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Enhanced Solar Photovoltaic Power Production Approach for Electric Vehicle Charging Station: Economic and Environmental Aspects

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ABSTRACT

In recent years, Electric Vehicles (EVs) are contributing a major share in Thailand and benefit the environment. Most of the EV charging stations are sourced from solar energy as it becomes a carbon-free source of energy production. Secondly, Thailand is rich in solar irradiance, and higher irradiance leads to higher power production. On the other hand, in tropical conditions, solar Photovoltaic (PV) module temperature increases following the solar irradiance due to high ambient temperature, resulting negative impact on the efficiency and lifespan of photovoltaic (PV) modules. Further, to increase PV power production, in this study, different rates of cooling strategies are proposed. The study found that reducing the temperature by 5% to 25% resulted in increased average power outputs of 5947.94W, 6021.43W, 6094.92W, 6168.41W, and 6241W, respectively. Notably, 25% of the cooling rate achieved higher production. However, it is lower than the nominal power production. Following that, economic analysis and environmental impacts are analyzed for Thailand's EV charging station using a different cooling rate of PV module. Overall, it is concluded that, depending on the economic viability of the EV charging station, cooling technology can be applied, and it will benefit the EV charging station both economically and environmentally. To further enhance the solar PV power production approach for EV charging stations in Thailand, it is imperative to prioritize future endeavors towards optimizing cooling technology, integrating energy storage, and implementing supportive policies.

INTRODUCTION

Electric vehicles (EVs) offer a promising alternative to fossil fuels in the transportation sector due to their increased energy efficiency and reduced local pollutants. However, the challenge remains to meet the energy demands of charging EV batteries using clean and renewable energy sources. Solar photovoltaic (PV) modules convert light photons into electricity and are a widely accepted future renewable energy technology (Velmurugan et al. 2020a, Bayrak et al. 2020, Homlakorn et al. 2023). However, PV module efficiency decreases as the cell temperature exceeds the optimal operating temperature. However, this can be addressed by adopting external cooling techniques (Prasannaa et al. 2021, Rajseakar et al. 2019, Velmurugan et al. 2021).

Active cooling techniques involve the use of pumps or fans to keep a flow of air or water over the front or rear of the PV panel, leading to higher PV performance rates than passive techniques (Teo et al 2012, Velmurugan et al 2022a, Velmurugan et al 2021). However, this method incurs higher expenditures associated with system upkeep and power usage. Various studies have investigated the effectiveness of cooling techniques, including spraying water on the PV module's rear surface, using rectangular heat exchangers affixed to the rear, and forced air cooling (Velmurugan et al. 2022b). Colt et al. (2016) discovered that spraying water on the back surface of a PV module resulted in a 32% decrease in module temperature and a 57% increase in electrical efficiency. In a study conducted by Baloch et al. (2015), the performance of a PV module equipped with a rectangular heat exchanger (RHX) attached to the PV module's back surface was compared to that of a module without cooling. The maximum efficiency for cooling with an RHX was found to be 13.07%, compared to 7.82% for modules without cooling. Sajjad et al. (2019) explored the use of forced air cooling to improve PV module performance and compared their findings to those of uncooled modules. The results showed that adopting air cooling technology led to higher electrical efficiency and power ratios, with respective improvements of 7.2% and 6%.

In comparison, passive cooling techniques rely on the three fundamental heat transfer mechanisms of convection, conduction, and radiation. They can be improved by combining phase change materials (PCMs) and PV panels into a single module (Velmurugan et al. 2020b, Velmurugan et al. 2020c, Velmurugan et al. 2018). PCM-enclosed PV systems have been found to reduce PV module temperature and increase PV module efficiency. Hasan et al. (2015) utilized phase change material (RT25) with internal fins to regulate the temperature rise of a PV system. They investigated the thermal performance of different internal fin arrangements and discovered that incorporating PCM into the PV system resulted in a cell temperature below 29^{o}C during the ambient temperature of 23^{o}C. Nada et al. (2018) examined the effectiveness of pure PCM and PCM combined with Al_2O_3 nanoparticles and compared them with a conventional PV module. Three identical PV modules were used in the experiment, with two of them connected to the chosen PCMs and one serving as a reference. Their findings revealed that the PV temperature was reduced by 10.6°C and 8.1°C, respectively, and the PV module efficiency increased by 13.2% and 5.7%, respectively.

The above literature studies have shown that the most effective method of reducing the temperature of PV modules was through active cooling, resulting in a temperature reduction of 20 to 38% (Velmurugan et al. 2022a, Alktranee & Péter 2023, Agyekum et al. 2021). Meanwhile, the passive cooling method, which can reduce the temperature of the PV module most significantly, achieved a range of 15 to 30% (Nižetić et al 2021, Ali 2020, Hudișteanu et al 2021). In this study, general cooling systems are proposed with a cooling rate of 5-25 % with an incremental of 5 % rather than determining the particular cooling strategies.

- Depending on the EV charging station's economical strength, any existing cooling methods can be adopted.
- This study highlights the importance of using a variable rate of cooling strategies to improve the PV system power production.
- Further, the economic and environmental analysis are performed and compared with the nominal PV systems operation mode.

MATERIALS AND METHODS

In this study, different cooling rates are performed for the 15.5 kWp solar PV system and EV charging station. The last three years of meteorological data are downloaded from the NASA Powerlac open source to understand the nature of Thailand's solar potential. Further, different rates of PV module cooling power production and economic analysis are conducted, and the outcomes are compared by analyzing the environmental aspects to determine the necessity of PV module cooling under tropical climatic conditions in the northern part of Thailand. Fig. 1 shows the schematic view of the present study.

Electrical Power Output

The electrical power output of the 15.5 kWP solar PV system is calculated using the meteorological data of 2022. PV module electrical power outputs are the product of the maximum voltage and current obtained from the PV module using Eq (1) (Velmurugan et al. 2020a).

$$P = IV_o = \left[I_{ph} - I_s \left(e^{\frac{q(V+IR_s)}{NKT}} - 1 \right) - \frac{V + IR_s}{R_{sh}} \right] V_o \ldots(1)$$

Where,

$$I_s = I_{or} \left(\frac{T}{T_r} \right)^3 \left[\left(\frac{1}{T_r} - \frac{1}{T} \right) e^{\left(\frac{qE_g}{N} \right)} \right]$$

In the above-given equation, I_{ph} represents the photo-generated current, and I_s represents the saturation current. The elementary electron charge is denoted by q. The Boltzmann constant is represented by K(1.38×10^{-23} J/K), T represents the absolute temperature, T_r represents the reference temperature, and R_s arises from the resistance of the metallic contacts and the ohmic resistance of the material. R_{sh} is derived from the current leakage across the p-n junction or at the edges of the cell.

Economic Analysis

Net present value: A major component of analyzing the effects of investment and flow direction is the net present

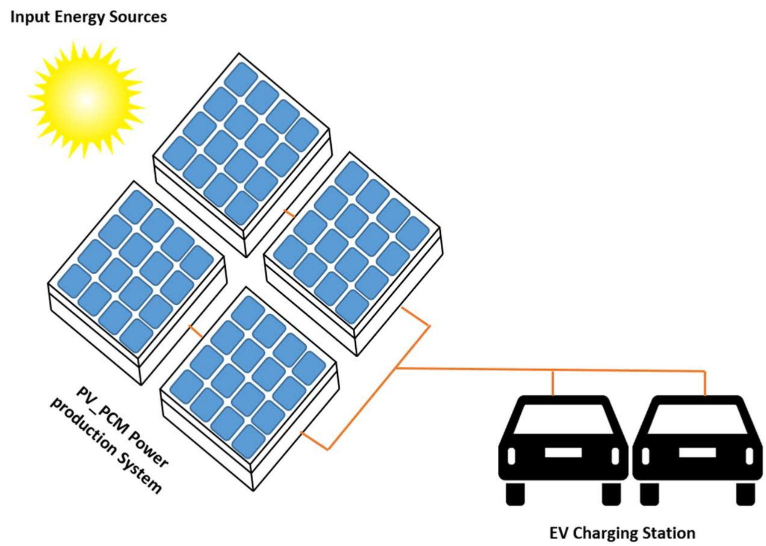


Fig. 1: Schematic view of study.

value (NPV), as expressed in Eq. (2). The overall capital investment, interest rate, discount rate, and the cost of running and maintaining the cooling system are all likely to be significant determinants of NPV (Nijmeh et al. 2020).

$$\text{Net present value (NPV)} = \sum_{t}^{T} \frac{C_t}{(1+r)^t} - C_0 \quad ..(2)$$

Where C_t is the total cash with respect to the system lifespan, r is the interest or discount rate, which is often considered less than 5%, t is the total lifespan of the system, and C_0 is the cost of the capital investment.

Profitability index: The profitability index (PI) is directly proportional to the ratio of net present value and the initial investment cost of the cooling system, as expressed in Eq. (3) (Kijo-Kleczkowska et al. 2022). The profitability index is expected to be at least unity, which means the system is yielding no loss or yielding benefit. If the PI is less than 1, the total investment cost was not recouped during the system's lifespan.

$$\text{Profitability Index (PI)} = \frac{\text{NPV}}{\text{Capital investment}} \quad \ldots(3)$$

Payback period: The payback period is often analyzed in the economic analysis, which shows the payback time for the invested project, which is derived by capital investment and annual cash flow length as expressed in Eq. (4) (Souayfane et al. 2019).

$$\text{Payback period} = \frac{\text{Total investment}}{\text{Annual cash flow}} \quad ...(4)$$

Environmental Analysis

The reduction of CO_2, PM2.5, and NOx emissions associated with the use of PV systems is a significant benefit to the environment and public health. However, it is important to consider the entire lifecycle of the system, including production, operation, and disposal. In this study, we analyze the environmental impact of the enhanced solar PV power production approach with different cooling rates. The reduction in greenhouse gas emissions and other particulate matter associated with combustion processes can have significant positive impacts on air quality and public health.

RESULTS AND DISCUSSION

Meteorological and PV Module Temperature

The temperature of a photovoltaic (PV) module is affected by several factors, including ambient temperature, solar irradiation, relative humidity, and wind speed. Among these factors, ambient temperature has the most significant impact on the rise in PV module temperature. In Thailand, the climate is characterized by hot and humid conditions, with long, hot summers and mild winters. During the summer months of March to June, the PV module temperature can peak at 72°C, with an average temperature range of 58-65°C. In contrast, the moderate winter season lasts from November to February, and the peak temperature during this period is 61°C, with an average temperature range of 53-57°C. These temperature variations can affect the performance of PV systems in higher order.

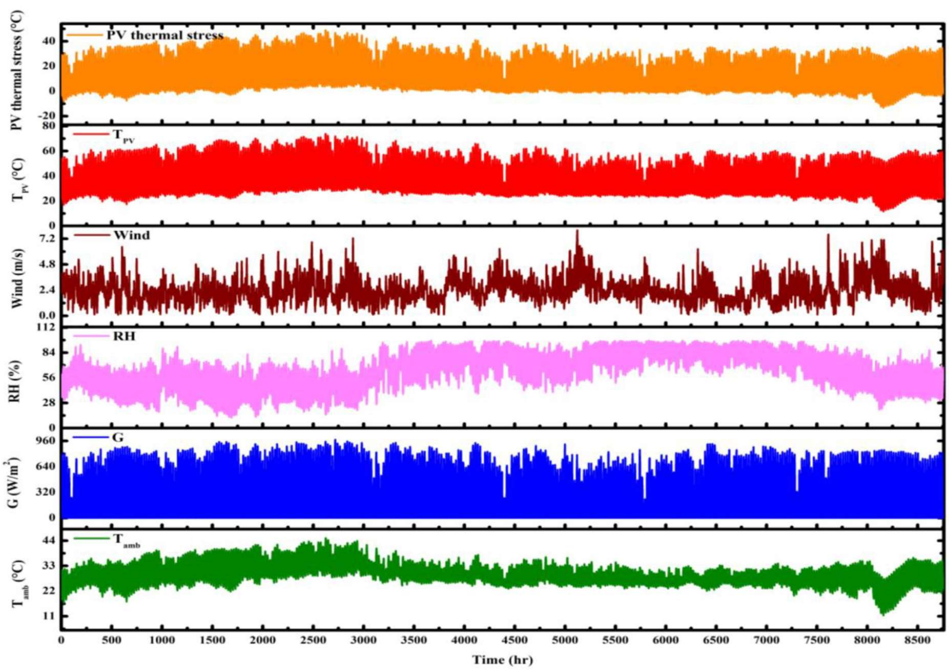
Fig. 2(a-c) depicts weather data and operating temperatures of a photovoltaic (PV) system situated in Thailand. The

PV system's thermal stress is correlated with the ambient temperature, as demonstrated in Fig.2(a-c). This indicates that when the ambient temperature increases, so does the PV temperature. The impact of wind speed on the convection heat loss and gain from a PV surface is demonstrated in the same figure. The wind speed varies between 3.2 m/s and 7.2 m/s throughout the year, and the energy incident on the PV is determined by total daily irradiation. Total daily insolation and solar irradiation are highest during the summer and lowest during the winter. The average solar irradiation ranges from 679 W/m^2 to 975 W/m^2. Between winter and summer, a difference of 30.35% is noted. Relative humidity varies throughout the year due to seasonal changes in temperature and moisture content in the air. During summer, the average relative humidity is 54% and can reach a maximum of 82%. Warmer air has a higher capacity to hold moisture, so the relative humidity tends to be lower.

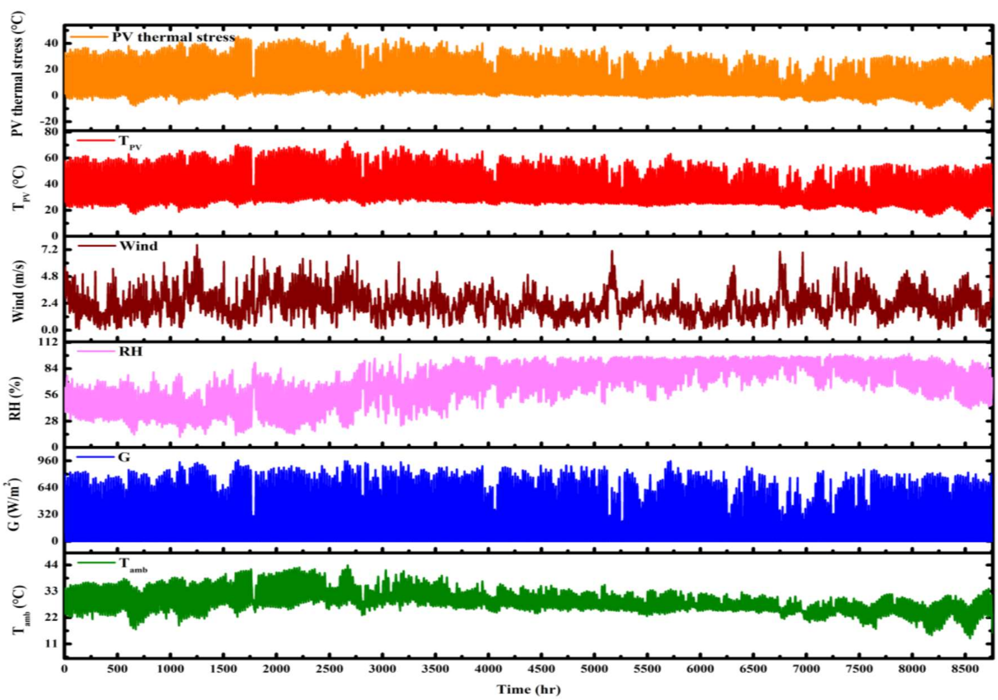
In contrast, during winter, the relative humidity ranges from 80% to 94%. Colder air has a lower capacity to hold moisture, resulting in higher relative humidity levels as the air becomes saturated more easily. These variations in temperature and moisture content contribute to the fluctuation of relative humidity throughout the year. Ambient temperature and relative humidity have an inverse relationship; when the ambient temperature rises, relative humidity drops, and vice versa.

PV Module Power Profile Under Variable Cooling

Fig. 3 illustrates the power production for 2022. The solar irradiance was followed without any temperature loss, resulting in nominal electrical power generation. However, real-time power conversion was greatly affected by the TPV rise, leading to an average actual power output of 5874.46 W, which is less than the average nominal power of 6600.27 W. The power loss is the difference between the nominal and actual power, and the maximum power loss in the system was found to be 725.81 W. To address this issue, researchers have used PCM and sensible materials as cooling materials to reduce the module temperature by 15 to 30%. The purpose of this study was to determine the maximum power production achievable by reducing the module temperature by 5% to 25%. The findings indicated that a reduction in temperature ranging from 5% to 25% resulted in an average power output of 5947.94W, 6021.43W, 6094.92W, 6168.41W, and 6241.90W, respectively. Without a cooling system, the maximum actual energy output was 26617kWh. However, with the implementation of a PV temperature reduction system, the energy output was enhanced, resulting in 26950kWh, 27283kWh, 27616kWh, 27949kWh, and 28282kWh for temperature reductions of 5%, 10%, 15%, 20%, and 25%, respectively. Notably, a 25% reduction in temperature led to a maximum energy output that was 1665kWh higher than that of a PV system without cooling.



(a)



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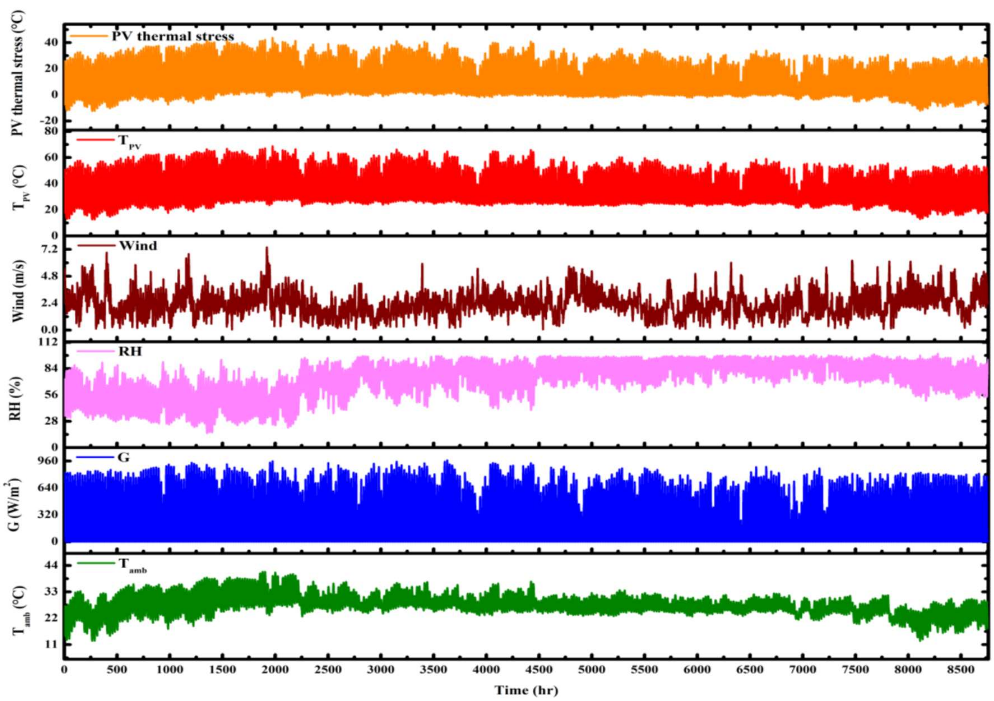

(c)

Fig. 2: Meteorological, PV module temperature and stress profile for (a) 2020, (b) 2021, and (c) 2022.

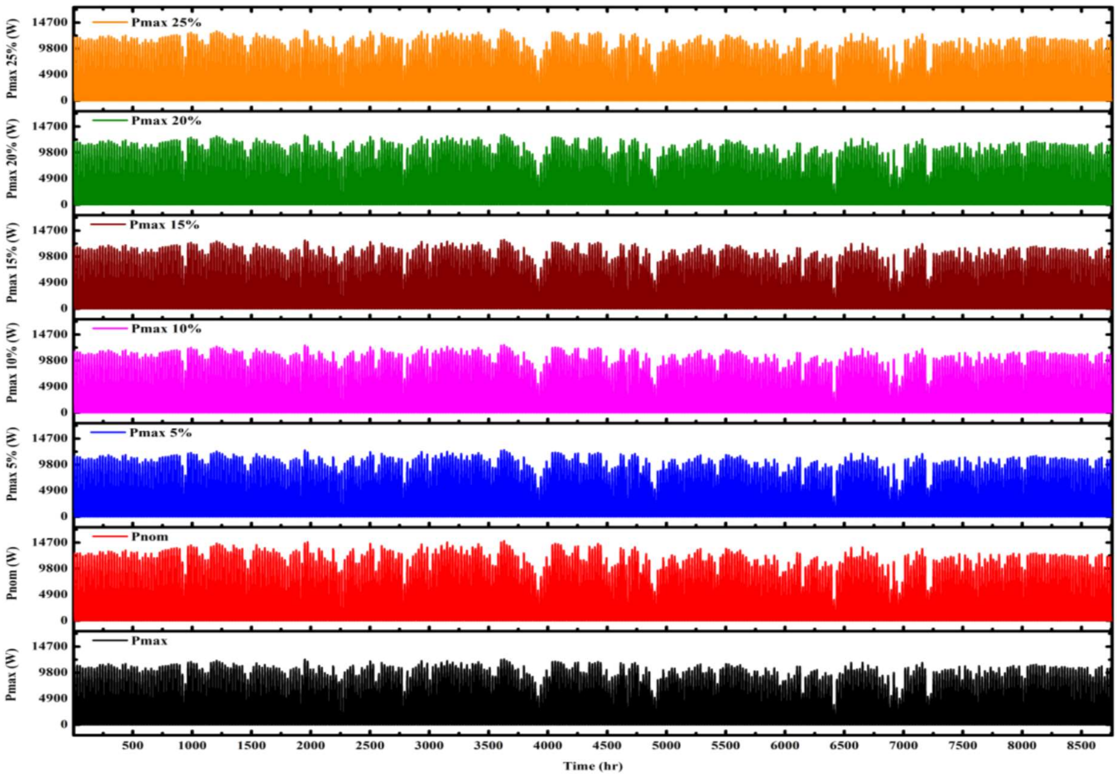

Fig. 3: PV module power profile under variable cooling for the year 2022.

Economic Analysis

The economic study is performed for a different cooling rate of 15.5 kWp in a solar system, as shown in Fig.4. Net Present Value (NPV) is a financial metric that calculates the present value of future cash flows for an investment or project using a discount rate. The NPV for a traditional PV system is 1410191.07, while for a PV cooling system with temperature reductions of 5%, 10%, 15%, 20%, and 25%, shows the NPV of 26108.39, 52202.72, 78297.06, 104391.4, and 130485.7 which is higher than the traditional PV system, indicating a positive return on investment.

The payback period for cooling methods with a 15.5 kWp PV system depends on various factors, including initial costs, energy savings, and electricity costs. It is found that a shorter payback period of 4.44, 4.39, 4.34, 4.29, and 4.24 years is attained as compared to conventional PV, which has a payback period of 4.5 years because the higher power output of the 15.5 kWP solar system with a cooling model generates higher power resulting in higher revenue attained.

The profitability index (PI) is a financial metric that evaluates the potential profitability of an investment. The PI increases linearly as the module temperature decreases, with a 25% reduction leading to a PI of 2.56 for the PV-PCM system. PI greater than 1 indicates a positive return on investment, with higher values indicating greater profitability. The savings for a 5% to 25% temperature reduction in a PV-PCM system range from 1.17% to 7.36%, which is 7.36% higher than conventional PV modules for a 25% temperature reduction.

Environmental Analysis

Cooling the PV module plays a significant role in reducing CO_2 emissions, which contribute to climate change. By reducing the temperature of PV modules, the efficiency of the solar cells is improved. This means that more electricity can be generated with the same amount of irradiance. This increased efficiency leads to a reduction in CO_2 emissions per unit of electricity generated. Fig. 5 shows that 5%, 10%, 15%, 20%, and 25% of module temperature reductions resulted in 13475, 13475, 13808, 13974, and 14141 kg of CO_2 reduction, respectively.

In addition to directly reducing PM2.5 concentrations, cooling the PV module can also indirectly reduce PM1.5 emissions by decreasing the demand for electricity from fossil fuel sources, which are major contributors to PM2.5 emissions. This indirect effect can have a significant impact, particularly in areas where fossil fuels are heavily used.

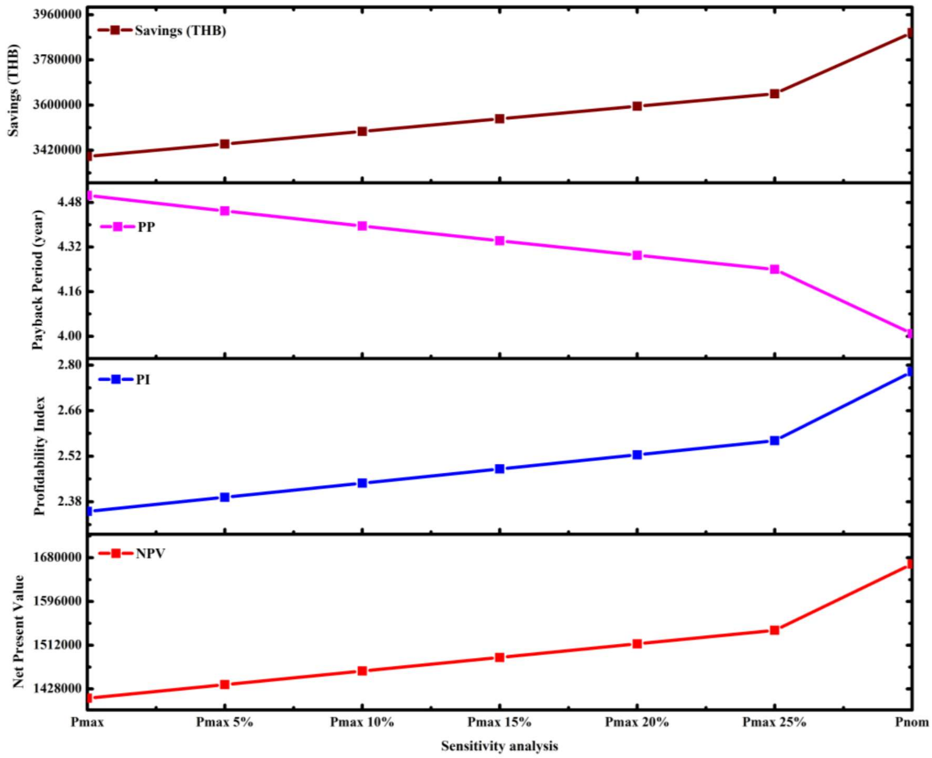

Fig. 4: Economic analysis of 15.5 kWp solar PV-powered EV charging station.

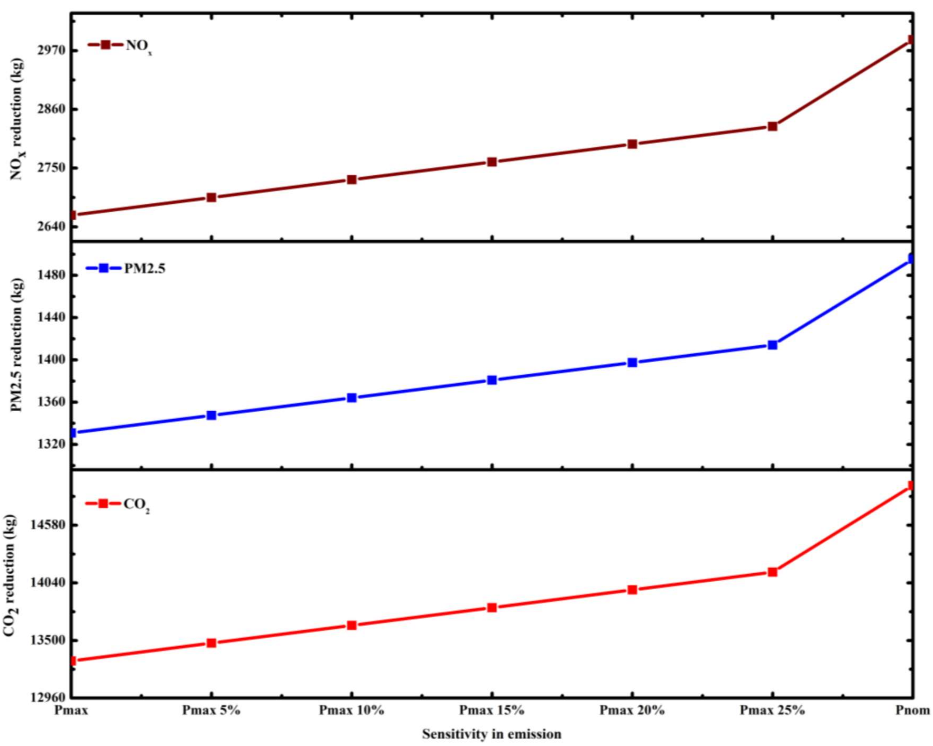

Fig. 5: Environmental Analysis of 15.5 kWp solar PV-powered EV charging station.

Based on Fig. 5, reducing module temperature by 25% results in a reduction of 1414 kg of PM2.5.

NOx refers to a group of nitrogen oxide gases produced by combustion processes, such as those used in power plants and transportation. NOx is a significant air pollutant and contributes to a range of environmental and health problems, including acid rain, smog, and respiratory diseases. Reducing NOx emissions is a crucial goal for improving public health and promoting a cleaner and more sustainable environment. Overall, cooling the PV modules will reduce NOx emissions and promote a cleaner and more sustainable environment. According to Fig. 5, module temperature reduction results in reductions of 2695 kg, 2728 kg, 2761 kg, 2794 kg, and 2825 kg in NOx, respectively.

CONCLUSION

This investigation aimed to assess the technical and economic feasibility of the improved PV power production by reducing the module temperature by 5-25%. The study evaluated the impact of different cooling rates on a 15.5 kWp solar PV system to recommend the EV charging station in tropical conditions of Thailand. The results showed that a 25% reduction in PV module temperature led to an increase of 1665kWh in energy production, surpassing the energy output of a PV system without cooling. Furthermore, the economic analysis of Net Present Value (NPV), Profitability Index (PI), and Payback Periods (PP) indicated a positive return on investment, suggesting that cooling technology is a feasible and economically viable option. In addition to the economic benefits, the reduction of greenhouse gas emissions, PM2.5, and NOx emissions can have significant positive impacts on the environment and public health.

In conclusion, the study suggests that the application of cooling technology can be beneficial for the EV charging station, both economically and environmentally. However, the decision to implement the cooling technology must be based on the economic viability of the EV charging station. Future efforts should focus on optimizing cooling technology, integrating energy storage, and implementing supportive policies to further enhance the solar PV power production approach for EV charging stations in Thailand.

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