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Multifunctional and Movable Solar Photovoltaic System for On-Grid and Water Pumping Applications Towards a Carbon-Free Society

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ABSTRACT

This study developed a multifunctional and movable solar PV system with a capacity of 3.3 kWp for on-grid and off-grid applications. The main objective of this study is to reduce diesel consumption in the agricultural water irrigation process, as most farmers depend on diesel-sourced water pumping systems. The agricultural lands in Thailand are widely remote, and electricity access is comparatively low. On the other hand, implementing the solar PV systems for agricultural water pumping is not cost-effective for farmers, as the water pumping requirements are not adequate. Considering the investment cost of the solar water pumping application, a movable solar PV system is designed to operate in on-grid and off-grid conditions. During the on-grid operation, the solar PV system-generated electrical energies are fed to the local grid whenever water pumping is required for farming, the movable solar PV system is detached from the grid and moved to the farming land, where it performs off-grid operation. It is found that a multifunctional solar PV system generates 12.4 kWh, which is fed to the local grid, and during the off-grid operation, the solar PV system generates 9.84 kWh of electrical energy, which yields 236412.97 liters of water. The multifunctional solar PV system significantly reduces 2.68 kg of CO_2 and is cost-effective for farmers with environmental benefits.

INTRODUCTION

In recent years, solar PV systems have transformed in many ways to meet the global energy demand, though they haven't achieved an efficient energy transition due to their immobilization. Notably, crystalline silicon solar cells are widely employed for domestic and commercial applications, and they are rigid in structure and installed for fixed-location power generation (Karthikeyan et al. 2019, Velmurugan et al. 2022). Temporary energy consumers widely rely on fossil fuels, as solar PV systems are not available on a rental basis. Renting a PV module increases the system's payback period compared to conventional PV systems and complex transportation (Sudikno et al. 2024, Mehmood et al. 2025). Further in this study, hybrid and mobilized solar PV systems are reviewed for developing futuristic renting solar PV systems.

Mobilized solar PV systems are affordable for smaller applications as the crystalline silicon solar cell is directly mounted over the small gadgets, which do not require conventional module structural arrangements (Karthikeyan et al. 2019). Secondly, smaller electronic appliances requiring a smaller battery and solar cells are used for emergency purposes, resulting in reliable and efficient methods. Solar lanterns are one of the most efficient portable applications with crystalline silicon solar cells, and they are widely used in remote villages where grid electrifications are not equipped. It is found that solar lanterns are effectively replaced by conventional kerosene-based lanterns in developing and underdeveloped nations (Mekonnen et al. 2023, Yaqoot et al. 2015).

The behavioural impact of solar lanterns is analysed in Indian villages (Mahajan et al. 2020). In total, 184 households participated in a satisfactory survey of using a solar lantern, which was provided free of cost to them, and the survey was conducted after six months. The survey includes energy expenditure, lighting quality between kerosene and solar lanterns, light satisfaction, and usage reliability to determine the behavioural changes on improved lighting effects. The study concludes that conventional energy sources are reduced, and higher satisfaction is achieved for indoor and outdoor activities, particularly reading, which attained the highest satisfaction. Solar portable refrigerators are a great initiative that provides medical aid for rural areas (Yusof et al. 2022, Doubabi et al. 2020).

A hybrid portable refrigerator is designed to operate on solar power and from the AC power supply. A year-round performance reveals that portable refrigerators attained a stable cooling operation under different climatic conditions in India. The developed system was portable, easily transported in all terrain conditions, and particularly efficient for off-grid electrification locations. It was found that the developed refrigerator maintained the cooling chamber temperature at 6°C, which demonstrated an effective cooling performance with a 5.89 coefficient of performance (Nayak et al. 2020). Apart from lighting and cooling chambers, portable solar systems play a crucial role in the agricultural sector. In modern society, most agrarian lands are far from the main cities, and in a typical case, forest zone agricultural lands are isolated from rural areas. Under these conditions, fuel-based water pumping techniques are widely used, greatly impacting forest ecosystems and reducing the benefit of farming outcomes (Terang et al. 2023, Amusan et al. 2023, Hilali et al. 2022). Solar PV systems are widely used for water pumping applications; however, hybridization of solar PV with water pumping relies widely on diesel pumps and battery energy storage systems (Maleki et al. 2025, Ahmed et al. 2025). Under certain cases, wind turbines are used as a backup for water pumping, particularly in a desert region where the water consumption is adequate (Al-Omari et al. 2025). A simulation study is performed for five different locations to meet the water requirement across summer, spring, autumn and winter using a 3.3 kW solar PV system. The study mainly focused on fulfilling the water requirements where the solar PV systems are grid-connected and maintained to reduce the grid dependency for power consumption (Omar et al. 2025).

An off-grid hybrid application for energy generation and water pumping using various renewable energy sources is developed, which includes PV, wind and biomass. The Homer simulation study reveals that PV with biomass and PV-alone are suitable for rural application, which is cost-effective and low maintenance as compared with wind turbine integration (Kabir et al. 2025).

Considering the intermittency and importance of solar power generation, Ramli and Jabbar incorporated IoT with a portable irrigation system to improve efficiency. NodeMCU microcontroller monitors the agricultural farm with the help of sensors and initiates the water pumping process. Using this automated watering technique results in less water usage and power consumption. Developed portable irrigation systems are controlled and monitored by the smart home, which reduces human resource costs and provides water only when the crops require water. Under the controlled and automated water dripping method, healthy crop growth is achieved, which yields higher production. Secondly, solar power irrigation systems are portable and designed using trolley methods, which can be dragged easily to other location s (Ramli et al. 2022).

Followed by portable solar appliances, solar-incorporated vehicles gained attention as they charged the battery during driving with the help of roof-mounted solar PV systems. Electric cars are eco-friendly and affordable replacements for fossil fuel-based vehicles. However, charging electric cars with a conventional electric grid was not attributed to an efficient, eco-friendly system. Several electric car charging stations have solar PV modules to reduce traditional power consumption, although they have failed to achieve a smooth energy transition (Nirmala et al. 2024, Amin Mirjalili et al. 2023). Pan et al. (Pan et al. 2017) developed a foldable solar PV system to cool the vehicle's indoor temperature while the vehicle is in parking mode.

In most cases, the vehicle engine or battery system operates to perform the cooling process, which reduces the vehicle's driving capacity. Incorporating a foldable solar PV system over the vehicle roof eases the cooling load; solar panels are unfolded whenever the vehicle is parked to generate electrical energy. In this case, a wireless power transmission technique favors transmitting the power from solar panels to vehicles' interiors to store in a supercapacitor without damaging the vehicle structure. The supercapacitor regulates the power flow between the solar panel and the cooling system, providing a stabilized cooling effect. Developed a prototype cooling system that reduced the vehicle's interior temperature by 4.2°C.

Mounting solar PV modules over the electric car in a foldable scissors model, where the PV modules are folded during driving and unfolded during the car parking period (Jin et al. 2024). This foldable solar PV system reduced the area occupancy by five times as compared to the conventional method and increased the total capacity of the energy generation. The experiment is performed under laboratory conditions using a solar simulator with foldable PV modules for toy cars. The power output from the PV module is transferred to the supercapacitor, which is placed inside the vehicle using a wireless power transmission technique. Increased load resistance and radial distance between the power transmission coil greatly impact power and transfer efficiency. Prototype experimental results depict 57.7% efficiency for 5Ω and 10 Ω, and the corresponding electrical power production is 1.736 W. The proposed system produces 2.033 GWh annually for real-time upscaling, which could greatly reduce fossil fuel consumption (Jin et al. 2024).

The Fiat Punto car was converted into a solar hybrid car and performed a field test under real-time conditions to reduce fossil fuel consumption and reuse the conventional vehicle (Rizzo et al. 2014). In this hybridization technique, the rear wheel is equipped with a 7 kW DC motor, a battery pack with an energy management system is integrated into the car's backside, and flexible solar panels are mounted on the roof. After the successful initiation, a second prototype hybrid car was implemented with a Volkswagen Polo performing the field test. Under the bench test, the in-wheel motor (IWM) indicates that the vehicle's speed increased after 130 seconds. Following that, the corresponding torque and current increased gradually. Under the road test, IWM efficiency reached more than 80%, and the electric motor speed went above 50 $km.h^{-1}$ after 985 seconds. This study concludes that hybrid vehicles are futuristic; however, technical complications are higher than those of solar-powered electric vehicles (Rizzo et al. 2014). However, hybrid cars have several operational complications, such as the conventional vehicle weight being higher than an electric car, and adding a battery, electric motors, and a Battery Management System (BMS) increases the total weight, resulting in electric motors performing inefficiently (Yang et al. 2023, Urooj et al. 2024, Leoncini et al. 2024).

Apart from portable and foldable solar PV systems, solar trailers are another prospect for mobility, and they are widely commercialized in developed nations. However, solar trailers have not been examined for technical performance and economic analysis in developed and developing nations, particularly Thailand. As mentioned earlier, solar trailers are widely used for remote locations where the grid facility is limited, and for a short-term event, the lessee is comfortable paying a high price. However, farmers cannot pay a higher amount to rent solar trailers. Considering these complications, in our study, we developed a solar trailer that can be used for fixed-location power generation as a conventional solar PV on-grid system. Farmers can easily disconnect the solar trailer from the grid, transport it to the agricultural field, and operate the system entirely off-grid during the requirement of water production requirement. The main objective of the study is given below:

- During the off-farming period, the movable solar PV system operates on-grid, and the generated electrical energies are fed to the conventional grid.
- Whenever the water pumpings are required for farming, solar PV systems are disconnected from the grid and transported to the farming land.
- To ease the transportation of solar PV systems, the PV modules are integrated over the trailer, which can easily be towed by any vehicle.
- To mitigate the risk of physical damage during towing, a mechanical jack system is integrated to adjust and stabilize the position of the PV modules, as the developed system is transformable for optimized solar energy harvesting.

MATERIALS AND METHODS

This study uses 550 Wp polycrystalline (PQ Solar) PV modules to make a movable solar trailer. At maximum power point and under standard test conditions, each solar PV module can generate 41.78 V and 13.17 A, and its corresponding open-circuit voltage and short-circuit current are 49.70 V and 14.09 A, respectively. Four PV modules are integrated as a gable roof type, two on each side and in a fixed position. One PV module is installed on each side and can be placed between $0-90^{\circ}$, depending on the application. Manual hydraulic-based tracking systems are used for the sides of the solar trailer; whenever the solar trailer is being shifted for water pumping, both sides of the solar PV modules are retained at 90° to avoid accidents, as shown in Fig. 1. During on-grid integration, all six PV modules are connected in series to meet the voltage and current requirements of the solar inverter. For portable water pumping operations, five PV modules are connected to the 2.2 kW water pump, and this operation is performed under off-grid conditions. The sixth PV module is preferred for backup operation as the water pumpings are widely performed in a remote village where the shading is unpredictable. The sixth and fifth PV module connections are swapped depending on the geographic shade conditions. However, the eliminated fifth/sixth PV module is connected to a 120-Ah battery for emergencies. The experiments are performed at Tambon Khonthi, Mueang District, Kamphaengphet Province. During the experiment, six PV module operating temperatures (center point) and ambient temperatures were measured using a K-type thermocouple. Electrical voltage and current generation were measured using a Fluke energy logger, and solar irradiance was recorded using the HT solar-02 logging system. All the experimental data are recorded at minute intervals as the standard procedure (Karthikeyan et al. 2018, Homlakorn et al. 2023). However, for solar water pumping applications, DC voltage and currents are not inverted and connected to the water pump using a Handuro auto solar controller, whereas the DC voltage and currents are recorded, and, following that, the water flow and quantities are measured in minute intervals.

Statistical and Environmental Analysis

Further, to understand the operational mechanism of the on-grid solar PV systems, a statistical approach is performed using the Pearson correlation method. The linear relationship between the solar PV module operating temperature, ambient temperature, solar irradiance, voltage, current and power is studied. Following that, environmental pollution analysis is performed for off-grid solar water pumping applications based on the conventional methods of diesel consumption.

RESULTS AND DISCUSSION

Ongrid Operating Conditions

Thailand is above the equatorial line, with rich solar potential and an average of more than 300 days of effective sunshine. Fig. 2(a) shows the experimental site's solar irradiance and ambient temperature with an average of 646.01 W.m^{-2} and 33.67°C. Tropical countries like Thailand generally face an excessive rise in ambient temperatures following solar irradiance due to their geographical conditions, such as higher inland temperatures than Indonesia and the Philippines. On the other hand, higher humidity retains the heat, which, in this case, increases the ambient temperature throughout the

Fig. 1: Real-time operational view of multifunctional and movable solar PV system.

year. The solar irradiance pattern in the examined site was enormous, as within 10:00 h, and the solar irradiance reached 615.1 W.m^{-2}, and during the peak sunshine period, between 936.1 W.m^{-2} and 962.8 W.m^{-2}, which is nearly the standard test conditions (STC). Due to higher humidity, the ambient temperature peaked at 37.24℃ at 14:06 h; however, solar irradiance was 873.3 W.m^{-2} during this time. Though the ambient temperature follows the solar irradiance trend, the

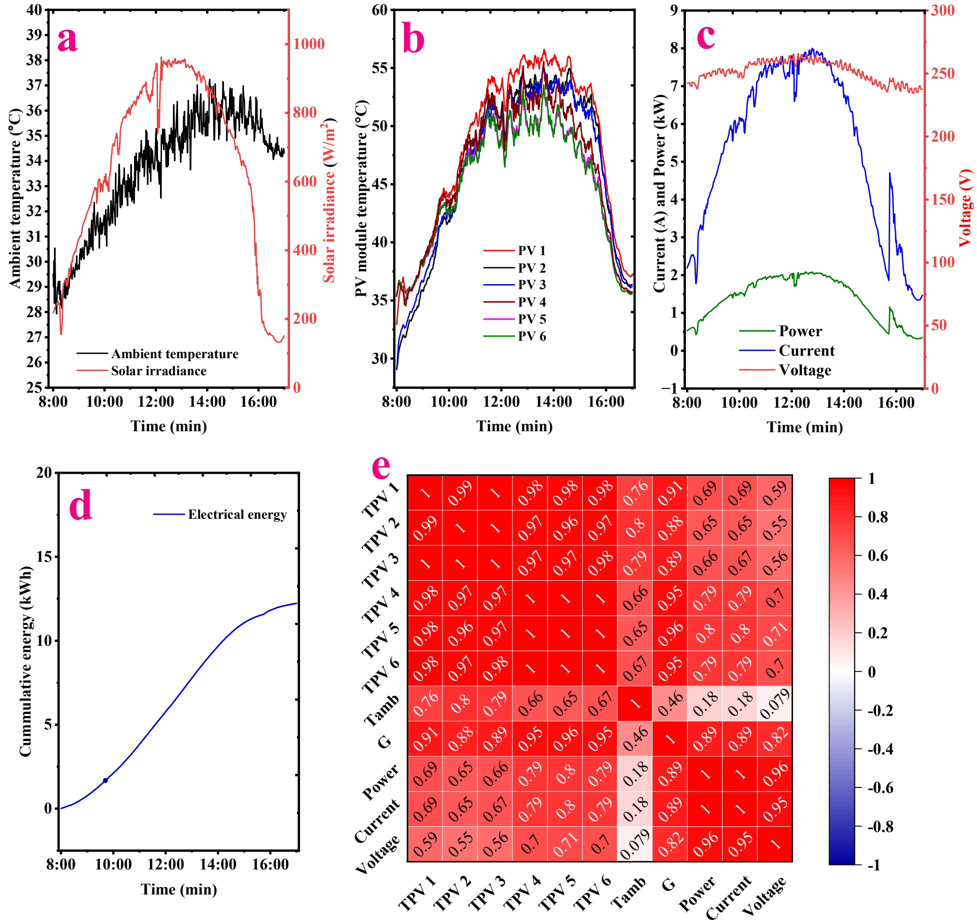

Fig. 2: Movable solar PV system under on-grid operating conditions (a) ambient temperature and solar irradiance, (b) PV module operating temperatures, (c) electrical power output, (d) cumulative energy yield, and (e) Pearson correlation.

Table 1: Consecutive day 02 operation of on-grid application.

Time [h]	Average T_{PV} [□]	T_{amb} [□]	G [W.m^{-2}]	Pmax [kW]	Vmp [V]	Imp [A]	Cumulative energy [kWh]
8:00	28.0	26.4	345.1	0.2	237.6	1.2	0.0
9:00	39.1	30.5	606.0	1.1	248.7	4.3	0.7
10:00	46.7	32.6	847.6	1.6	254.9	6.4	2.1
11:00	52.8	34.1	983.7	1.9	259.8	7.5	3.9
12:00	58.4	35.8	1047.0	2.0	266.0	7.7	5.9
13:00	56.6	35.6	984.7	2.1	264.0	7.8	7.9
14:00	56.2	35.7	824.7	1.5	256.0	6.1	9.8
15:00	52.2	36.5	627.8	0.6	242.9	2.5	10.9
16:00	45.2	36.7	382.1	0.8	245.5	3.3	12.0
17:00	36.3	35.8	80.9	0.2	236.5	1.1	12.4

peak ambient temperature period is not attained at the peak sunshine periods.

The solar irradiance and ambient temperature are directly proportional to the PV module's operating temperature (T_{PV}). Generally, an increase in solar irradiance mainly increases the T_{PV}; however, elevated ambient temperature cools the PV module by dissipating the T_{PV} to the surroundings through natural convection and radiation mode of heat transfer. The ambient temperature is crucial in increasing the TPV and solar irradiances in certain cases. In this study, four different orientations are used for the six PV modules due to the physical structure of the developed solar trailer. Specifically, the first and second PV modules are oriented north-south facing, significantly improving their operating temperatures. 3/4th of the absorbed solar irradiance is converted into heat energy during the photovoltaic effect. Comparatively, the third and fourth T_{PVs} are much lower due to their orientation, and following that, the fifth and sixth PV modules are lower than the other PV modules. The average T_{PV} for PV1, PV2, PV3, PV4, PV5 and PV6 were 48.18°C, 46.37°C, 46.2°C, 46.1°C, 45.1°C, and 44.9°C, and their corresponding peak T_{PV} were 56.6°C, 55.11°C, 55.2°C, 55.58°C, 53.07°C, and 53.55°C, respectively as shown in Fig. 2(b). Considering the limited area for installing a PV module, 10% of the shading losses are accounted for operation, which acts as a non-uniformity on the T_{PV} for all six PV modules.

Solar cells are current generators that respond to solar irradiance. Secondly, TPV's influence over current generations is likely negligible compared to voltage generation. The current generation increases over the increase in solar irradiance, as shown in Fig. 2 (c). During the experimentation starting period, the current generations are 2.2 A, whereas the voltage generation reached 242.4 V for 218.3 W.m^{-2}. The maximum and minimum voltage generation reached 265.8 V and 234.3 V.

On the other hand, the highest and lowest current generations were recorded at 8.1 A and 1.3 A, respectively. Though the voltage generations are not majorly dependent on the rise in solar irradiance, they are vulnerable to an increase in T_{PV}. A drop in voltage generation significantly reduces power generation. A sudden surge in the current generation was noted during the off-sunshine, as the experiment location is a residential area where the load consumption is high during the evening time, which, in turn, the solar inverter reacts for several minutes; however, within a few minutes, the current generation drops following the solar irradiance pattern. The average voltage, current, and power generation are 251.5 V, 5.4 A, and 1.4 kW, respectively. Fig. 2 (d) shows an on-grid power feeding to the local grid; over the rise in solar irradiance, energy generation has increased by 12.3 kWh. The thermal and electrical parameters of the multifunctional and movable 3.3 kW solar PV system are analysed using a Pearson correlation, as shown in Fig. 2 (e). The solar irradiance has a strong positive correlation with $T_{PV,}$ with coefficients of 0.91, 0.88, 0.89, 0.95, 0.96, and 0.95.

On the other hand, ambient temperature plays a significant role in T_{PV} with a strong and moderate positive correlation with coefficients of 0.76, 0.8, 0.79, 0.66, 0.65, and 0.67. Voltage generations have a mild positive correlation with $T_{PV,}$ as an increase in PV module operating temperature significantly reduces the voltage generation with a coefficient of 0.59, 0.55, 0.56, 0.7, 0.71, and 0.7. However, PV4, PV5, and PV6 are less effective for T_{PV} rise due to the increasing shading effect and their orientation towards the sun. Though the increase in solar irradiance is attributed to higher T_{PV} and voltage generation loss, ambient temperature has a low positive correlation with solar irradiance. The developed multifunctional solar PV system is suitable for hybrid applications, and the consecutive day operations are listed in Table 1, where the cumulative electrical energy fed to the local grid was 12.4 kWh.

Solar Water Pumping

According to the World Bank (2021), 23500 square kilometers are used for agricultural purposes in Thailand, approximately 45.8% of the total area. The major agrarian cultivations rely on river and canal irrigations, which are remote in most cases. Farmers widely use a conventional diesel engine-based water pumping system to pump the water from the rivers/canal beds. Multifunctional and movable solar PV systems reduce diesel consumption and produce water using renewable energy sources. The operational mechanisms of on-grid and off-grid-based solar water pumpings are similar, but the solar inverter is replaced with the Handuro controller to power the water pump. The solar water pumping experiment is performed under clear-sky conditions where the solar irradiance reaches an average and peak of 559.7 W.m^{-2} and 1029 W.m$^{-2,}$ as shown in Fig. 3(a). Owing to the clear sky and increased solar irradiance, the peak and average ambient temperature reached 37.5 °C and 34.2 °C, respectively. The PV module operating temperature follows a similar trend, as PV1, PV2, PV3, PV4, PV5, and PV6 recorded a maximum of 60.3°C, 57.5°C, 56.9°C, 57.14°C, 54.85°C, and 55.5°C, respectively, as shown in Fig. 3(b). For solar water pumping applications, DC voltage and current from the multifunctional solar cells are directly connected to the solar pump using a Handuro controller. The current generations are following the trend of solar irradiance, as in this case, the load is independent, and the controller is not required to respond to surge load demand compared to on-grid applications. The average voltage and current generations are 197.3 V and 4.3 A,

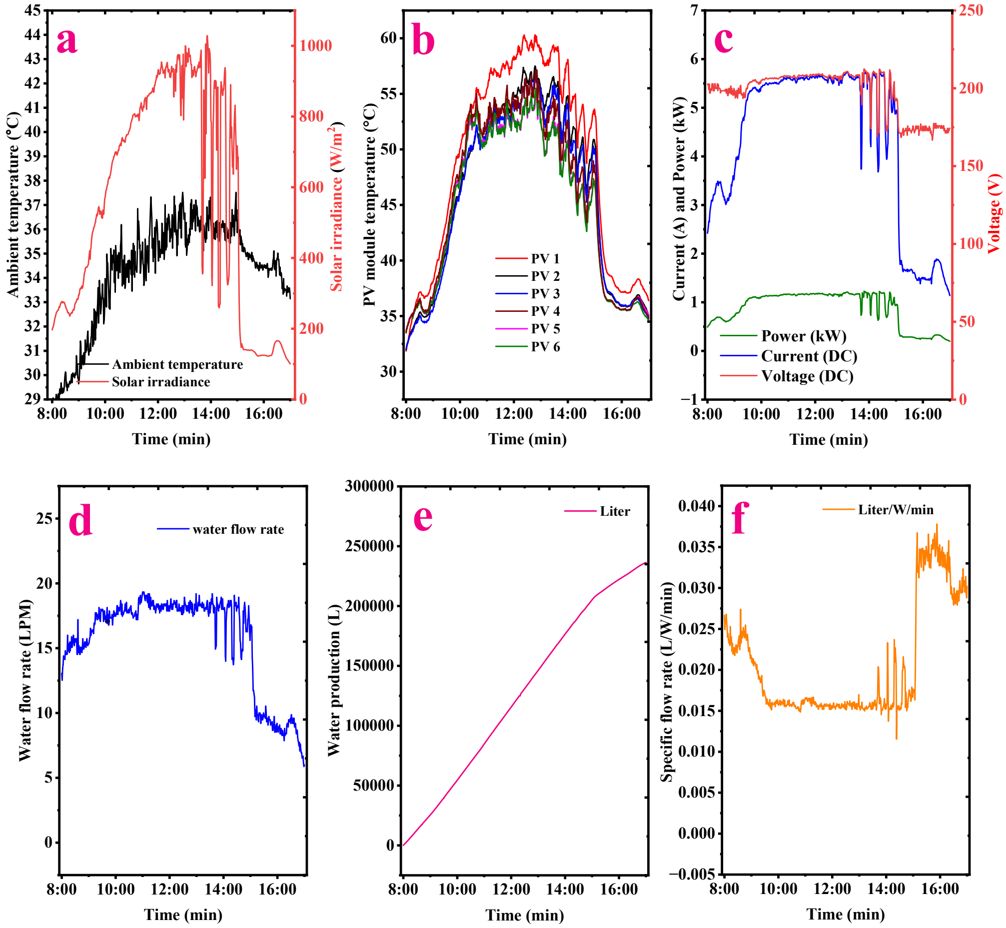

Fig. 3: Movable solar PV system under off-grid operating conditions (a) ambient temperature and solar irradiance, (b) PV module operating temperatures, (c) electrical power output, (d) water flow, (e) cumulative water production, and (f) specific flow rate of the solar pump.

Table 2: Consecutive day 02 operation of solar water pumping application.

Time [h]	Average T_{PV} [°C]	T_{amb} [°C]	G [W.m^{-2}]	Pmax [kW]	Vmp [V]	Imp [A]	Flow rate [LPM]	Water production [L]
8:00	29.4	26.5	127.9	0.50	228.2	2.2	1.5	35.7
9:00	40.1	32.3	318.6	0.76	205.5	3.7	15.1	25704.0
10:00	46.4	31.4	645.5	1.17	210.7	5.6	15.9	51810.5
11:00	54.3	32.4	832.8	1.13	207.5	5.5	14.9	77913.2
12:00	50.3	33.9	921.3	1.17	208.5	5.6	14.4	105163.3
13:00	61.1	36.8	1007.0	1.20	202.7	5.9	16.7	134381.7
14:00	56.1	36.2	994.3	1.11	206.7	5.4	16.4	161319.3
15:00	56.3	35.8	871.9	1.09	205.2	5.3	16.3	187823.8
16:00	47.0	35.1	614.4	0.91	192.5	4.7	15.7	212686.2
17:00	36.1	34.6	95.0	0.18	169.3	1.0	6.9	230551.1

and the peak voltage and current generations are 212.5 V and 5.8 A, respectively, as shown in Fig. 3 (c). In solar water pumping conditions, power conversion loss is less as the DC power from the solar PV array is not converted into AC, whereas the neglect of inverter loss improves the system's overall performance. During the starting time of the experiment, water flow was recorded to be 13.07 LPM, and within a two-hour experimentation starting period, the water flow rate reached higher than 18 LPM, as shown in Fig. 3 (d). The average and peak water flow rate was recorded to be 15.60 LPM and 19.3 LPM, respectively. Late 14:00 h, a higher fluctuation was noted in the water flow rate due to the fluctuation in solar irradiance. During the eight-hour experimentation period, a multifunctional and movable solar PV system pumped 236412.97 liters, as shown in Fig. 3 (e). The specific flow rate indicates an effective water production for the developed system with an average of 0.02 $L.min^{-1}.W^{-1}$, as shown in Fig. 3(f). Table 2 depicts a consecutive day 02 solar PV systems' power and water generations; notably, a cumulative water production reached 230551.1 liters, indicating the developed multifunctional and movable solar PV system is suitable for on-grid and water pumping applications.

Comparative Analysis of On-Grid and Off-Grid Systems

The conventional solar PV systems are widely used in on-grid operating conditions; under certain conditions, they are decentralised to support the local load demand using a smart microgrid. However, the energy generations are shared with a closed network. In this study, a multifunctional solar PV system is developed to support both on-grid and off-grid operation at different locations. Conventionally, a multifunctional solar PV system feeds electrical energy to the grid. Whenever the water pumping requirements arise, in less than five minutes, the on-grid system is transformed into a portable off-grid system and can produce a cumulative of 236412.97 liters. This transformable and movable solar PV system significantly reduces the diesel consumption and favours the farmers from an economic and environmentally friendly perspective.

Environmental Analysis

The multifunctional and movable solar PV system generates 9.84 kWh, equivalent to 2.81 liters of diesel. In the environmental aspect, one liter of diesel can produce 2.68 kg of CO_2, whereas the total CO_2 pollution could be minimized by 7.53 kg of CO_2 daily. Over the 25 years of solar PV system life expectancy, 68.71 tonnes of CO_2 will be reduced.

CONCLUSIONS

Thailand is a tropical and agricultural country where 45.8% of the land is used for farming. Most agrarian lands depend on the irrigation of rivers and canal beds. During the summer, most inland areas must use a water pump to access the water, as the water levels are comparatively low in the canals. Conventionally, farmers use a diesel engine-based water pumping system, which is neither environmentally friendly nor affordable. In this study, multifunctional and movable solar PV systems are developed and utilized for both on-grid and water irrigation processes. During on-grid application, average voltage and current generations are recorded to be 251.5 V and 5.4 A, and the corresponding power generation was 1.4 kW, respectively. The cumulative electrical energy reached 12.3 kWh, which is fed to the local grid. The Pearson correlation indicates that the solar irradiance has a strong positive correlation with $T_{PV.}$ Comparatively, PV4, PV5, and PV6 T_{PV} have slightly lower correlation with other PV modules due to variation in tilt angle. In the off-grid operating conditions, solar PV systems' 9.84 kWh is sourced to the water pump, producing 236412.97 liters. The multifunctional and movable solar PV system operates efficiently under on-grid and off-grid conditions, reducing 2.68 kg of CO_2. Apart from the on-grid and off-grid application of the developed multifunctional solar PV systems, in the future, they can be used for a remote electric vehicle charging station and rented for several cultural activities where the conventional grid is not available.

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