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Research Article

Techno-Economic Assessment of a 100 kWp Solar Rooftop PV System for Five Hospitals in Central Southern Thailand

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Abstract. This paper presents a techno-economic assessment of a 100 kWp solar rooftop photovoltaic (PV) system at five hospitals in central southern Thailand. The system encompasses 100 kWp PV panels, 100 kW grid-tied inverters and balance of system (BOS) under the grid code of the Provincial Electricity Authority (PEA). The latest PV technology of bifacial mono-crystalline solar panels, inverters and BOS were simulated along with the Meteonorm 7.3 database using the PVsyst simulation toolkit with different tilt angles, orientations, solar radiations and ambient temperature. The technical aspects of solar rooftop PV power generation systems include the annual energy output and the performance ratio (PR) under IEC standard. Further, an economic analysis of the model was examined using a cost benefit analysis (CBA) and various assumptions. Four main financial criteria, i.e., benefit cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and payback period (PBP) were evaluated under three different scenarios: (1) self-consumption scheme, (2) feed-in tariff (FiT) scheme, and (3) private power purchase agreement (PPA) scheme. Finally, the levelized cost of energy (LCOE) was also calculated. The results reveal that the Takua Thung hospital is characterized by the maximum average global horizontal irradiation (GHI) and the maximum annual produced energy of 199 kWh/m^2 and 164.8 MWh/year, respectively. The PR calculated for all hospital sites is above 85%. The outcomes of the financial analysis show that the optimum scenarios are PPA and FiT schemes. The LCOE analysed in this study indicates that the Takua Thung hospital site has the lowest LCOE at 2.47 THB/kWh (0.07 USD/kWh). This research confirms the potential for hospitals and stakeholders in central southern Thailand for investments in solar rooftop PV systems.

Keywords: Solar Rooftop PV, Bifacial Photovoltaic, Performance Ratio, Levelized Cost of Energy, Economic Analysis.

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1. Introduction

The average daily solar radiation is a significant factor in the forecasting of various applications, mainly sizing of photovoltaic (PV) systems, building design, agrometeorology and agriculture (Chelbi *et al.,* 2015; Sabziparvar and Shetaee, 2007; Waewsak *et al.,* 2014). Solar energy is widely acknowledged as a solution to mitigate environmental pollution and the climate changes caused by greenhouse gas emissions (GHG) from the energy industry (Han *et al.,* 2022; Shukla *et al.,* 2016). On average, the earth receives approximately 1,400 J/m^{2}s of radiation from the sun; this radiation possesses considerable potential for electricity generation. Harvesting solar energy using PV systems is an efficient approach to generate clean electricity, with limited operating costs and relatively minor environmental impacts (Hassan *et al.,* 2021). A solar PV system employs solar modules to generate direct current (DC) electricity, which is then converted to single or three-phase alternating current (AC) using inverters (Ali and Khan, 2020; Formica *et al.,* 2017; Hansen and Vad Mathiesen, 2018). The costs of solar PV have fallen 82% worldwide since 2010 (IRENA, 2020). The global solar PV generation at the end of 2020 reached 821 TWh, and is expected to rise further to 6,970 TWh by 2030 (IEA, 2021).

Solar rooftop PV has been recognized to be a successful approach in terms of social, economic and environmental perspectives. It can contribute to boost local energy security and reduce air pollution (Buonocore *et al.,* 2016; Gómez-Navarro *et al.,* 2021; Spillias *et al.,* 2020). Solar rooftop PV is a very fruitful and sustainable alternative for the building sector, which is a major energy end-user and having large shares of total power consumption. The deployment of solar PV rooftop systems to commercial building can alleviate the burden on the traditional power grid and hence the power consumption (Haffaf *et al.,* 2021).

Various studies on techno-economic assessments of solar PV systems have been conducted in different parts of the world. For instance, Lang *et al.* (2016) evaluated the techno-economic assessment of solar rooftop PV for residential and commercial buildings under self-consumption. Tomar and Tiwari (2017)

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investigated the techno-economic evaluation of grid-tied PV systems for domestic usage, with feed-in-tariff (FiT) and time of day tariff regulations. Imam and Al-Turki (2019) studied the technical and economic feasibility of a PV system with a capacity of 12.25 kWp for a typical residential building. They established that 87% of the electricity could be covered by the building demand. Shabbir *et al.* (2022) examined the techno-economic analysis and the potential of energy in domestic and commercial PV installations in different areas of Estonia. They found that PV systems are self-sufficient when retailing the extra energy on a nominal payback period to the grids. Hassan *et al.* (2021) used a MATLAB based PVAnalytX software toolkit for the techno-economic assessment of rooftop PV systems. They analyzed that end users can take benefits of rooftop solar PV in terms of power generation and electricity demand variability. Chang *et al.* (2022) investigated the combined potential of rooftop solar PV and electric vehicles (EVs) to economically decarbonaize urban energy systems. They found that up to 86% of CO_2 emissions and 51% of the energy costs can be reduced in cities in Korea. Mokhtara *et al.* (2021) combined spatial analyses with techno-economic optimization for a grid-connected rooftop solar PV system. They identified that 60% of the available roof area would be appropriate for solar PV panels and multi-crystalline PV panels with the highest annual energy production (AEP) of 2333 MWh/year. Finally, Gul *et al.* (2022) developed the System Advisor Model (SAM) to maximize the electricity and load demand. They analyzed the solar power generation, the energy demand, the financial indicators, the levelized cost of energy (LCOE), along with performing an environmental analysis of the project.

Thailand is a tropical nation, georgaphically positioned to the north of the equator. The country has an abundant potential of solar energy, particularly the northeastern and southern parts, and some areas in the central region (DEDE). According to the Global Solar Atlas (Solargis, 2019), the solar PV annual power potential in Thailand varies between 1,314 kWh/kWp in certain areas of the southern and eastern regions, up to 1,534 kWh/kWp in the northeastern and central regions of the country (Figure 1).

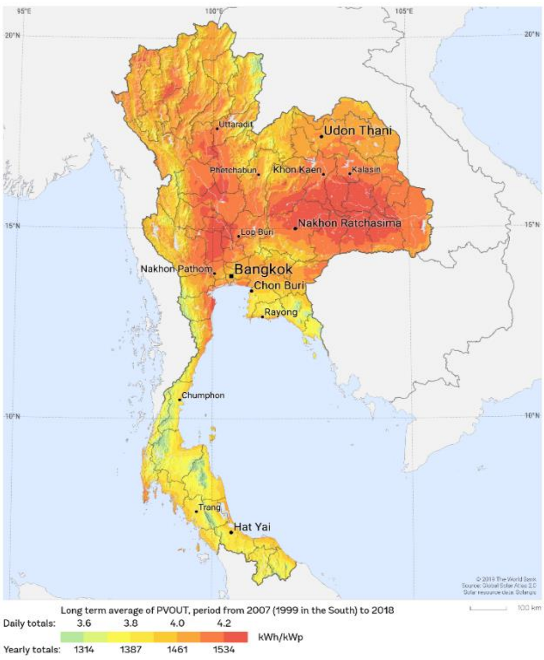

Fig. 1 Solar PV power potential map of Thailand (Solargis, 2019).

As of 2000, the generation capacity of large-scale hydropower in Thailand reached nearly 3000 MW, which raised concerns regarding environmental impacts. Simultaneously, the production of bioenergy increased by a factor of five. Similarly, Thailand exploited wind energy in 1983 by installing numerous small scale wind turbines ranging from 1 kW to 150 kW in Phuket Island in southern Thailand. The geothermal potential is at very modest level, particularly in northern Thailand. The first geothermal power plant was established in Fang district in 1989, with a capacity of almost 300 kW. In 1996, the Electricity Generating Authority of Thailand (EGAT) installed the first solar PV power plant with a capacity of 504 kW. However, favorable policy and regulatory schemes were introduced in 2007. (IRENA, 2017).

Formerly, Thailand primarily invested in utility-scale solar system installations (Tongsopit, 2015). However, because of the declining costs of solar PV systems, the number of prosumers significantly increased in both the industrial and residential sectors. Subsequently, solar rooftop PV played a vital role to increase the production of renewable energy in the residential and commercial sectors of Thailand (Yoomak *et al.,* 2019). In the past, numerous articles and case studies focused on solar rooftop PV systems in Thailand (Chaianong and Pharino, 2015; Chaianong *et al.,* 2019; Eskew *et al.,* 2018; Tantisattayakul and Kanchanapiya, 2017; Tongsopit *et al.,* 2015; Tongsopit *et al.,* 2019; Tongsopit *et al.,* 2016).

Tongsopit *et al.* (2019) analyzed the economics of PV systems under self-consumption, net metering, and net-billing in Thailand and they recommended that the net-billing schemes are the most appropriate for PV systems. Prapanukool and Chaitusaney (2020) proposed solar power purchase agreements and behind-the-meter schemes to determine the discount rates for solar PV rooftop systems. Chaianong et al. (2019) conducted a cost-benefit analysis of solar rooftop PV on three electric utilities and ratepayers under nine PV adoption scenarios and determined that the net economic impacts on both utilities and retail rates. Nevertheless, studies on techno-economic assessments of solar rooftop PV systems in tropical climate regimes for commercial buildings under self-consumption, FiT and private power purchase agreement (PPA) schemes are scarce in the scientific literature.

Hence, in our study, we present a techno-economic assessment of 100 kWp solar rooftop PV systems at five hospital sites in central southern Thailand, where the region has lower solar resource than the other regions of the country. This research aims to present a techno-economic assessment of solar rooftop PV systems under three different scenarios: (1) self-consumption scheme, (2) FiT scheme, and (3) PPA scheme. The proposed model, which is based on a techno-economic assessment, will assist the stakeholders to invest in solar rooftop PV systems at hospital buildings, which may also be replicated in other jurisdictions.

2. Materials and Methods

2.1. Study area

The study area is concentrated to five hospitals, namely Pak Phanang, Pak Phayun, Patong, Plai Phraya, and Takua Thung, situated in central southern Thailand (Figure 2). The latitude and longitude for the five hospital sites are latitude: 8.36° N and longitude: 100.20° E for Pak Phanang; latitude: 7.35° N and longitude: 100.32° E for Pak Phayun; latitude: 7.90° N and longitude: 98.30° E for Patong; latitude: 8.53° N and longitude: 98.87° E for Plai Phraya; and latitude: 8.28° and longitude:

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98.30° for Takua Thung. The climate of central southern Thailand is tropical, including southwest and northeast monsoons, with hot summers (Kamdar *et al.,* 2021; Waewsak *et al.,* 2020).

Thailand has high feasibility for solar energy due to its geographical position near the equator. In order to obtain the maximum potential of solar energy, it is significant to assess the incident solar radiation over a specified region. The amount of available solar radiation over earth's surface keeps great importance for numerous applications, such as 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 (Waewsak *et al.,* 2014; Yoomak *et al.,* 2019).

The Ministry of Energy of Thailand aims to introduce renewable energy, up to 37% of the electricity portfolio, under the Power Development Plan (PDP) 2018 – 2037. This renewable energy will be introduced into the national power grid, notably through the installation, by the end of 2037, of 15,574 MW of solar PV systems, which would include 10,000 MW of solar rooftop PV systems (APRICUM, 2021). Thus, the Government of Thailand supports the private firms and the residents to install solar rooftop PV systems to increase the solar energy installed capacity of the country.

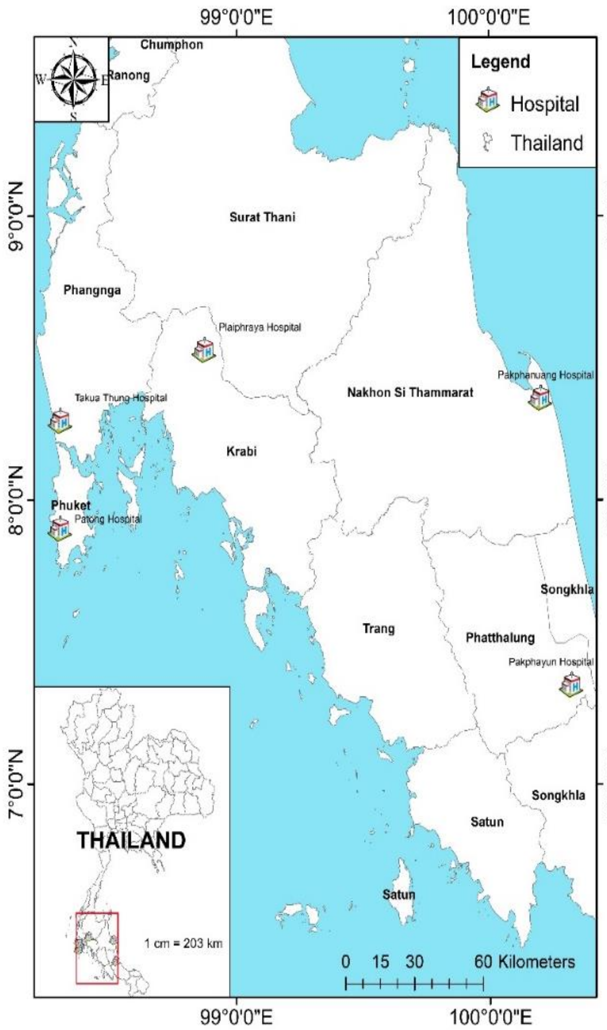

Fig. 2 Geographical distribution of the five hospital sites studied in central southern Thailand.

2.2. Simulation model

This study builds on the PVsyst simulation toolkit to analyze the technical and economic potential for 100 kWp solar rooftop PV systems at five hospital sites in central southern Thailand. PVsyst has emerged as a robust and convenient tool for the design and the simulation of grid-tied, stand-alone, pumping and DC-grid PV systems (Husain *et al.,* 2021; Poudyal *et al.,* 2021). It effectively utilizes the extensive information of PV technology, solar irradiance data and PV panels system (Boddapati *et al.,* 2021). The detailed data of commonly used PV modules and inverters are available in the PVsyst library, which are basically required for PV projects. It identifies the financial viability of the designed projects. In addition, it calculates losses in the system due to mismatch effects between connected PV modules, partial shadowing phenomenon, wiring and inverter losses and the effect of ambient temperature variations on its electrical output power calculations. This feature makes PVsyst a precise tool to estimate the amount of electrical energy generated by a designed system (Gharakhani Siraki and Pillay, 2010; Husain *et al.,* 2021). PVsyst is compatible with various meteorological databases, such as Meteonorm, NASA-SSE, and Solar Prospector. This study has used the Meteonorm 7.3 database, which is widely used as meteorological input for the simulations in solar applications (Remund, Müller *et al.,* 2010).

2.3. Configuration of the solar PV rooftop

Figure 3 displays the single line diagram layout connection of the PV modules with the solar inverters. The PV modules are made of bifacial mono-crystalline type. The rating capacity of the PV modules used for the design is 445 Wp. The configuration of the PV modules is assembled into two PV units. The first PV unit corresponds to 8 parallel strings, with 17 PV modules in each string and connected in series to a 60 kW solar inverter. Similarly, the second PV unit refers to 6 parallel strings, with 15 PV modules in each string and connected in series to a 40 kW solar inverter. The combiner box connects the PV modules to the inverters in both PV units. In the end, both inverters are connected to the Main Distribution Board (MDB) via power cables.

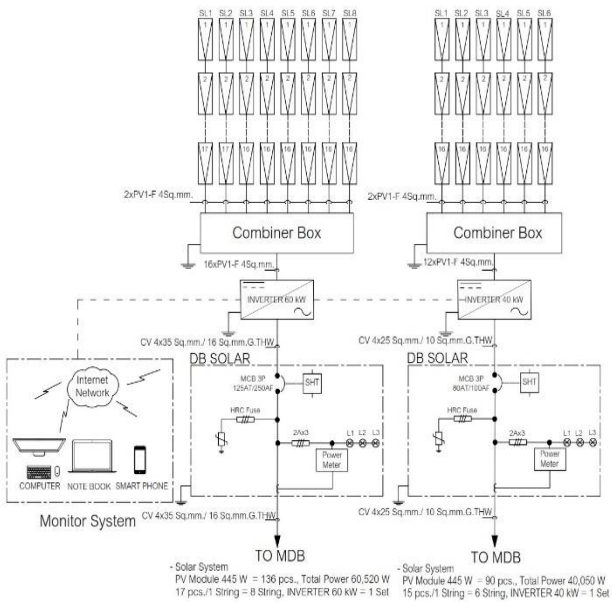

Fig. 3 Single line diagram of a 100 kWp solar rooftop PV power generation system.

2.4. Losses of the solar PV rooftop

The annual global horizontal irradiation (GHI) on the collector plane for Pak Phanang, Pak Phayun, Patong, Plai Phraya and Takua Thung are 1,853 kWh/m^2/year, 1,851 kWh/m^2/year, 1,846 kWh/m^2/year, 1,844 kWh/m^2/year, and 1,949 kWh/m^2/year, respectively. Because of global incident and array incidence losses (IAM) in the collector plane, the actual annual solar irradiation on the collector is 1,761 kWh/m^2/year, 1,790 kWh/m^2/year, 1,808 kWh/m^2/year, 1,784 kWh/m^2/year, and 1,855 kWh/m^2/year for Pak Phanang, Pak Phayun, Patong, Plai Phraya and Takua Thung, respectively. After the PV conversion, at an STC efficiency of 20.47%, the array nominal energy for Pak Phanang, Pak Phayun, Patong, Plai Phraya and Takua Thung are 175.6 MWh, 180.1 MWh, 183.5 MWh, 179.5 MWh and 187.4 MWh, respectively. Similarly, the array virtual energy found at maximum power point (MPP) for Pak Phanang, Pak Phayun, Patong, Plai Phraya and Takua Thung are 157 MWh, 160.9 MWh, 163.7 MWh, 160.7 MWh and 167.5 MWh, respectively. During this stage, various losses are encountered, such as PV losses due to irradiance level and temperature, module quality loss, mismatch loss, modules and strings, ohmic wiring loss and mix orientation mismatch loss, as indicated on Figure 4. The available energy output injected into the grid after the inverter losses for Pak Phanang, Pak Phayun, Patong, Plai Phraya and Takua Thung are 154.6 MWh, 158.4 MWh, 161 MWh, 158.2 MWh and 164.8 MWh, respectively.

2.5. Performance indices of the solar PV system

The performance of a solar PV system depends on the solar irradiation, the energy output and the temperature under working conditions. It specifies the monthly or yearly effects of the PV system losses on the nominal array capacity. PV system losses usually occur due to incomplete solar irradiation, system component failures and PV module temperature (Boddapati *et al.,* 2021; Emmanuel *et al.,* 2017). Two important parameters, i.e., the AEP and the performance ratio (PR), are used to estimate the quality of the PV system installation. The PR is a dimensionless quantity and expressed as:

$$PR(\%) = \frac{Actual\ energy\ (kWh)}{A \times r \times H} \times 100 \qquad (1)$$

where A indicates the total solar panel area (m^2), r specifies the solar panel efficiency or yield (%) and H represents the solar irradiance on titled panels (kWh/m^2).

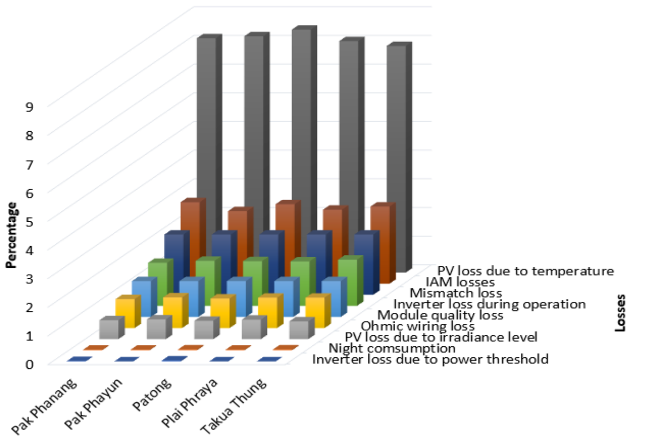

Fig. 4 Losses of the solar rooftop PV systems for five hospital sites in central southern Thailand.

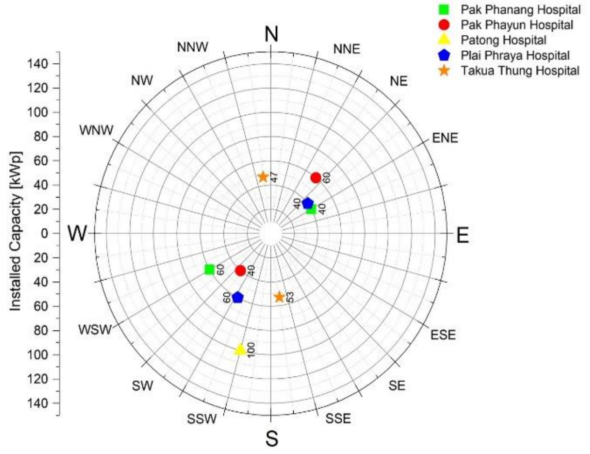

Fig. 5 Rose diagram of the installed capacity of the PV system for the five hospital sites.

2.6. Solar rooftop PV system

The 100 kWp solar PV modules are fixed with a tilt angle of 15° for the five hospital sites. The PV modules are distributed as follows: Pak Phanang (40 kWp), Plai Phraya (40 kWp) and Pak Phayun (60 kWp) are facing northeast; while the other modules of Pak Phanang (60 kWp), Plai Phraya (60 kWp) and Pak Phayun (40 kWp) are facing southwest. Similarly, the installed capacity of 100 kWp in Patong is facing southwest, while it is northwest with 47 kWp and southeast with 53 kWp in Takua Thung. The rose diagram of the installed capacity for the five hospital sites are shown in Figure 5.

2.7. Cost-benefit analysis

A cost–benefit analysis (CBA) is a systematic approach to determine the strengths and weaknesses of a given project, such as those associated to energy projects (Chaianong *et al.,* 2019; Leurent *et al.,* 2018; Pikas *et al.,* 2017). Benefits of energy projects comprise positive environmental impacts, employment creation, reduction of fossil fuels, and reduction of oil imports to save foreign currency. The environmental and social benefits associated with energy projects have been reported by various studies (Dincer, 1999; Kopp *et al.,* 1997; Ramadhan and Naseeb, 2011), with a main focus on evaluating the economic impacts from the perspectives of self-consumption of electricity, FiT and PPA. Various methods are used to determine the CBA of a project, which are discussed below.

2.7.1. Benefit cost ratio

The benefit cost ratio (BCR) is the ratio of the total project benefits versus the total project costs over a period of time. It gives an estimate of the rate of return to the investors regarding the project and may sometimes indicate the risk. A BCR above 1 indicates that the project would be allowed to proceed (Schultz *et al.,* 2010). The mathematical expression for BCR is given as (Eltamaly and Mohamed, 2018):

$$BCR = \frac{\sum_{t=0}^{T} \frac{B_t}{(1+r)^t}}{\sum_{t=0}^{T} \frac{C_t}{(1+r)^t}} \qquad (2)$$

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.

2.7.2. Net present value

The net present value (NPV) of a project is the difference between the present value of all cash inflows and outflows over a period of time. Projects are considered to be viable when NPV > 0. Similarly, projects with higher NPV are measured to be more profitable. On the other hand, negative NPV value is expected to result in a net loss for a project (Yoomak *et al.,* 2019). The formula to calculate NPV is expressed as (Thanarak and Lhazom, 2021):

$$NPV = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \quad (3)$$

2.7.3. Internal rate of return

The internal rate of return (IRR) is another term for the discount rate "r". It can be defined as the value of the discount rate that makes the NPV of a project equal to zero. The higher the IRR, the more net cash a company achieves from a project (Eltamaly and Mohamed, 2018). The IRR can be computed as:

$$0 = \sum_{t=0}^{T} \frac{c_t}{(1+r)^t} \quad (4)$$

where c_t = cash flow in period t and r = internal rate of return.

2.7.4. Payback period

The payback period (PBP) is the time period required to determine the profitability of a project (to recover an investment). It is usually expressed in years (Reniers *et al.,* 2016). A short recovery period from the start-up of the project is an indication of a viable and profitable project. The PBP is given as:

$$PBP = \frac{Investment}{Net\ annual\ cash\ flow} \quad (5)$$

In this study, the financial metrics for the 100 kWp solar rooftop PV system are determined using a number of assumptions and inputs, as given in Table 1.

Table 1
Inputs and assumptions used for the evaluation of the 100 kWp solar rooftop PV system (Sykes, 2021).

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

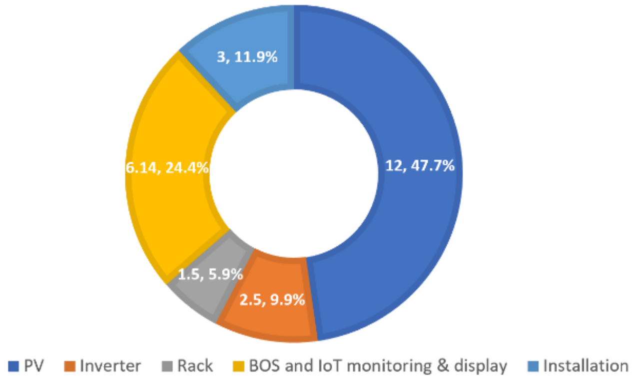

Fig. 6 Breakdown of the costs of a 100 kWp solar rooftop PV system for installation at five hospital sites in central southern Thailand in terms of THB/W and percentage of total costs.

2.8. Levelized cost of energy

The LCOE is a measure of the lifetime costs to the total electric power generation for a system over a specified time period (Alhammami and An, 2021). In terms of solar PV projects, it is measured as the entire costs of the PV system, the costs of the PV installation, maintenance expenditures, and the replacement costs of components that are experienced in the lifespan (~25 years) of a PV system (Ali and Khan, 2020; Quansah *et al.,* 2017). The LCOE in mathematical form is expressed as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (6)$$

where I_t, M_t, F_t and E_t are the investment costs in year t, the maintenance costs in year t, the fuel expenditures in year t and the electric power production in year t, respectively. Here, r denotes the discount rate and n shows the lifespan, in years, of the PV system.

The total costs of a 100 kWp project is 2,514,000 THB (~ 72,722 USD), which includes the PV system, the rack, the balance of system (BOS) and the internet of things (IoT) monitoring display, inverter and installation costs. Hence, the total installed costs per capacity is 25.14 THB per watt (~ 0.73 USD per watt). The breakdown costs in terms of THB/W and percentage of total costs are shown in Figure 6.

3. Results and Discussion

3.1. Analysis of the solar irradiation and the ambient temperature

The monthly GHI and the ambient temperature for the five hospital sites are shown in Figure 7 and Figure 8, respectively. It is clear from the figure that the maximum average GHI is observed in March at Takua Thung, with a value of 199 kWh/m^2, while the second is Patong, with a GHI of 187.6 kWh/m^2. The minimum irradiance level is noticed for Pak Phayun, with a GHI of 109.8 kWh/m^2, followed by Pak Phanang, with a GHI of 113.6 kWh/m^2. The ambient temperature measured in this study, mapped with the plotted lines, indicate that, in December, Patong has recorded the maximum average temperature of 29.13 °C in March, whereas the lowest average temperature is 24.9 °C in January at Plai Phraya.

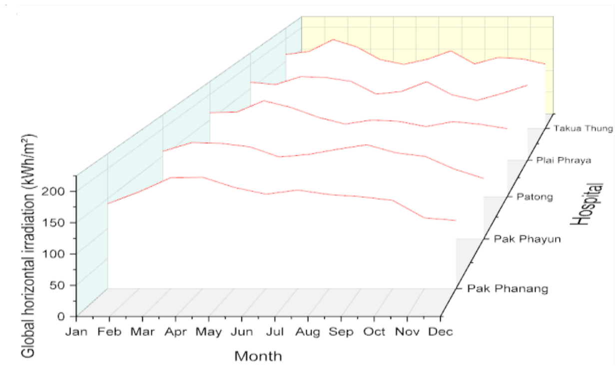

Fig. 7 Variation of the monthly GHI at the five hospital sites studied in central southern Thailand.

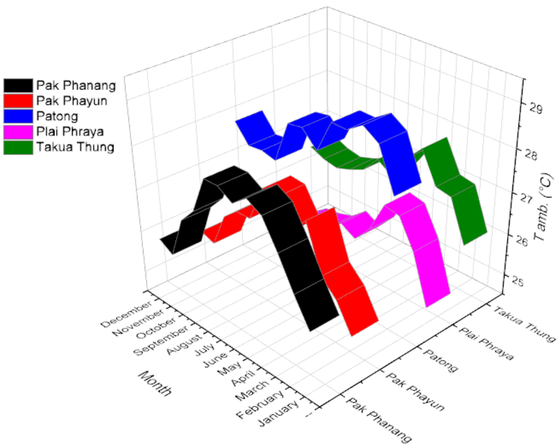

Fig. 8 Variation of the monthly air temperature at the five hospital sites studied in central southern Thailand.

In addition to the tearly cycle, the figure shows that the average GHI and the ambient temperature in the study area reach their maximum values in the months of March and April, both months characterized by the dry season and clear sky conditions.

3.2. Annual energy output and performance rati

The AEP and the PR show the performance of each PV systems. Figure 9 displays the AEP and the PR for the five hospitals sites studied in central southern Thailand. It is noticeable that the Takua Thung site has recorded the maximum AEP of 164.8 MWh/year, while the Pak Phanang site observed the minimum AEP of 154.6 MWh/year. In addition, the PR calculated for the five hospital sites are above 85%. A PR above 80% is always considered desirable as it usually accounts for an economic gain (Shukla *et al.,* 2016). The overall technical performances of 100 kWp solar rooftop PV systems at the five hospital sites are given in Table 2.

3.3. Economic analysis

This study presents the economic indicators for three different scenarios of the solar rooftop PV systems at the five hospital sites in central southern Thailand. Scenario 1 and Scenario 2 focus on self-consumption and FiT schemes, which will offer the hospitals to invest in 100 kWp solar rooftop PV systems. Scenario 3 concentrates on the private PPA scheme. In the case of Scenario 3, the hospitals would invite private companies for competitive bidding. The company with the highest offer in competitive bidding procurement would normally be invited to invest in the project.

The outcomes of the financial analysis of all scenarios in terms of BCR, NPV, and PBP are shown in Figure 10. The various financial indicators from the figure confirm that Scenario 3, which is based on private PPA investments, is the best opportunity for solar rooftop PV installations at the five hospital sites studied in central southern Thailand. Similarly, Scenario 2 is the second most interesting opportunity for hospitals itself to invest in 100 kWp solar rooftop PV systems. It is clear from Figure 10 that Scenario 2 and Scenario 3 present promising opportunities in terms of investments, whereas Scenario 1 is the least interesting opportunity.

Table 3 compiles the various economic indicators for the three scenarios. Scenario 3 (PPA scheme) is the most suitable case, with values in the range of 1.51 to 1.85 BCR; 70,829 USD to 117,609 USD NPV; and 13% to 21.4% IRR. Similarly, Scenario 2 (FiT scheme) shows 1.51 to 168 BCR; 70,829 USD to 94,002 USD NPV; and 13% to 17.1% IRR; and makes it the second preferable case. The PBP for Scenario 2 and Scenario 3 fall in the range of 5 to 7 years, which is within the acceptable range found in the scientific literature (Anang *et al.,* 2021) and indicates a profitable PBP for installing solar rooftop PV systems (Sewchurran and Davidson, 2021). On the other hand, Scenario 1 (self-consumption scheme) is the least interesting case, with PBP in the range of 13 to 26 years. For instance, Pak Phanang, in terms of Scenario 1, shows a PBP of 26 years, with a BCR of 1, an IRR of -0.04% and a NPV of 194 USD. Finally, the LCOE computed fall in the range of 2.47 THB/kWh (0.07 USD/kWh) to 2.63 THB/kWh (0.08 USD/kWh) for all scenarios, which is slightly above the global weighted average of 0.068 USD/kWh due to the reduction in the breakdown costs (IRENA, 2019). The LCOE calculations in this study reveal that the Takua Thung site has a minimum LCOE of 2.47 THB/kWh (0.07 USD/kWh), while the Pak Phanang site has a maximum LCOE of 2.63 THB/kWh (0.08 USD/kWh).

Table 2
Overall technical performances of 100 kWp solar rooftop PV systems at the five hospital sites.

Hospital Site	Produced Energy under STC (MWh/year)	Produced Energy at Maximum Power Point (MPP) (MWh/year)	Produced Energy at Inverter Output (MWh/year)	Specific Production (kWh/kWp/Year)	Losses (%)	PR (%)
Takua Thung	187.4	167.5	164.8	1,631	12.06	85.58
Patong	183.5	163.7	161.0	1,587	12.26	85.37
Plai Phraya	179.5	160.7	158.2	1,573	11.86	85.91
Pak Phanang	175.6	157.0	154.6	1,551	11.95	85.59
Pak Phayun	180.1	160.9	158.4	1,575	12.04	85.75

Note: STC: standard test condition, MPP: maximum power point.

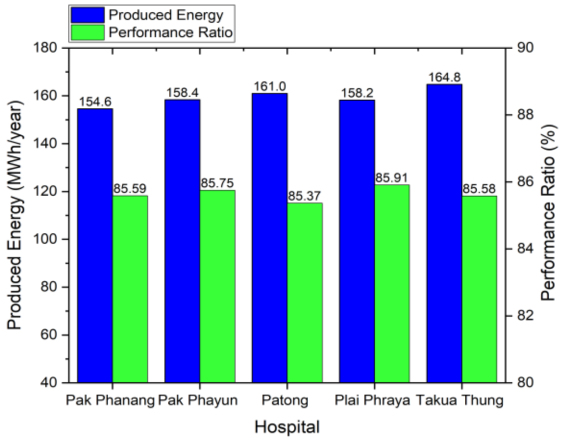

Fig. 9 The AEP and PR of solar rooftop PV systems for the five hospital sites in central southern Thailand.

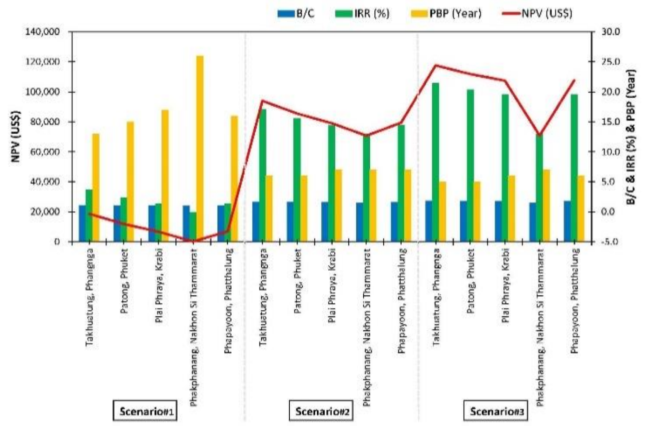

Fig. 10 Evaluation of the various financial scenarios for investment opportunities in solar rooftop PV systems at the five hospital sites studied.

Table 3
Economic indicators for self-consumption, FiT and PPA schemes.

Site	Scenario 1				Scenario 2				Scenario 3				LCOE	
	BCR	NPV (USD)	IRR (%)	PBP (Year)	BCR	NPV (USD)	IRR (%)	PBP (Year)	BCR	NPV (USD)	IRR (%)	PBP (Year)	LCOE (THB/ kWh)	LCOE (USD/ kWh)
Takua Thung	1.14	18,709	3.7	13	1.68	94,002	17.1	6	1.85	117,609	21.4	5	2.47	0.07
Patong	1.09	11,922	2.4	15	1.62	85,507	15.6	6	1.81	111,839	20.3	5	2.53	0.07
Plai Phraya	1.05	6,762	1.3	17	1.57	79,049	14.4	7	1.78	107,454	19.5	6	2.57	0.07
Pak Phanang	1.00	194	-0.04	26	1.51	70,829	13.0	7	1.51	70,829	13.0	7	2.63	0.08
Pak Phayun	1.05	7,000	1.39	16	1.57	79,347	14.5	7	1.78	107,656	19.6	7	2.57	0.07

In comparison, the statistical outcomes of the Takua Thung, Patong, Pak Phayun and Plai Phraya sites, in terms of a PPA scheme, present the ideal model for stakeholders with NPV of above 100,000 USD and PBP of 5 to 6 years. Interestingly, the Pak Phanang site depicts the identical economic indicators in terms of FiT and PPA schemes, while it shows negative IRR in terms of self-consumption scheme, resulting a net loss. Similarly, the Takua Thung, Patong, Plai Phraya and Pak Phayun sites offer the second-best opportunity in terms of the FiT scheme, with NPV ranging between 79,000 and 94,000 USD and PBP of 6 to 7 years. However, this configuration is less attractive in the self-consumption scheme, where the BCR equal 1 or slightly above 1, minimum NPV, minimum IRR and prolong PBP. In comparison to the FiT and PPA schemes, the self-consumption scheme is the least interesting opportunity for investments. In a nutshell, the PPA and FiT schemes show promising economic indicators for all stakeholders.

4. Conclusions

Solar energy is an inexhaustible source of energy on earth. If harnessed in a proper way, solar energy could simply surpass the present and future energy demands. Jurisdictions throughout the world are looking at models to increase solar power in their energy portfolios, notably under energy security perspectives. Through various initiavies, public and private, Thailand is considering various models for the continued growth in the integration of solar power in the energy mix of the country. A recent program has identified hospitals as potential sites to install solar rooftop PV systems.

In this context, this study addresses a detailed techno-economic assessment of solar rooftop PV systems for five hospital sites in central southern Thailand. The main overview of our results includes:

- The maximum average GHI of 199 kW/m^2 was analysed at the Takua Thung site, followed by the Patong site with a value of 109.8 kWh/m^2. The average GHI and ambient temperature were noticed at the highest peak in March and April.
- The Takua Thung site produced 164.8 MWh/year of maximum annual energy output, whereas the Pak Phanang site observed a minimum annual energy output of 154.6 MWh/year. The overall PR experienced for all hospital sites were above 85%.
- The financial model identifies Scenario 3 (PPA scheme) as the best opportunity for solar rooftop PV installations for the five hospital sites studied in central southern Thailand, with Scenario 2 (FiT scheme) a close second, and Scenario 1 (Self-consumption scheme) a distant third.
- Comparatively, the Takua Thung, Patong, Pak Phayun and Plai Phraya sites, under a PPA scheme, present the best model for stakeholders, with NPV above 100,000 USD and PBP of 5 to 6 years.
- The LCOE calculated ranges from 2.47 THB/kWh (0.07 USD/kWh) to 2.63 THB/kWh (0.08 USD/kWh) for the considered study area, which is slightly above the global weighted average of 0.068 USD/kWh.

The work presented in this paper concentrated on the scientific, economic and technical assessments of installing solar rooftop PV systems on hospital sites in Thailand. The work shows that the hospitals studied can effectively by targets for the installation of such systems. While not being the object of this work, potential challenges and barriers to benefit from this program include lack of coordination between the institutions, planning issues, internal technical limitations, difficulty to integrate in the utility grid, etc. Cooperations with the private sector could be considered on a case by case basis.

The outcomes of this project not only depict that the rooftop of hospital buildings can be used for the installation of solar panels, it also presents promising benefits in terms of cost and energy saving for the hospitals. This model supports the deployment of a 100 kWp installed solar rooftop PV systems for the targeted hospitals through a new program of the Energy Regulatory Commission (ERC) of Thailand.

The techno-economic assessment model presented by this work would be applicable to other hospital buildings in Thailand and ASEAN member states. This model provides an opportunity of investments to hospitals and stakeholders. Future work may include a techno-economic analysis of PV-battery systems in commercial applications.

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