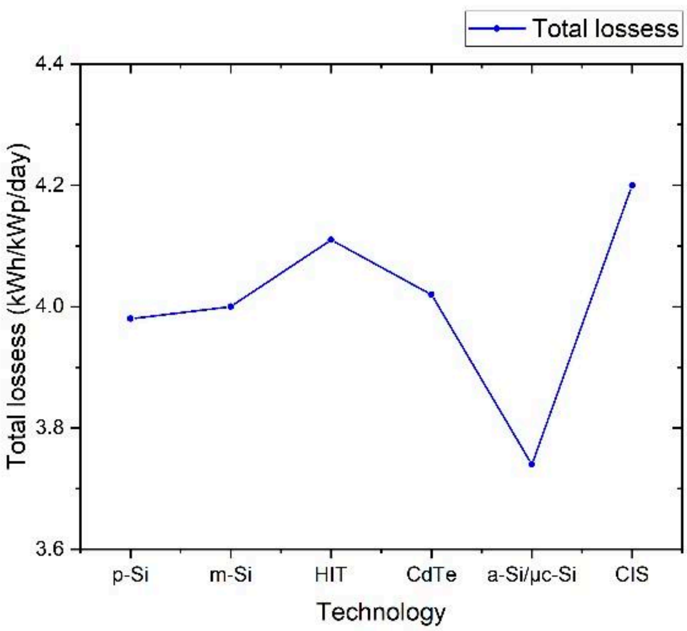


Figure 8. Total losses for six PV technologies.

3.1.3. Effect of the tilt angle of the PV panels and the orientation of PV panels

Figure 9 shows the variation of the annual energy production, specific production, and the performance ratio concerning the tilt angle, which ranges from 10° to 45°. The annual and specific energy production declines by increasing the tilt angle. The largest annual energy production and the largest specific production have been observed at a tilt angle of 10°, with values of 1,545 MWh/year and 1,541 kWh/kWp/year, respectively. In contrast, the lowest annual energy production and the lowest specific production have been observed at a 45° tilt angle, with values of 1,304 MWh/year and 1,300 kWh/kWp/year. On the other hand, the PR increases by varying the tilt angle from 10° to 40° and slightly declines at a tilt angle of 45°.

Figure 10 shows the effect of the orientation of the solar PV panels on the annual energy production, specific production, and PR. It is clear from the figure that the installed solar PV rooftop system produces the largest annual energy production and the largest specific production, with PV modules facing south (S), southeast (SE), and southwest (SW). This is because Thailand is situated in the Northern Hemisphere. Additionally, the largest annual energy production and the largest specific production reached values of 1,456 MWh/year and 1,451 kWh/kWp/year with PV modules facing S, while the lowest annual energy production of 1,358 MWh/year and the lowest specific production of 1,353 kWh/kWp/year were noticed with PV modules facing north (N). However, the PR reaches its maximum value when the PV modules are facing the northeast (NE) and the north (N) orientations, while it shows the lowest value with the PV module facing the west (W) orientation.

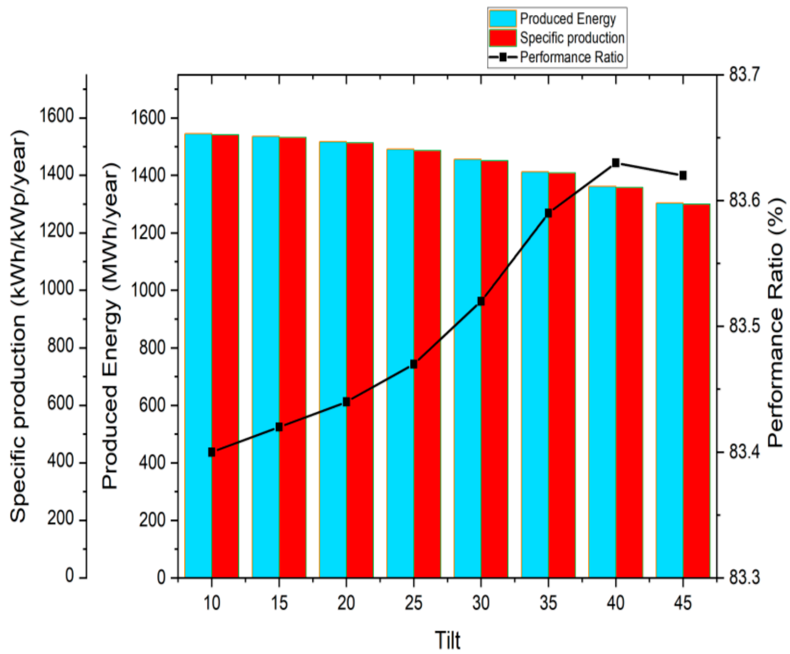


Figure 9. Effect of the tilt angle of the PV panels on the annual energy production, the specific production, and the performance ratio.

3.1.4. Optimal tilt and azimuth angles

The optimization of the tilt angle of the PV panels and the azimuth angle of the PV modules can increase the performance of the solar PV rooftop system. The optimal tilt angle of the panels versus the azimuth angle of the modules for the maximum energy injected into the grid and the maximum global incident radiation on the collector plane is shown in Figure 11 and Figure 12, respectively. It is seen from both figures that the solar PV rooftop system operates the most efficiently with a tilt angle of 10° and an azimuth angle of 0°, where it injects the maximum energy of 1,546.3 MWh into the grid with a maximum global incident radiation of 1,848.2 kWh/m^2 in the collector plane.

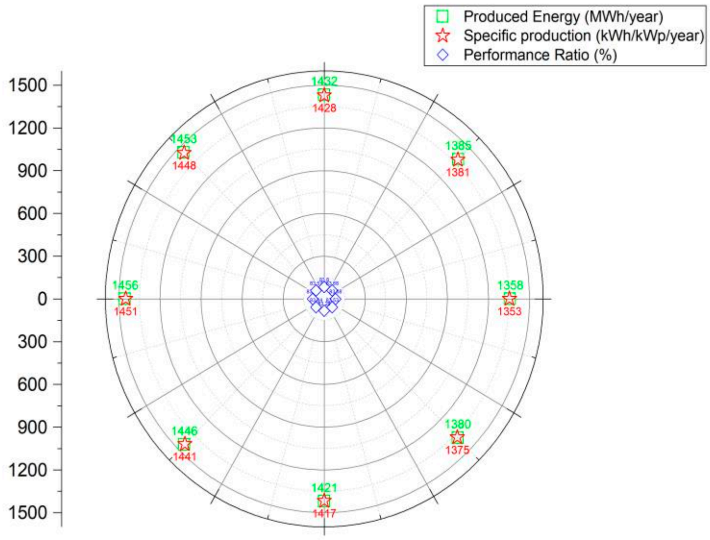


Figure 10. Effect of the orientation of the PV modules on the annual energy production, the specific production, and the performance ratio.

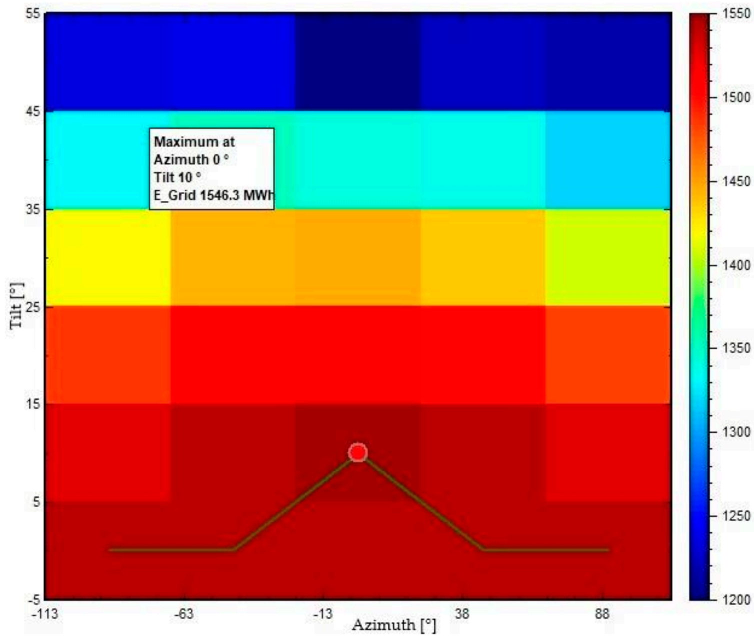


Figure 11. The optimal tilt angle of the panels and the azimuth angle of the modules for the maximum energy injected into the grid.

The appropriate design of a 1 MW Solar PV rooftop at Thaksin University (Phatthalung Campus) consists of 6 units of 80 kWac inverters, which are connected to 95 strings of PV panels, including 18 PV panels per string on one side and 4 units of 60 kWac inverters connected to 10 strings of PV panels with 14 PV panels per string on another side with the single line diagram as shown in Figure 13.

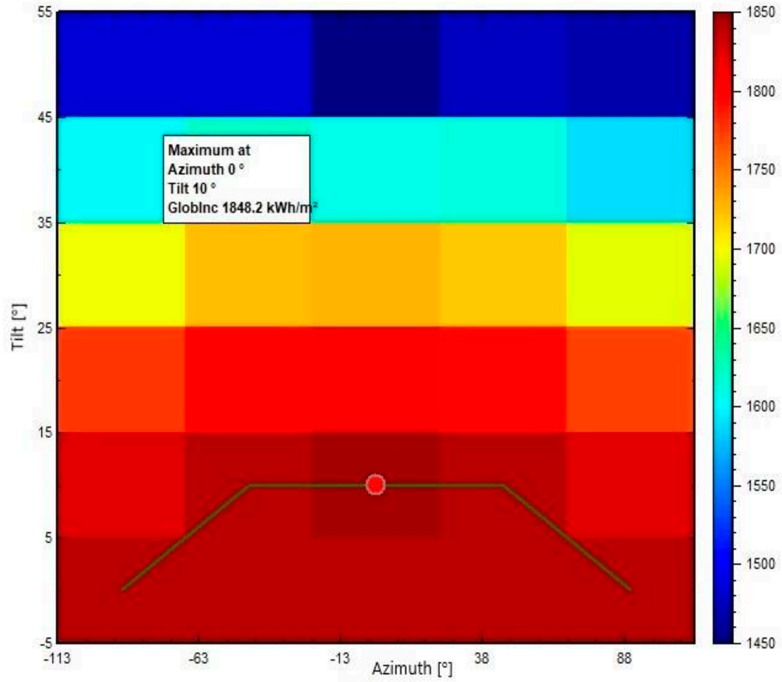


Figure 12. The optimal tilt angle of the panel and azimuth angle of modules for the maximum global incident radiation on the collector plane.

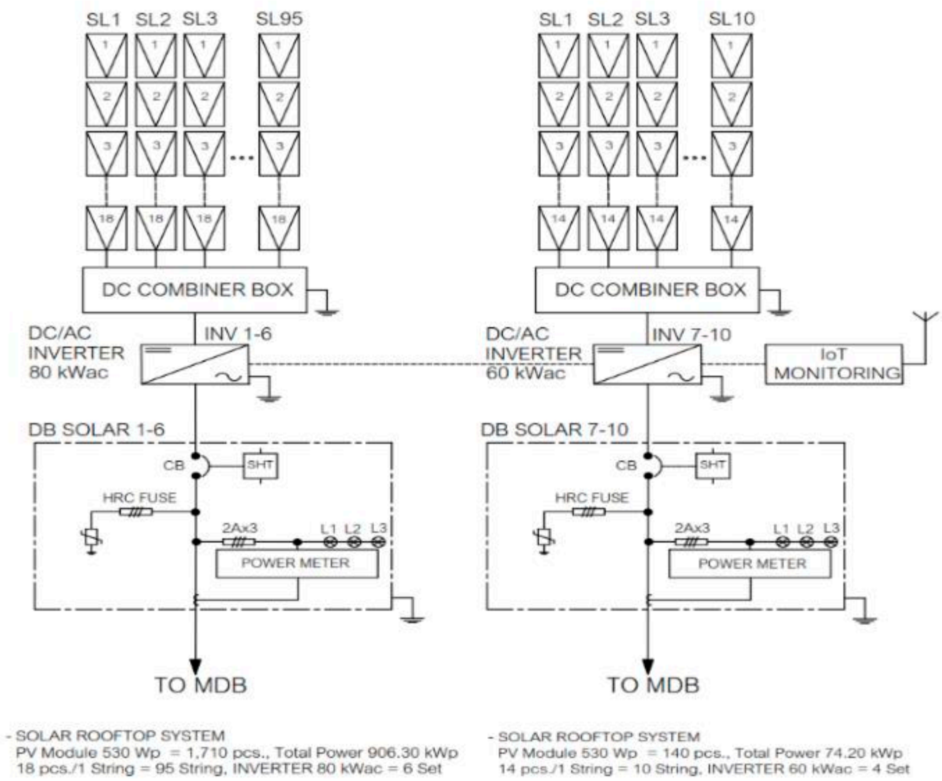


Figure 13. Single line diagram of a 1 MW solar PV rooftop at Thaksin University (Phatthalung Campus).

3.2. Economic analysis

The current study evaluates four possible economic scenarios for a 1 MW solar PV rooftop system installed at Thaksin University (Phatthalung Campus). Scenario 1 is related to a self-investment and self-consumption scheme, where the university (the project owner) would invest in the project and produce its solar power for consumption. Both are based on bankable projects. Scenario 2 is a self-consumption scheme, while Scenario 3 is a feed-in tariff (FiT) scheme. For these two scenarios, commercial banks would invest in the project. Furthermore, the solar power produced would be utilized by the university in the case of Scenario 2, while in the case of Scenario 3, the produced energy by the solar PV rooftop system would be fed into the national grid. Scenario 4 is associated with an energy service company (ESCO) scheme, where private companies would be invited to participate in the project through a competitive bidding process. The company with the highest offer would be asked to invest in the project.

The economic indicators of every scenario are shown in Table 6. Scenario 3 (bankable and FiT scheme) offers a BCR of 3.34; an NPV of 71,963,009 THB; an IRR of 30%, and a PBP of 5 years, which makes it the best-case scenario. The PBP in this scenario is within the acceptable range of 5-7 years [43] for profitable solar PV rooftop projects [44]. Scenario 1 (self-investment and self-consumption scheme) is the second favorable case, with a BCR of 1.68; an NPV of 20,817,144 THB; an IRR of 10%; and a PBP of 9 years. On the other hand, Scenario 4 (ESCO scheme) and Scenario 2 (bankable and self-consumption scheme) are the least preferable cases, with PBP of 13 and 15 years, respectively. The LCOE calculated for all scenarios is 0.80 THB/kWh.

For comparison, the economic analysis indicates that the bankable and FiT scheme (Scenario 3) is the best model for the stakeholders, with the highest NPV and the shorter PBP. The self-investment and self-consumption scheme (Scenario 1) is the second-best model for the university itself. This model presents the project owner with an opportunity to invest, with an NPV of above 20,000,000 THB and a PBP of 9 years. On the other hand, the ESCO (Scenario 4) and the bankable and self-consumption schemes (Scenario 2) are the least interesting models due to the long PBP of 13 to 15 years.

Table 6. Economic indicators for the 1 MW solar PV rooftop system.

Sr.	Sr. Details	BCR	NPV (THB)	IRR (%)	PBP (Year)	LCOE (THB/kWh)
1	Self-investment and self-consumption	1.68	20,817,144	10	9	0.80
2	Bankable and self-consumption	1.14	4,332,252	1	15	0.80
3	Bankable and FiT	3.34	71,963,009	30	5	0.80
4	ESCO	1.34	10,512,475	5	13	0.80

Key: Sr.: scenario, BCR: benefit-cost ratio, NPV: net present value,
IRR: internal rate of return, PBP: payback period, LCOE: levelized cost of electricity, FiT: Feed-in-Tariff.

4. Conclusions

This study addresses the performance of six solar PV technologies: p-Si, m-Si, HIT, CdTe, a-Si/μc-Si, and CIS. The effect of the tilt angle of the solar PV panels and the orientation of the solar PV modules are also assessed and discussed. Further, four economic scenarios for a 1 MW solar PV rooftop system are evaluated at the Phatthalung campus of Thaksin University (Thailand).

The CIS technology recorded the highest annual energy production of 1,537 MWh and a performance ratio of 88.24%, while the a-Si/μc-Si technology showed the lowest annual energy production of 1,370 MWh and a PR of 78.6%. The CIS and HIT technologies achieved the maximum monthly energy production in March, with 156.1 MWh and 152.5 MWh values, respectively. The CIS technology detected the largest total losses, with a value of 4.2 kWh/kWp/day, while the a-Si/μc-Si noticed the lowest total losses of 3.74 kWh/kWp/day. The largest annual energy production and the largest specific production, with values of 1,545 MWh/year and 1,541 kWh/kWp/year, were respectively obtained for the PV panels positioned at a 10° tilt angle, while the lowest annual energy production and the lowest specific production, with values of 1,304 MWh/year and 1,300 kWh/kWp/year, were respectively obtained for the PV panels positioned at a 45° tilt angle. Furthermore, the largest annual energy production and specific production, with values of 1,456 MWh/year and 1,451 kWh/kWp/year, were respectively obtained with the PV modules facing South (S), while the lowest annual energy production of 1,358 MWh/year and the specific production of 1,353 kWh/kWp/year were noticed when the PV modules were facing North (N). The economic analysis shows that the bankable and FiT scheme (Scenario 3) is the best model for the stakeholders, offering the highest NPV and the shortest PBP.

Similarly, the self-investment and self-consumption scheme (Scenario 1) is the second-best model, which offers the university an NPV of above 20,000,000 THB and a PBP of 9 years.

The solar PV rooftop methodology defined in this work can be applied to other regional buildings. Future research may include the techno-economic evaluation of solar PV rooftop systems and a DC battery storage system for the university and other provincial buildings. Other technical aspects, e.g., evaluation of the thermal performance of rooftop PV and shading loss affecting overall performance, would also be recommended for further study.

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