

Full Length Article

An innovative low-cost and water-saving direct photovoltaic water heating system using simplified near maximum power point tracking

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ABSTRACT

Photovoltaic (PV) water heating systems are one of the water heating technologies that have been attracting significant attention in recent years. Although from the thermodynamics point of view, solar thermal systems such as vacuum tubes, are more efficient in heating water for the same area exposed to the sun, but this is not the only factor influence the utilisation of solar energy. The main reason for the interest in using PV solar systems for water heating and thermal storage is their lower cost, higher reliability, reduced maintenance, water savings and minimising complexity of retrofitting. In this work, a novel PV water heating system is proposed where the near maximum power point tracking (Near-MPPT) is performed using different rated heating elements via a simple control circuit without the need for a relatively expensive DC-DC converter. The selection of the heating elements equivalent resistance is made based on the photovoltaic array size and the solar irradiation data. An optimisation process is considered in the design to reduce cost and maximise efficiency. A novel generic methodology is developed to select the values of the heating elements for optimum performance. This has been achieved by obtaining the maximum number of possible variations in resistance configurations from two selected heating elements while sustaining high efficiency and DC voltage switching capability. The control circuit is designed by utilising electromechanical and semiconductor switching devices. A control algorithm is created to track the maximum power point via the manipulation of the switching circuit using PV power measurements. The proposed system is compared to a PV system equipped with a DC-DC converter and a PV system directly connected to fixed heating elements. The system is experimentally tested to evaluate the idea including the payback period, performance and costings. Further, simulation is conducted and validated for conditions in Jordan as well as Egypt and the UK. The results have shown that proposed system provides a lower cost and reasonable efficiency when compared to the conventional system. The results of the proposed solar technology system in Jordan, for example, have shown a small reduction in the yearly produced energy of only 3.8 % when compared to a conventional system equipped with MPPT DC-DC converter system and an increase in efficiency of about 11.5 % in comparison to a fixed load system. However, the cost saving is expected to be 44.7 % when the proposed simple switching system is compared to a standard DC-DC converter; with water savings in winter of 83.7 % in comparison to a solar thermal system. The payback period of the system for Jordan, Egypt and the UK is found approximately 2.75 years, 6.5 years and 3 years respectively. In comparison to the conventional MPPT DC-DC converter, the proposed novel system Near-MPPT is expected to provide a much lower cost system (between 24.5 % and 44.7 %) to encourage the adaptation of renewable energy and also address energy poverty with more affordable technologies, particularly in developing countries. The results also show that the proposed PV heating system has a better water saving features when compared with Solar Vacuum Tubes (SVT) heating systems, an important feature for arid countries. The flexibility of the PV system allows the use of electricity when the heating system is not needed for heating of water, particularly during the summer months.

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1. Introduction

This research work has been developed to encourage the utilisation of renewable energy in developing countries with limited financial resources, by selecting a low-cost and easy to install system that provides a compromise between cost and performance. Jordan, as a developing country, is selected to be the focus of the experimental location of this research work and its environmental conditions are selected for the detailed description of the methodology and results. However, the system has been also tested in Egypt and the UK to compare cost vs benefits as benchmarks for Africa and Europe. Jordan is one of the developing countries that is located in the Middle East, and on the contrary to its neighbouring countries, it is an arid country with limited energy resources. The country imports about 90 % of its energy sources which puts a huge burden on the country's budget and makes it vulnerable to the fluctuation of oil prices [1]. Referring to [2], 73 % of the produced electricity is from fossil fuels, while 26 % is from renewable energy. Due to the geographic location of the city of Amman in Jordan, the country benefits from decent insolation during the whole year. Jordan is one of the highest countries in the Middle East and the world with PV potential where the Global horizontal irradiance measure is about 2700 kWh/m²/year [3]. This solar potential has pushed the government to diversify energy resources, increase energy independence, and work towards sustainable development goals by enhancing the utilisation of renewable energy. The kingdom has set goals to increase renewable energy production [4], which in turn launched the Jordan Renewable Energy and Energy Efficiency Fund (JREEEF) to increase the utilisation of solar energy in the domestic, industrial, agricultural, and public sectors [5]. The total electric energy consumption in 2019 totalled about 8259.9 GWh, including domestic and governmental buildings, of which 92.5 % is purely domestic [6,7]. 11–15 % of the electric energy is used to heat water in a typical Jordanian household [8,9], which is a significant portion of the country's total consumption. In the last decade, there has been growing popularity of thermal solar water heaters in Jordan, where about 15 % of all households have installed the systems with plans to increase the number of owners using government subsidies [5]. Solar vacuum tube (SVT) water heater performs ideally in sunny and warm weather, while on cloudy days, their performance decreases significantly [10]. Vacuum tubes solar collectors and standard flat plate collectors have significant heat loss coefficients, while the latter has higher than the former [11]. In some studies, the solar water heater does not meet its cashback target and needs periodic maintenance [12]. Although solar heaters in Jordan are popular, the conventional electric water

heater tank is the most preferable in the country [13], where the electric energy consumption bill is mostly dominated by the water heating energy. However, several factors can impact water losses because of the distance between the hot water storage of solar vacuum tubes system and the taps [14], see Fig. 1. Key factors in the case of Solar vacuum tube (SVT) water heater systems that influence heat losses via conduction, convection and radiation include pipe length, pipe material time of water flow, insulation type and pipe material. While proper insulation of the pipes can help to reduce heat losses during water flow, long static water in pipes will lead to heat losses, hence causing water losses when people wait for the hot water to arrive to the tap wasting significant amount of cold water as a result of staying in the pipe for considerable time. Water losses in SVT water heater systems are also observed in hot weather, see Fig. 2. On summer sunny days in Jordan there is an excess of energy in the form of hot water that cannot be utilised in any way and venting mechanisms are used to release pressure of the steam formed inside the hot water tank. This also causes further maintenance and risk issues on the short and long terms such as corrosion and fatigue of its external structure or water burns for people. Therefore, the proposed PV heating system could address many of the drawbacks, and is normally easier to install specially for retrofitting applications.

Another solution for water heating systems is the photovoltaic-thermal (PV/T) collector, which is the combination of a solar water heater and a PV cell where water or air is used to cool down the PV sandwiched cells in order to achieve higher efficiencies while exploiting the heated water [15]. A study of investigation focused on assessing the dynamic performance of a photovoltaic thermal (PV/T) system operating under zero reduced temperature conditions, as per the ASHRAE standard 93–2010. This system demonstrated favourable electric-thermal characteristics suitable for integration into district heating and electric power generation infrastructures [16]. However, such system(s) is complicated and will need significant maintenance. PV/T systems tend to be more expensive in terms of capital investment in comparison to traditional PV panels for water heating because of their dual functionality and more complex design. The additional components required for heat capture and conversion can increase both material, installation and maintenance costs.

An alternative strategy involves enhancing the utilisation of photovoltaic (PV) systems by incorporating thermal storage capabilities, such as those found in water heaters. This can be achieved by scheduling the operation of appliances capable of performing these functions [17]. Other water heating solutions have been reviewed in [18]. One of the simple solutions to water heating is a heating element connected directly

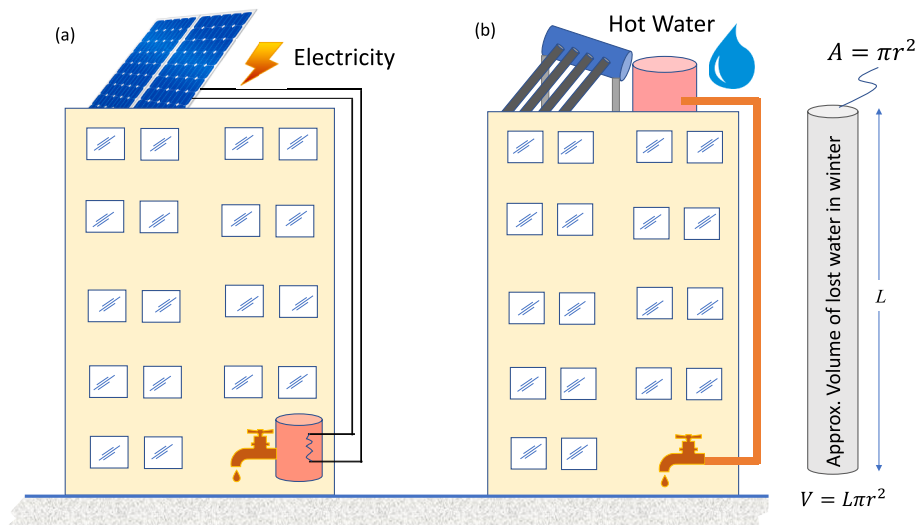


Fig. 1. A schematic diagram showing a comparison between solar PV for water heating (a) and solar thermal system (b) where the water volume in the pipe is a main cause of water losses in winter due to thermal losses.

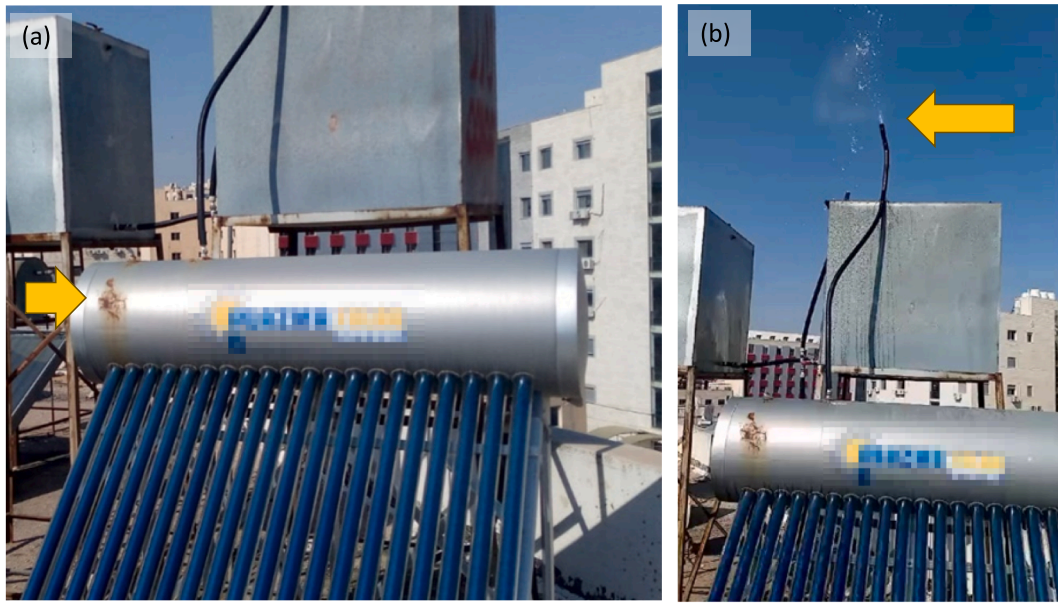


Fig. 2. Installed Solar Vacuum Tube (SVT) heating system with venting mechanism showing some corrosion due to high temperatures (a); and water losses due to steam build up at high pressure (b).

to a PV system by utilizing the generated electrical current from the cells to a heating element installed in a thermal storage water tank. This system of PV water heating system is first proposed by [19]. However, no further studies have comprehensively analysed such systems. Recently several commercial products utilised the idea of using DC-DC converters, [20] presented a modified commercially available water heating tank with a heating element that is connected to PV modules via a DC-DC converter. The DC-DC converter is designed according to the customer PV module size, along with the customized heating element. Another example is presented in reference [21], where a tankless system with fixed 2 kW heating element with embedded MPPT is investigated, which can be directly connected to a PV system.

Due to the nature of varying I-V characteristics of a solar cell in different uncontrollable environmental conditions, maximum power is not always possible for all electrical loads. A maximum power tracker is required to extract the maximum potential of the PV module. Directly connecting the photovoltaic system to any type of load, ideally requires the usage of an MPPT algorithm. There are several methods that track the MPP reviewed by literature [22]. Some of the methods include: considering the tracking techniques as constant parameters, trial and error, mathematical calculation, and intelligent prediction based on available solar power during the day and season. Each of these methods has its own pros and cons. The classical methods, such as Perturb and Observe (P&O), suffer from the constant oscillation around the maximum power point, in addition to the uncertainty of the global maximum power point. The limitations in classical techniques have been resolved using other methods and algorithms, however this will require powerful controllers and memory [23]; which will add to the cost of the system. For example, one of the earlier researched methods suggested using a look-up table [24], which stored the values of the maximum power point voltage V_{MPP} for all possible irradiances and temperature in a database. Nevertheless, this is rarely used due to the large memory requirement for effectiveness of the implementation. Enforcing the reference MPP generated by the MPPT algorithm requires the usage of a DC-DC converter. Many types of DC-DC converter types have been used extensively; converters such as buck, boost, and buck-boost are commonly used. The efficiencies of such converters can vary significantly from as low as 70–99 % depending on the type of the converter, power level and the MPPT algorithm [25]. Reference [26] has compared experimentally between two PV water heating systems, one is directly

connected to a fixed resistance heating element while the second is connected to the same heating element but with a DC-DC converter with an MPPT algorithm and controller. The PV water heating system equipped with the MPPT yielded 20–35 % more energy at the end of the year than its fixed-resistor system counterpart. In the addition, the authors in [26] have also investigated a solar thermal which was found to have the most efficient performance, but it is heavily influenced by the tank temperature and fluid operation. And as discussed above, such systems will need significant maintenance in comparison to PV systems. From the above discussion it can be observed that research is still needed to investigate the use of PV systems to heat water but at reduced system cost and enhance efficiency.

Several optimisation algorithms have been suggested recently. For example [27] suggested an algorithm based on horse herd optimisation MPPT technique; while [28] has suggested an algorithm using Machine learning to increase speed and accuracy of MPPT using real-time data. In [29] a voltage scanning-based MPPT method is suggested. The above algorithms provide reliable MPPT algorithms, however, despite the advancement of the algorithms, the cost of the system was not taken in detailed consideration.

Recent studies have also explored different approaches to optimizing the use of renewable energy sources for heating and power management. For instance, Authors investigated advanced control strategies and energy management schemes for photovoltaic and renewable-based systems under varying climatic conditions. Although their focus differs from the present work, these studies further emphasise the importance of adaptive control and optimisation methods to enhance the overall efficiency and reliability of renewable energy applications [30,31].

In this paper, a novel PV water heating system is proposed with a novel control MPPT system. The system does not require a DC-DC converter or battery for energy storage. It uses simple static and electro-mechanical switches to obtain the equivalent resistance that will optimise the power as ideal as possible. The proposed system with its simple electronic circuit and the lack of batteries means a much lower cost for the system hardware and installation, for both as new and retrofitted systems. This cost is also much lower to install and maintain in comparison to solar thermal systems. The adoption of such a system has facilitated the exploration of another crucial factor: a comparative analysis of water loss between the proposed electricity-based heating system and solar thermal systems. This investigation holds particular

significance in Jordan, given its status as being in one of the most water-scarce regions.

2. Methodology and system description

The proposed system was simulated using MATLAB/Simulink and then validated experimentally. The overall schematic diagram of the proposed system and its components is shown in Fig. 3, the PV arrays, a customized heating element with dual heating resistors, and switching circuit.

2.1. Photovoltaic system

The photovoltaic system shown in Fig. 1 is made of serial and parallel modules depending on the required voltage and current. The building block of the PV module is the solar cell shown in Fig. 4, which mainly consists of an ideal current source (I_{ph}), anti-parallel diode, shunt resistor (R_{sh}), a series resistor (R_s), and the equivalent load resistance (R_L). Each of the lumped circuit parameters models the characteristic behaviour of the solar cells [32]. Analytically the PV solar cell-generated current is described by the equation:

$$I = I_{ph} - I_D - I_{sh}$$

$$= I_{ph} - I_0 \left(e^{\left[\frac{V + IR_s}{V_T} \right]} - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

where, I_0 is dark saturation current, V ; R_L is the load voltage and equivalent resistance; V_T is the thermal voltage; and I_{ph} is the light-generated current. The thermal dependence on the temperature is neglected in this module due to the fact that the application will have low accuracy in tracking the MPPT, as will be later discussed. While the photogenerated current at time instant t is given by:

$$I_{ph}(t) = [I_{sc}^* + k_i(T(t) - T^*)] G(t)/G^* \quad (2)$$

where I_{sc}^* is the short circuit given at the standard test conditions at irradiation of $G^* = 1000W/m^2$ and cell temperature $T^* = 25^\circ C$. The PV module data reported in Table 1 are used to build up the PV array configuration shown in Fig. 1 with two strings of two series connected modules.

The high-fidelity MATLAB/Simulink PV array block model is used in this evaluation study. In order to choose an appropriate load resistance for the system, it is important to analyse our location's irradiation data.

The analysis has carried a location in Amman, Jordan, as the obtained result in this paper will be validated experimentally in comparison to an already installed solar system. Extracting the solar data is conveniently available from the European Commission website [33], see Fig. 5. The downloaded irradiation data was chosen for a fixed installation with a slope of 27° and an azimuth angle of 0° facing the south. A boxplot is shown in Fig. 3 using the average hourly irradiation for a year in Amman, Jordan. As noticed, the PV window starts from 5 AM until 4 PM in a total of 12 sunny hours. The upper four median points are selected from the hourly data being $1000W/m^2$, $767W/m^2$, $550W/m^2$, and $300W/m^2$. The chosen irradiation points are used as a reference point to find the P-V characteristic of the PV array, as shown in Fig. 6.

2.2. Heating elements

The proposed system is designed to produce heat from electricity generated from the PV array directly via typical immersion heating elements without the usage of converters. In order for the system to track the maximum power point, the heating elements are designed to have different rated power and are connected in different combinations of serial and parallel connections to provide several values of equivalent resistance. Thus, a form of tracking the maximum power is achieved. The graph in Fig. 4 shows P-V characteristic curves based on the average amount of solar radiation in Jordan. It is clear that the maximum power equivalent resistance is not the same for all levels of solar radiation. Instead, it changes depending on the specific amount of solar radiation and the temperature of the solar cell. However, the highly accurate tracking of the maximum power point is not possible with fixed resistors, even with the effect of change in temperature is ignored. As the working principle of the heating elements is to produce heat through the process of joule's law, by passing a current through a resistor, they are modelled as pure lumped resistors. It is possible from Fig. 4 to calculate the equivalent heating elements resistance needed to maximize the extraction of power at the median points using the equation:

$$R_i = \frac{P_i^2}{V_i} \quad (3)$$

where R_i is the equivalent resistance to achieve the maximum power P_i at voltage V_i for the chosen median irradiation i . Eq. (3) yields the following resistances: $R_{p1} = 3.9\Omega$, $R_{p2} = 5\Omega$, $R_{p3} = 6.9\Omega$ and $R_{p4} = 12.4\Omega$. While the possibility of designing fitting heating elements with the given specification is viable, obtaining all of the four calculated values using two switches at the same time is difficult, as will be

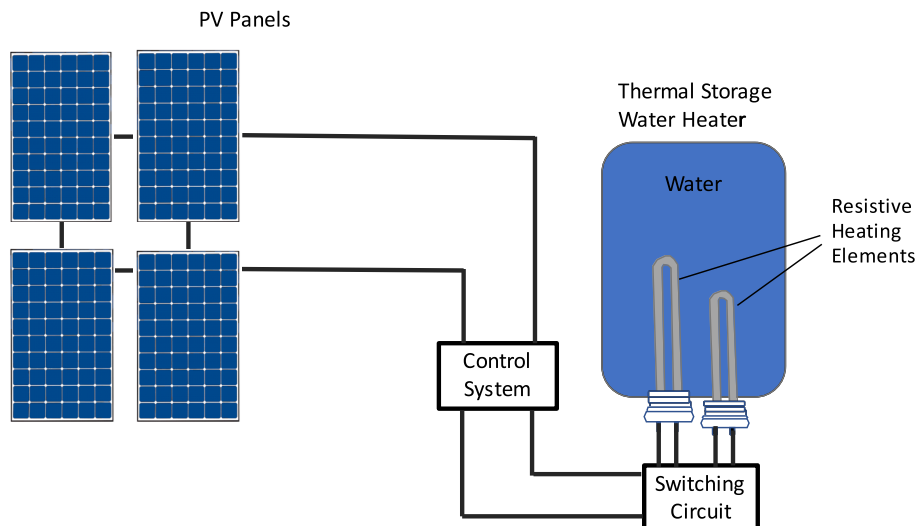


Fig. 3. Proposed PV water heating system with a novel control MPPT switching circuit.

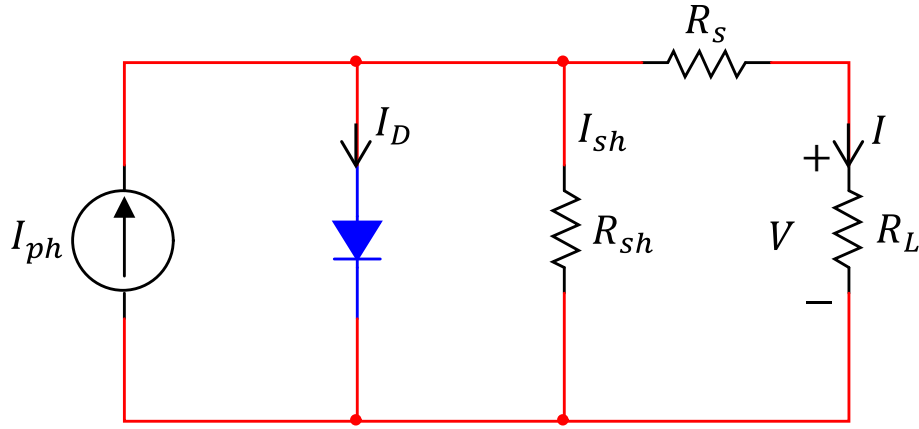


Fig. 4. Solar cell electrical model.

Table 1

Solar Module data, based on data from [26].

Symbol	Parameter	Value
P_{max}	Rated Maximum Power	455W
V_{oc}	Open circuit Voltage	49.8V
I_{sc}	Short circuit Current	11.65A
V_{mp}	Voltage at Maximum Power	41.6V
I_{mp}	Current at Maximum Power	10.93A
k_i	Current Temperature coefficient	0.050%/°C
k_v	Voltage Temperature coefficient	-0.350%/°C

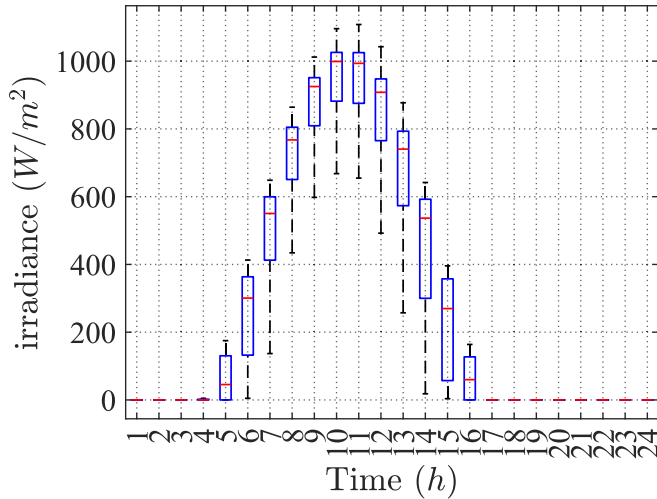


Fig. 5. Jordan irradiance data.

discussed in the following section.

The resistive heating elements are expected to work between a temperature range from about 5 °C to 80 °C. To assess the effect of temperature variation during operation, the expected change in resistance is estimated using the material's temperature coefficient from the manufacturer for a typical operating temperature rise of 75 °C, this corresponds to a resistance increase of about 3 %, which has a minor influence on the overall power matching with the PV module. Hence, the resistive elements can be considered approximately constant for the purposes of the Near-MPPT control strategy. For example, for the resistor of 5.5 Ω and 11 Ω, the variation will only be circa 0.165 Ω and 0.33 Ω respectively.

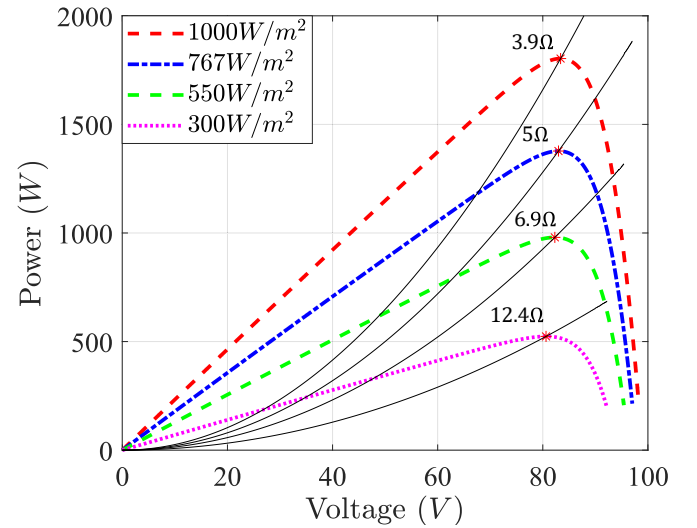


Fig. 6. P-V characteristic curves under several irradiances.

2.3. Switching circuit

The proposed switching circuit in this work, shown in Fig. 7, is to achieve three objectives: (a) to provide the maximum number of equivalent resistance configurations using a minimum number of switches and resistive loads to maximise power output; (2) to disconnect the DC voltage of the PV array for reliability during switching; and (3) to achieve the main objective of reduced cost. In order to meet the objectives, four main switches are used in the design, namely S_1 , S_2 , S_g and S_m as shown in Fig. 5.

The switches S_1 and S_2 are single pole double throw (SPDT) switches specified with low internal resistance. The switch S_m is a static semiconductor MOSFET switch used to connect or disconnect the PV-DC voltage, which is in parallel with the S_g switch. Where S_g switch is an electromechanical relay to provide an alternative lower resistive path for the DC current. The S_m is a static semiconductor MOSFET is designed to prevent contact sparks on S_g when switched on or off. And the S_g switch is the main switch to disconnect S_1 and S_2 when changing the load values.

The relay operates at a low switching frequency since load changes occur only during significant irradiance variations. The MOSFET (S_m) suppresses contact sparking during DC switching, which is essential because such sparks can damage relay contacts within a few cycles. By nearly eliminating sparking, the relay's electrical wear becomes negligible, and its lifetime is limited only by its mechanical durability.

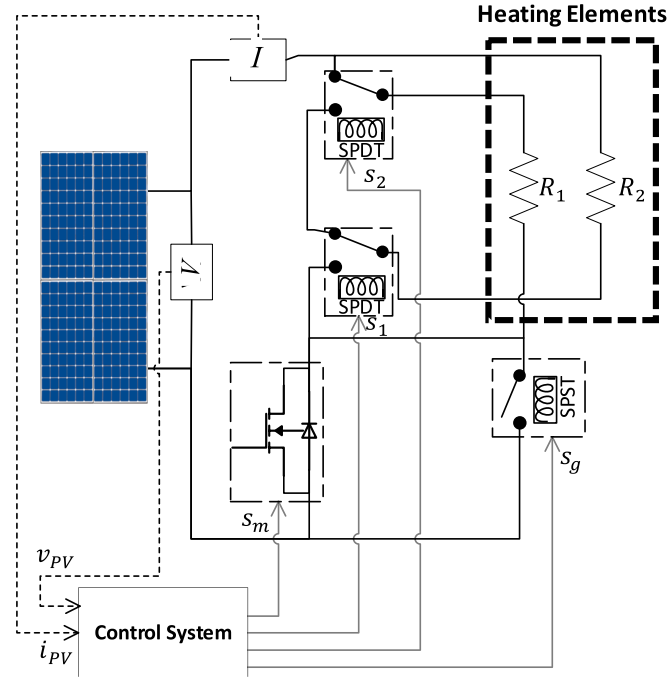


Fig. 7. The proposed system's block diagram.

Commercial relays typically provide an electrical lifetime of about 100,000 cycles at maximum current and a mechanical lifetime exceeding 500,000 cycles. Given the low switching rate in the proposed system, the relay lifetime is expected to be determined solely by its mechanical rating, ensuring reliable long-term operation.

The presented circuit topology can provide up to four equivalent resistances by manipulating the current direction using the two SPDT switches. The four configurations are illustrated in Fig. 8, where from the point PV connection, it is possible to have the following configurations ordered in an ascending ohmic value: $R_{con1} = R_1 // R_2$ (Fig. 6-a), $R_{con2} = R_1$ (Fig. 6-b), $R_{con3} = R_2$ (Fig. 6-c) and $R_{con4} = R_1 + R_2$ (Fig. 6-d).

Due to the fact that obtaining all of the suggested values from the previous section ($R_{p1}, R_{p2}, R_{p3}, R_{p4}$) is not feasible. A trade off must be considered, while giving more priority to R_{p1} and R_{p2} to maximize the amount of power extracted from the higher irradiation values. In this

paper two heating elements are used with the equivalent resistance of $R_1 = R_{con2} = 5.5\Omega$ and $R_2 = R_{con3} = 11\Omega$; by the usage of the switching circuit the first configuration and fourth are obtained: $R_{con1} = R_1 // R_2 = 3.7\Omega$ and $R_{con4} = R_1 + R_2 = 16.5\Omega$. The parallel connection of the switches S_g and S_g is used to exploit the low resistive path of the electromechanical relay and the DC voltage disconnection capability from the semiconductor switch simultaneously; the circuit working process is discussed in the next section. Further details on the generic method of selecting the values will be discussed in the following sections.

The variation in power occurs due to the change in solar irradiance or temperature changes, in either case, this change will present itself as a total power variation in the output of the solar panel. And regardless of the cause of the power change, the tested range of the solar power should be sufficient to cover the expected power variation.

2.4. Control algorithm

The main objective of the control algorithm is to maximise the power extracted from the PV system. As shown in Fig. 5, the control system produces four control signals for each of the switches. The control is designed to disconnect the DC voltage of PV array using the MOSFET switch S_m before attempting to modify the configuration using the switches S_1 and S_2 . Finally, S_g is connected once the proper configuration is used to provide a lower resistance path. The selection of the suitable equivalent resistance configuration is made based on the range of the expected power, as shown in Table 2. The threshold limits are extracted from the power generated based on an average irradiance day in August. As shown in Fig. 7, the control system should select the corresponding configuration that matches the outer envelope for the fixed resistor values. However, this method does not compensate for the temperature variance in the cells, which is needed for precise MPPT techniques. This is justified due to the fact that the available resistive

Table 2
Power ranges of different heating elements configuration.

Irradiance (W/m^2)	Configuration	Equivalent resistance (Ω)	S_1	S_2	Power (W)
> 873	$R_1 // R_2$	3.7	OFF	OFF	>1444
628–873	R_1	5.5	ON	OFF	734–1444
281–628	R_2	11	OFF	ON	449–734
< 281	$R_1 + R_2$	16.5	ON	ON	<449

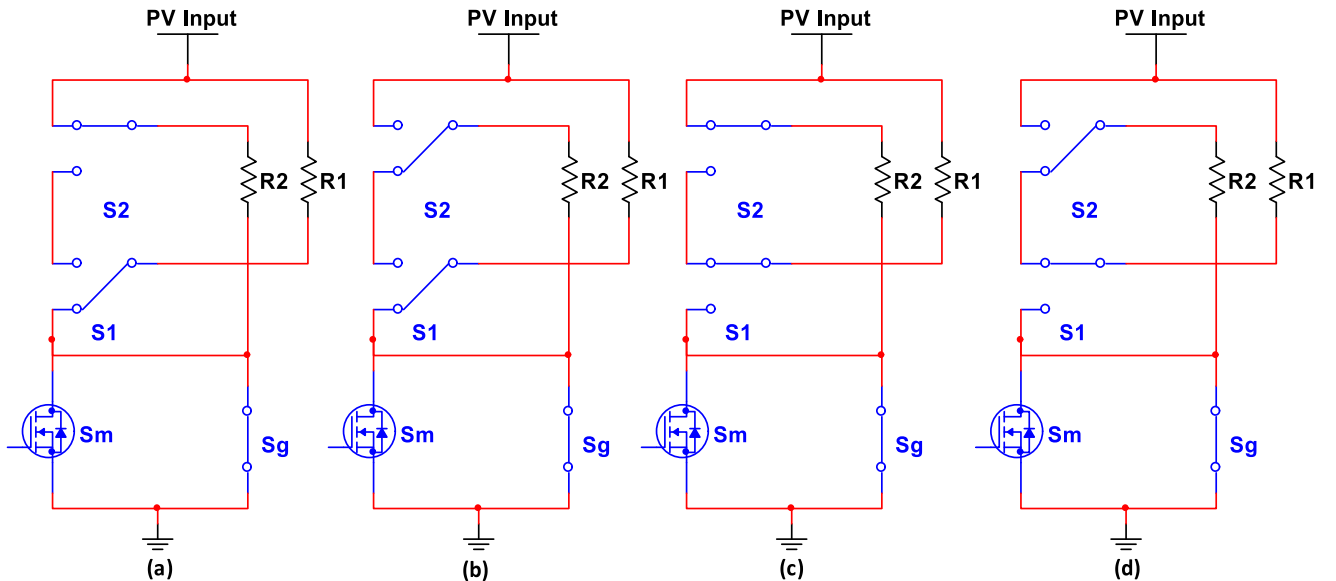


Fig. 8. Configurations maintained by switching circuit: (a) $R_1 // R_2$. (b) R_1 . (c) R_2 . (d) $R_1 + R_2$.

load configuration has only four discrete steps. The extracted threshold power values at which the configuration with more yielding power are illustrated in the zoomed portion of Fig. 9 and reported in Table 2 which includes power ranges of different configurations of heating elements. The algorithm simply measures the power of the active configuration at the discrete time step k and decides to stay in the same configuration or to set other configuration depending on the threshold values as explained in the main flow chart in Fig. 8. The subroutine in the flow-chart of Fig. 9 shows the process of safely switching between the configurations. The S_m is a static semiconductor MOSFET is a parallel switch designed to prevent contact sparks on S_g when switched on or off. And the S_g switch is the main switch to disconnect S_1 and S_2 when changing the load values. The MOSFET frequency is relatively very slow as is based on the change in light intensity only. The MOSFET is there only to protect the relays and the circuit when changing the configuration between the resistors (to prevent sparking on the relay contacts). Hence, the MOSFET here works completely in a novel way in comparison to standard switching circuits. The frequency is normally in minutes on average. This change happens based on Table 2. Depending on the value range, switches will be open or closed to provide the resistance that will maximise the power, as presented in Table 2. S_m is the main switch that should be switched off before switching S_1 and S_2 to avoid damage to the contact due to sparking.

The control logic relies on real-time PV power measurements rather than pre-defined voltage or temperature models. Therefore, any temperature-induced variation in PV performance is inherently reflected in the measured power, allowing the system to automatically select the optimal configuration without explicit temperature compensation.

As shown in Fig. 10a and Fig. 10b, the voltage and current are measured by the controller, from which the power is calculated based on solar energy from the PVGIS website for different locations (see Fig. 11).

2.5. Water loss

The ongoing investigation seeks to validate the efficiency of heating systems incorporating photovoltaic panels by examining not only the energy generated but also the energy consumed for household purposes. One significant contributor to energy wastage is the heat lost in the pipelines linking the hot water tank to the taps, see Fig. 1. To assess this, a water flow rate sensor was deployed at the primary pipeline along with an Omega data logger (OM-CP-PULSE101A). Temperature measurements were conducted using thermocouples in conjunction with an Omega data logger (OM-CP-TC101A), strategically positioned near the taps. This experimental setup was implemented in two residences: one equipped with an evacuated tube heating system mounted on the roof

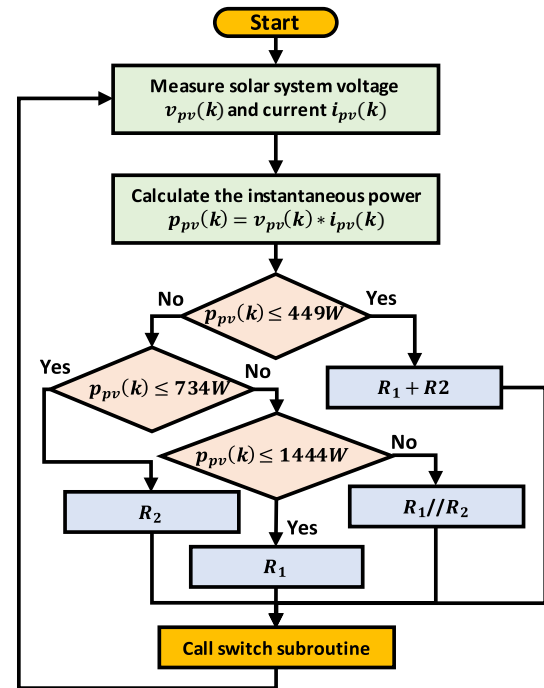


Fig. 10a. Main program flowchart to maximise power output from solar panels.

(see Fig. 1), situated five floors above, and the other employing electric heating (see Fig. 18), located at the same vertical distance.

2.6. A generic method for selecting the values of the heating elements

This section highlights the generic methodology suggested in this paper to decide on the values of the resistors at different global locations for Near-MPPT solar energy applications. Fig. 1 presents the locations discussed in this paper, namely Jordan (Amman), Egypt (Cairo) and UK (Nottingham).

As will be described and discussed in detail in the following sections, the methodology is based on using two resistors. The choice to use only 2 resistors to develop the Near-MPPT system is primarily due to the simplicity in the design and mechanical and physical constraints of most water heaters. Most existing household electric water heaters use a 1.25 in. pipe coupling or similar, making it challenging to design a system

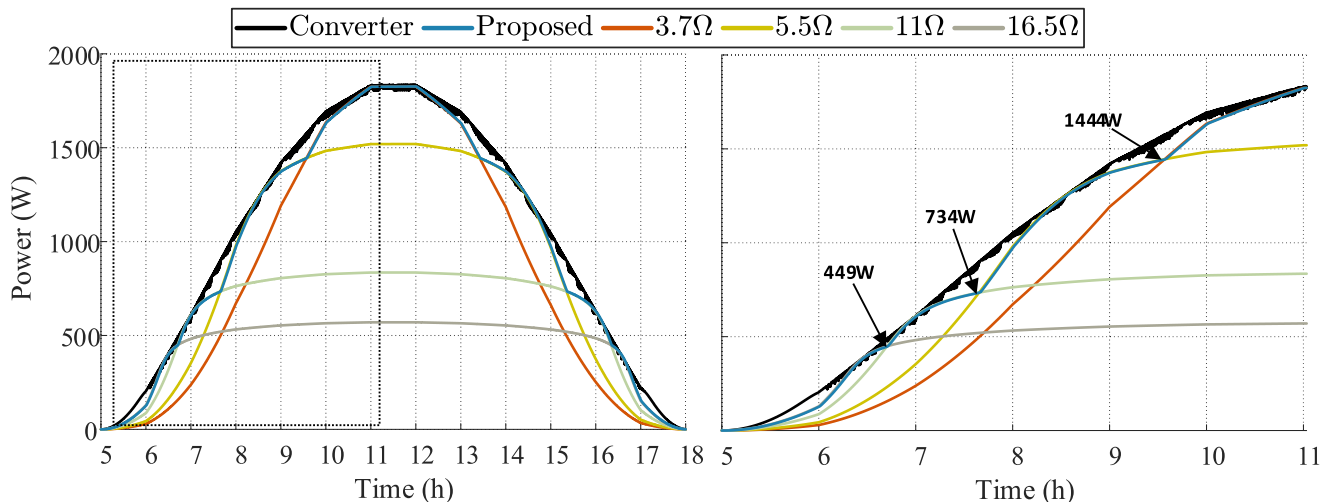


Fig. 9. Power produced from a PV array on an August day showing the ideal curve, typical MPPT system, four fixed resistive values, and the proposed system.

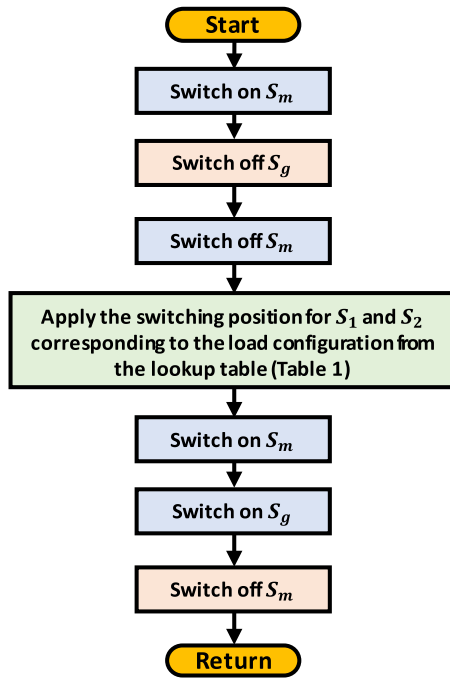


Fig. 10b. Subroutine flowchart for safe switching.

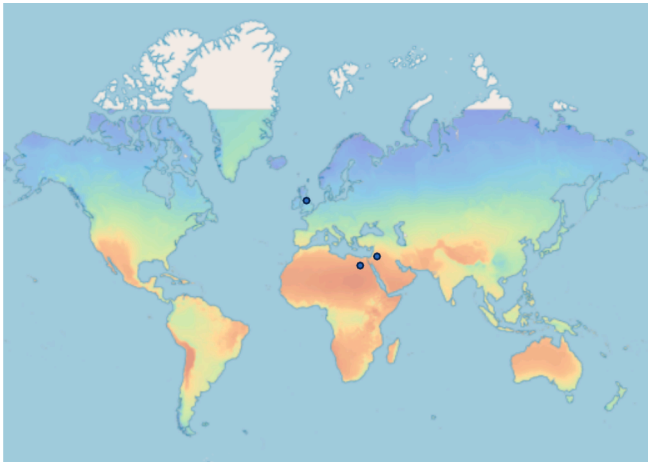


Fig. 11. The average annual solar energy with the selected countries (Based on PVGIS [34]).

with three heating elements (resistors). Additionally, incorporating more resistors would significantly increase the complexity and cost of the control circuit and the hardware. For instance, using 3 resistors would allow for 13 different configurations, potentially achieving greater precision and efficiency compared to the simpler design. However, this approach would require 6 electromechanical relays for switching between configurations and a 7th relay to disconnect the circuit during transitions, please see Appendix C. This would increase both the complexity, reduce reliability and the cost of the system; particularly that the lost energy is minor for the two resistors Near-MPPT system in comparison to an ideal MPPT system (circa 3.8 %).

The research initially considered the location of Jordan, experimentally and in the simulation process, and then a generic methodology was adopted where the values of the resistors are adjusted based on the location to optimise Near-MPPT performance. The optimum resistor values are determined for its solar conditions to maximise power in Jordan using two resistors, in this case they were 11 Ω and 5.5 Ω for R_1

and R_2 respectively. According to PVGIS data, Jordan has a solar irradiation rate of 4400 W/m²/day. Appropriate resistor values for other locations can be calculated based on the following method.

For the two resistors and to create suitable values, the second resistor is assumed to be 50 % of the first resistors, mathematically:

$$R_2 = 0.5 R_1 \quad (4)$$

For Jordan (Amman), the GPS location is approximately 32.06° North and 35.87° East, and hence the optimum values, as discussed above are found to be 11 Ω for R_1 and 5.5 Ω for R_2 . The GPS locations is approximately indicated where the exact location of the building is kept anonymous due to the ethical approval process.

For any other location, the value of R_1 will change based on a new factor, k , named Resistor Optimization Factor, where k_i is defined for location i as:

$$k_i = \frac{\text{Average annual solar irradiation at } (32.06^\circ \text{N and } 35.87^\circ \text{E})}{\text{Average annual solar irradiation at location } i}; \quad (5)$$

hence,

$$R_{1i} = k_i * R_1; \quad (6)$$

where:

$$R_{2i} = 0.5 * R_{1i}. \quad (7)$$

For Egypt (Cairo) for example,

$$k_i(\text{Cairo}) = \frac{4400}{4600} = 95.6\%; \text{ hence } R_{1i}(\text{Cairo}) = 0.956 \times 11 \Omega = 10.52 \Omega \approx 11 \Omega \quad (8)$$

Hence for Cairo (Egypt), similar values as Amman (Jordan) can be used.

However, for example for the UK (Nottingham), the solar irradiation is 1800 W/m²/day; hence:

$$k_i(\text{Nottingham}) = \frac{4400}{1800} = 244.4\%; \text{ hence } R_{1i} = 2.44 \times 11 \Omega \approx 27 \Omega \quad (9)$$

$$R_{2i}(\text{Nottingham}) = 0.5 \times 26.8 \Omega \approx 13 \Omega \quad (10)$$

The use of Jordan, UK, and Egypt as case studies for our analysis is mainly to explain the methodology and engage the reader in practical applications. However, the methods can be used in any location. The resistor selection method presented in Section 2.6 is indeed generic and can be applied to any global location. The section describes a Resistor Optimization Factor (k), which scales the resistor values according to the average annual solar irradiance of any site. This mathematical formulation allows adaptation to other climatic conditions beyond Jordan, Egypt, and the UK.

3. Results

This section includes the simulation results and the experimental validation. Jordan was selected to conduct the experimental work to validate the simulation. And once this is achieved, the simulation process is continued for Egypt and UK as two additional implementation case studies.

3.1. Simulation results

In order to validate the proposed system, a MATLAB/Simulink models of three systems, as shown in the schematic diagrams of Fig. 12, are developed. Fig. 12-a, is the conventional system equipped with standard perturb and observe MPPT algorithm applied via a boost DC-DC converter; and for the sake of simplicity we refer to the second system as *converter*. The second system in Fig. 12-b is the proposed novel

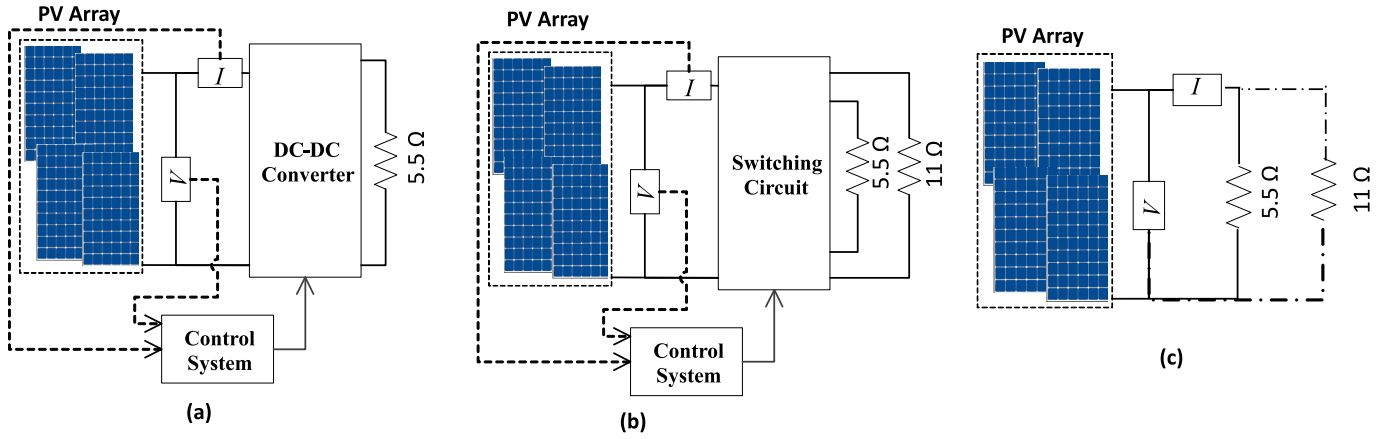


Fig. 12. System block diagram: (a) conventional (converter), (b) proposed (switching) and (c) fixed resistors.

system as detailed in previous sections. The first system, finally, Fig. 12-c is the simple and directly connected uncontrolled system where the heating elements are directly connected to the PV array terminals with fixed load values. In this study, the directly connected system is simulated with the heating elements rated at 5.5Ω and 11Ω connected individually and in parallel while the series connection is dropped out of this comparison study due to its expected low relatively overall production of energy due to the increase in resistance.

The PV array for the three systems contains identical four $455W_p$ PV modules of Monocrystalline Silicon with the specification shown in Table 1 [35], where the modules provide total peak power of $1820W_p$. The array configuration has an open voltage of 98.6 V and 83.2 V at maximum power point. The maximum current at $1000W/m^2$ and can reach up to $23.3A$. The common components between the three systems are the PV arrays and heating elements. For the PV array, it is simulated

using a high-fidelity model written in MATLAB. While the heating elements required resistance ($R_1 = 5.5\Omega$ and $R_2 = 11\Omega$); in reality this can be obtained by modifying the length of its metal rod which is available from suppliers based on the needed specifications. The heating elements can be fitted into a standard electric thermal storage tank by customizing its flange. For that purpose, the simulation uses simply standard lumped resistors in order to be applied in the real world with no complexity.

Fig. 13 shows the power generated for the proposed system against the standard converter system and fixed system with 5.5Ω for an average day for each month, taking Jordan as a case study. The power of the standard converter system is found to be on the outer envelope and the inner curve are for the proposed system. As illustrated for March as it can be noticed the threshold values that are extracted from August gives an ideal performance in comparison to the rest of the months. As can be

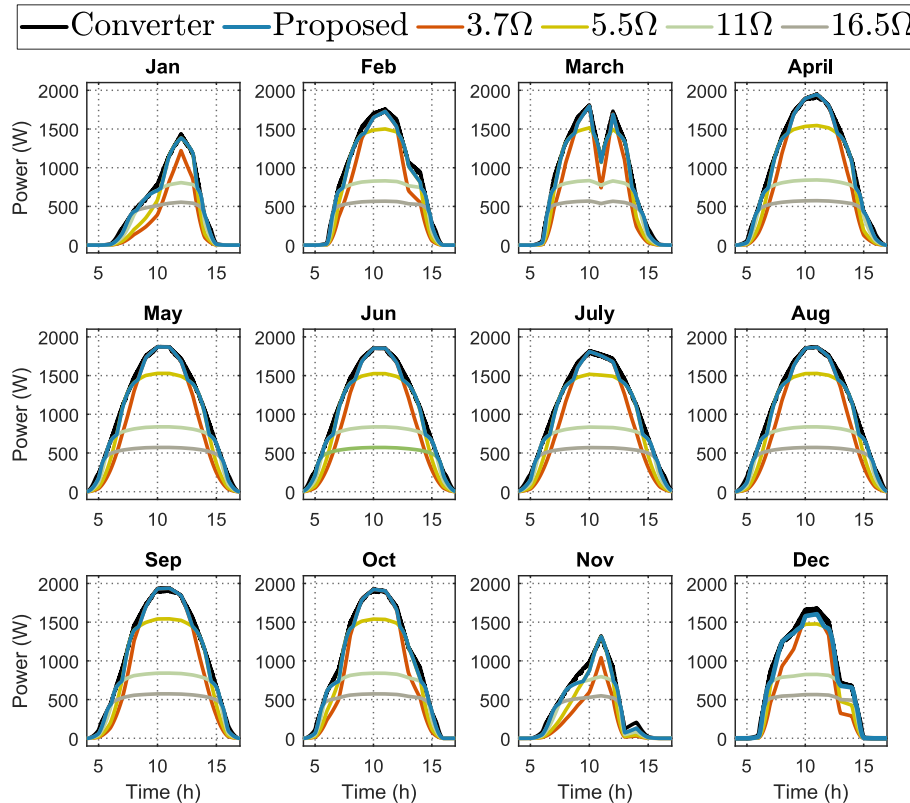


Fig. 13. Power generated for the converter, proposed and fixed resistors systems for an average day in each month, taking Jordan as a case study.

expected, the proposed system shows a loss of potential power, as indicated in the power levels between 500W and 1000W in each of the presented months. In addition, the proposed system fails to extract the maximum power at around the peak irradiation time at around noon time ($t = 12h$) for Feb and Nov. However, the system shows a loss of potential power for small gaps with respect to the total extractable power of the converter system.

Fig. 14 shows an analytical comparison between the three systems, where the monthly total energy is plotted which is generated by the conversional DC-DC converter, proposed, and fixed systems. For comparison purposes, the fixed system is simulated with 3.7Ω , 5.5Ω and 11Ω . The converter yields the highest monthly produced energy among all other simulated profiles, followed closely by the proposed system. As for the fixed system, it is noticed that the fixed resistance value of 5.5Ω produces higher energy for all months compared to 3.7Ω and 11Ω , especially at low irradiance months, as Jan., Feb., Nov., and Dec.; while the fixed resistance value of 3.7Ω has a higher produced energy for 10 months it produces less energy in Dec. and Jan. compared to the energy produced by the 11Ω fixed system. Fig. 15 shows a clearer numerical comparison between the simulated systems where it outlines the monthly percentage difference in the produced energy between the proposed system against the converter system and 5.5Ω fixed systems. As can be noticed from the Fig. 15, the proposed system produces, in the worst-case scenario, 5.20 % percent less energy when compared to the conversional MPPT converter system in January. The yearly total energy produced using the proposed system is $3.98 \times 10^3 kWh$ when compared to the converter system with $4.14 \times 10^3 kWh$ resulting a yearly difference of about 3.86%. However, the benefit of installing the proposed system against the best-fixed resistor value of 5.5Ω is proven to yield more monthly energy ranging from 9.5 % to 11.5 % depending on the month, as shown in Fig. 15. In total, the proposed system produces more yearly energy of about 14.10% from the fixed system at $3.51 \times 10^3 kWh$.

3.2. Experimental validation

Fig. 16 illustrates the three different configurations that have been investigated. The Proposed system in configuration (B) of the switching

circuit was compared with traditional inverter shown in configuration (A) and compared with fixed load resistor shown in configuration (C). The three configurations were simulated to investigate the power output for comparable systems with similar solar panel size. The fixed load configuration included two separate sub-configurations 5.5Ω and 11Ω heating element resistors. The simulation was done in three countries, Jordan, UK, and Egypt. The system was experimentally validated in Jordan using the three main configurations were the fixed load including the two sub-configurations.

This research work implements inverters that are common and commercially available for cost and practical reasons.

The influence of temperature on the power output of photovoltaic (PV) panels is well established; nevertheless, this factor has been implicitly addressed within the scope of the present study. The developed work focuses primarily on the proportion of power captured relative to the maximum available power, which can be affected by variations in either solar irradiance or temperature. In both cases, the proposed Near-MPPT system is designed to respond dynamically to power fluctuations, irrespective of their underlying cause. Furthermore, the temperature-induced reduction in PV output would impact all configurations (A, B, and C, as illustrated in Fig. 16) in a comparable manner. Therefore, varying the power level in the simulation effectively represents the influence of both irradiance and temperature changes on system performance. Accordingly, the simulation model spans the entire operational power range from zero to the maximum possible value; thereby encompassing all potential environmental variations.

The experimentation of the proposed system, see Fig. 17, involved the utilisation of four photovoltaic (PV) panels, each boasting a capacity of 455Wp. Additionally, a heating element with dual threads and a sophisticated control circuit, depicted in Fig. 17, were employed. The PV panels were organized in pairs, with each pair connected in series. The resulting series connections of the two pairs were then joined in parallel, yielding an output of approximately 83 V at the maximum power point.

The heating element, as previously mentioned, featured two thread values, namely 5.5Ω and 11Ω . The key components comprising the control circuit included two double-throw relays, a current sensor, an Arduino Nano Microcontroller, a MOSFET, and barrier terminals facilitating the connection of all sources and loads to the printed circuit

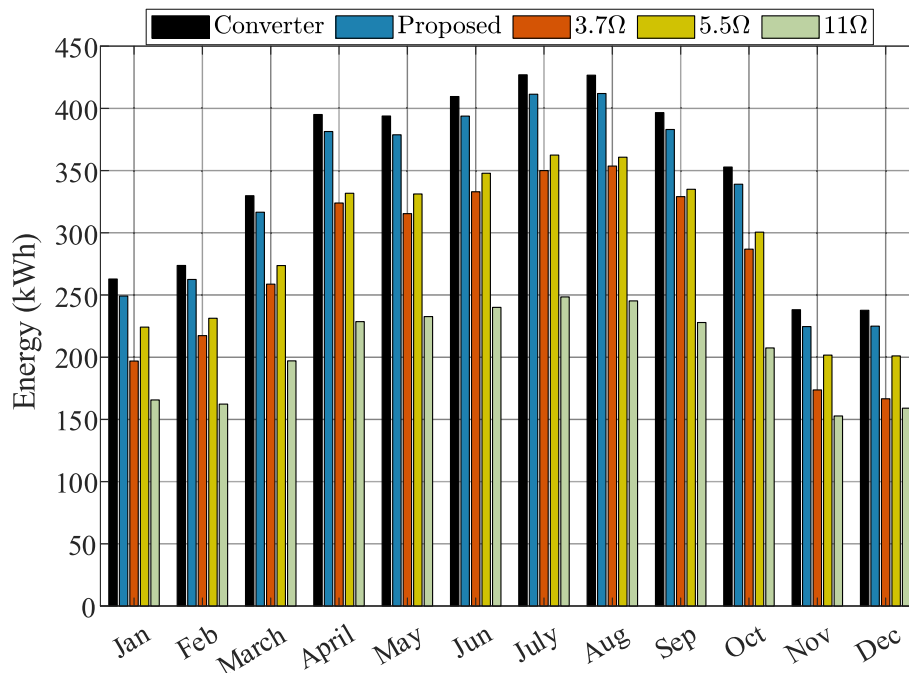


Fig. 14. Monthly produced energy for a conventional MPPT system with a converter, proposed, and directly connected system with fixed resistors of 3.7Ω , 5.5Ω , and 11Ω .

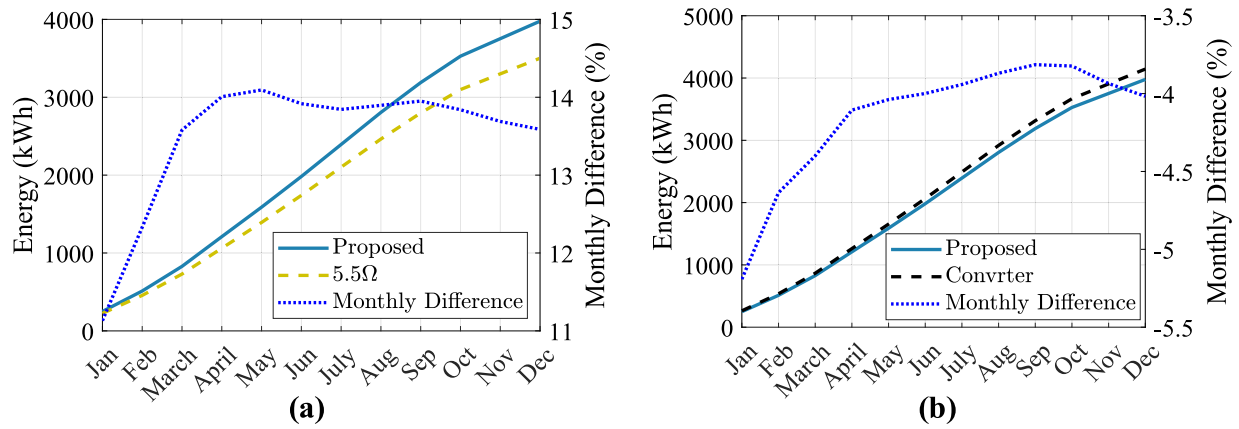


Fig. 15. Percentage difference and accumulative monthly produced energy for (a) proposed system against converter; and (b) proposed system against fixed 5.5Ω.

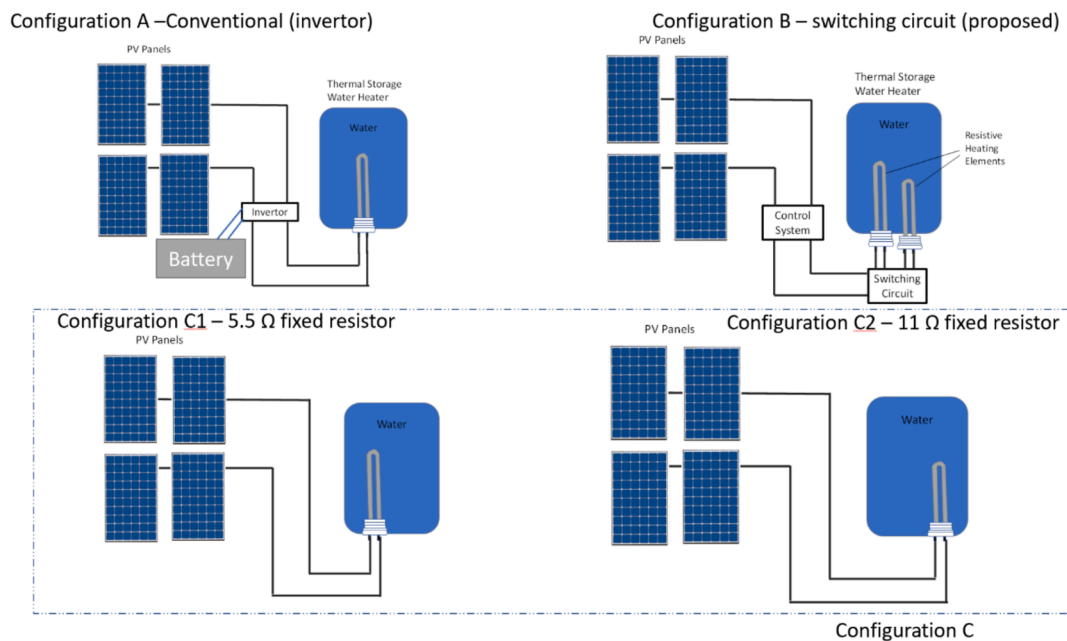


Fig. 16. The three different configuration: (A) Conventional (inverter), (B) switching circuit with dual heating elements (Proposed), and (C) using single fixed heating element with two different values.

board (PCB).

A comparison was conducted among four systems: the 5.5 Ω, the 11 Ω, the proposed (Switching), and the conventional system. The conventional system was exemplified by a 3000-watt MPPT hybrid off-grid solar inverter equipped with a charge controller and four batteries of size 12 V/100A Gel type.

This clarification has been added to the paper.

Data loggers for each system involved the use of two synchronized voltage data loggers (OMEGA-OM-CP-VOLT101A) to record both voltage and current. The conversion of current to voltage was achieved through the utilization of a shunt resistor. A high level of precision in the data was ensured by collecting records at 10-second intervals. The experimental tests were conducted in November, a period characterized by relatively low solar radiation levels.

Fig. 18 illustrates the average daily power generation in November for the four systems. The data align with expectations based on simulation results, showcasing the anticipated ranking of power generation across all systems. Notably, both the fixed resistors and the proposed system exhibit greater fluctuations compared to the conventional MPPT converter system. This discrepancy arises from the finer power tracking

capability of the inverter in contrast to the proposed system, which is limited to four configurations for maximizing power generation. Furthermore, it's evident that the curve representing the 5.5 Ω configuration is narrower from the base than the others, while the conventional system's curve is the widest.

Fig. 19(a) depicts the total energy generated (kWh) throughout November. Specifically, for the conventional system, the total energy amounted to 240 kWh, while it reached 210 kWh for the proposed system. In comparison, the 5.5 Ω fixed resistor system generated 165 kWh, and the 11 Ω fixed resistor system produced 131 kWh. These values are further contextualized by comparing them to the conventional system, as shown in Fig. 19(b). In November, the proposed system demonstrated a 12.5 % reduction in energy production compared to the conventional MPPT converter system under the worst-case scenario. Additionally, the best-fixed resistor configurations, 5.5 Ω and 11 Ω, generated 31 % and 45 % less energy, respectively, in comparison to the conventional (converter) system.

Fig. 20 presents a comparison between experimental and simulation results for November. Notably, the results for the MPPT converter demonstrate a close alignment between experimental and simulated

This clarification has been added to the paper.

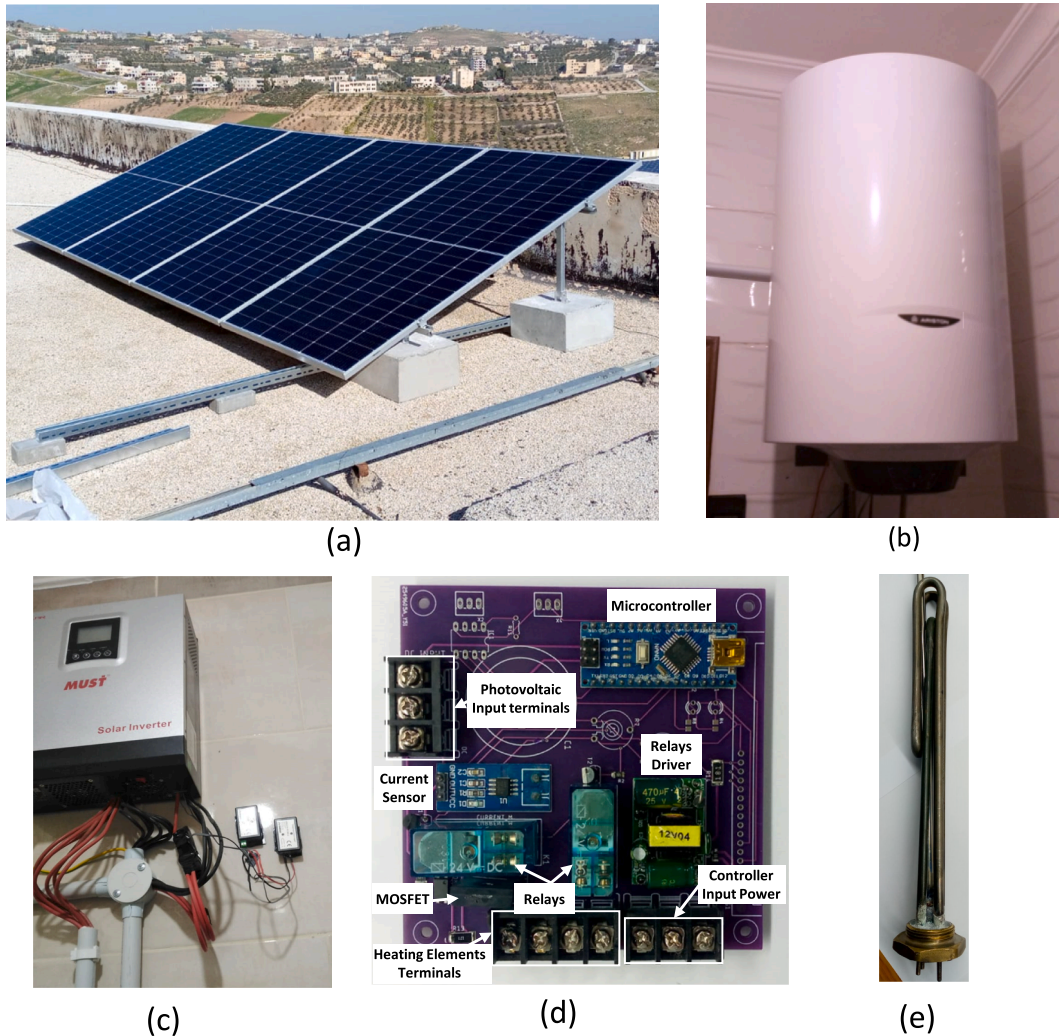


Fig. 17. Key components of the experimental work (a) PV panels, (b) the thermal storage, (c) the converter, (d) control unit and (e) Dual thread heating element.

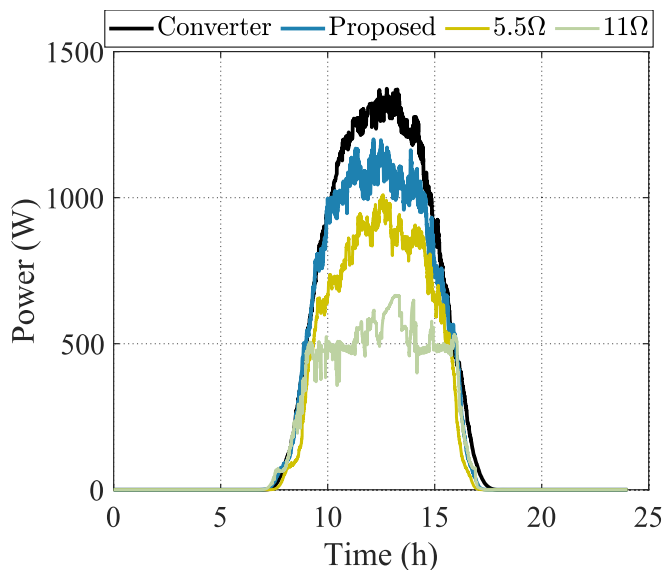


Fig. 18. Experimental average power generated per day in November in Jordan.

data. However, discrepancies between experimental and simulated results are more pronounced for other systems. Interestingly, the proposed system exhibits smaller differences compared to systems utilizing fixed resistor values.

When looking at the results, the lower the value of the resistance of the heating element, the higher the mismatches. This discrepancy can be attributed to an increased mismatch between the load resistance and the internal resistance of the photovoltaic cells.

Upon comparing the fixed resistor values of $5.5\ \Omega$ and $11\ \Omega$, it's evident that the $5.5\ \Omega$ configuration displays larger disparities. This discrepancy can be attributed to increased mismatch between the load resistance and the internal resistance of the photovoltaic cells. It's worth noting that simulation results are based on average solar radiation per hour, mitigating mismatch rates compared to practical experimental data gathered at 10-second intervals, which heightens the likelihood of mismatch. To further elucidate this phenomenon, with a fixed load connected to a PV panel, variations in irradiation will lead to fluctuations in the panel's output power. These fluctuations may not follow a perfectly proportional pattern due to the nonlinear behaviour of PV panels. The significance of this outcome becomes even clearer when examining simulation results, particularly under heavy loads like $3.7\ \Omega$, as depicted in Fig. 18. Although heavier loads may produce more heat (power), they ultimately yield less energy over the course of a year, as evidenced by the hourly data upon which these results are based.

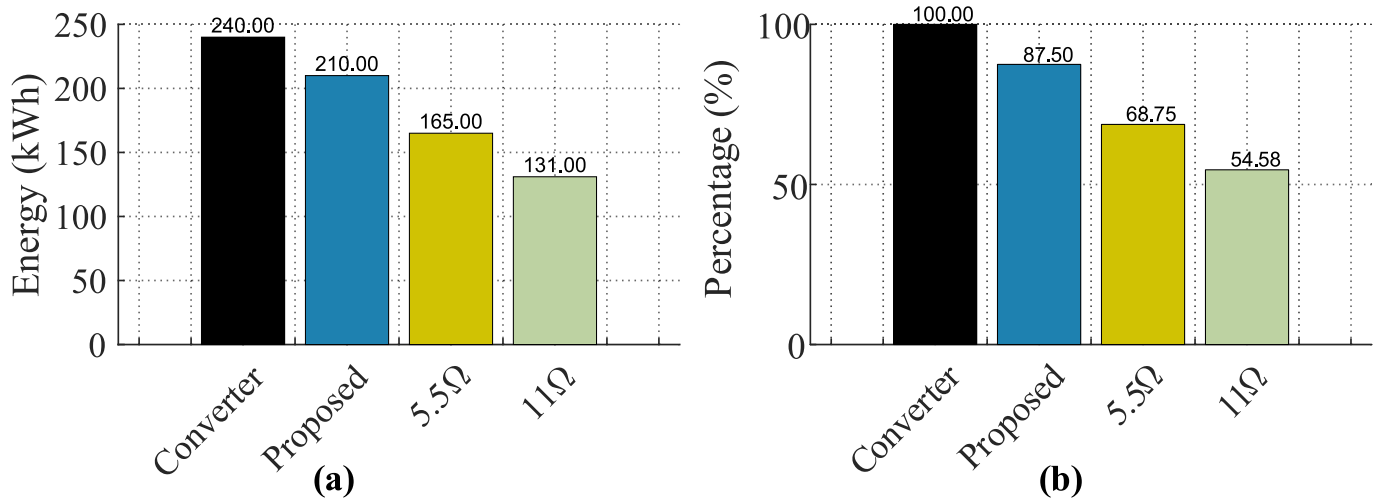


Fig. 19. Total energy generated for each configuration in kWh and in percentage relative to the converter system.

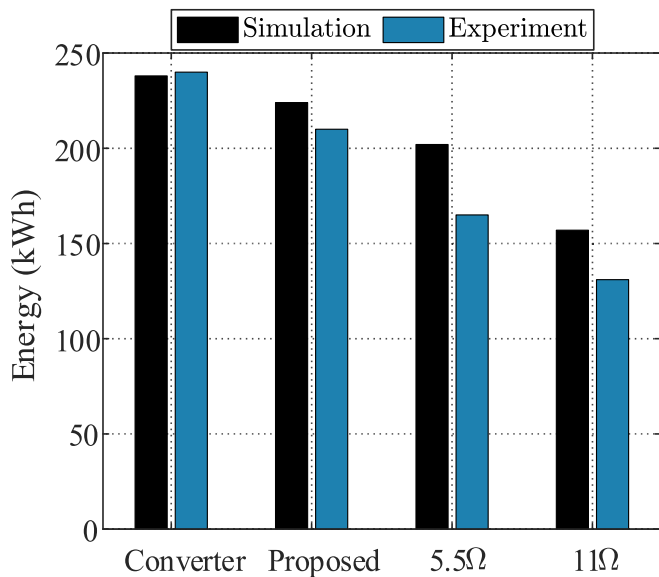


Fig. 20. Comparison between experimental & Simulation results.

3.3. Water loss measurements

The Fig. 21 illustrates the experimental findings regarding water loss in January, a typical winter month. In Fig. 21(a), the results indicate a notable disparity between the electric water heating system and the SVT (Solar Vacuum Tube) system. Specifically, the PV system records only 645 L of water loss across 2872 uses, while the latter exhibits a substantially higher loss of 2838 L over only 2131 uses. Fig. 21(b) further highlights this contrast, revealing an average water loss per use of approximately 0.22 L for the electric water heater, compared to a significantly higher 1.33 L for the SVT system. This means the suggested system in winter will provide water savings of circa 83.7 % in comparison to a solar thermal system.

4. The payback period and return on investment

4.1. Jordan's scenario

To assess the economic feasibility of the three systems at the designated location in Jordan, we conducted a comparison based on the payback period and long-term return. Our analysis began with estimating the installation costs of the three systems in a household in Amman, Jordan. The costs were calculated using suitable components available in Jordan and included a 30 % additional cost to account for cost of installation based on current indication rates at the time of this study. While some costs were straightforward to estimate, such as those related to the components discussed earlier, others proved more

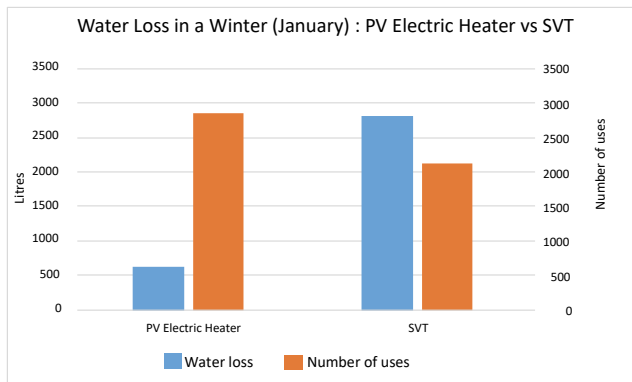


Fig. 21a. Water loss in January (a) Water loss & No. of uses, and (b) Average loss per use.

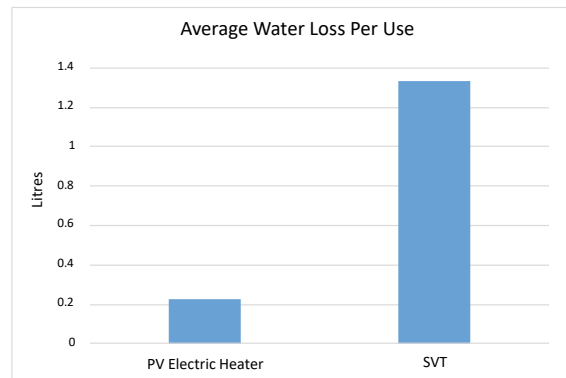


Fig. 21b. Accumulative savings in USD for the three systems (Amman, Jordan) (a); and the annual energy produced per system (b).

challenging, such as the control circuit for the proposed system, as its commercial cost is uncertain as it is still under development. The switching circuits require several components, including a controller, SPDT relays, MOSFETs, driving circuit, power supply modulators, PCB, and terminal blocks components, which has been approximately estimated based on the implemented components. After analysis, we found that the cost of installing the proposed system is approximately \$858, which is circa 44.7 % less than installing the system equipped with the MPPT converter, with a total cost of \$1,552. Additionally, we estimated that the added cost of installing the control circuit from the fixed load system accounts for an extra 14 %. The estimated costs for the three systems are summarized in Table 3.

The second critical economic parameter is energy prices. In Jordan, the residential cost for energy is divided into categories based on energy consumption, with each category priced accordingly. Table 4 shows the prices in Jordanian Dinars (JOD) and the equivalent USD [36] at the time of writing the paper. Energy costs range from 0.070 USD/kWh to 0.28 USD/kWh and do not vary based on the time of the day. Given the difficulty in forecasting energy costs, we have assumed a constant rate throughout the study period. We set the study period to be as long as the warranty of the solar modules since they have a longer lifespan compared to other system components. In this case, the solar modules [37] are assumed to last their average warranty period of 15 years, while the heating elements, MPPT converter, and control circuit are replaced every five years. We also assumed that the system's efficiency remains constant throughout the warranty period.

The cashback analysis in Fig. 21-a shows that the payback period for the systems is relatively short. The converter system has a payback period of about 4 years and 7 months, while the proposed system has a payback period of 2 years and 9 months. The fixed system falls in the middle ground, with a payback period of about 3 years. The cost of the MPPT converter is the primary contributor to the longer payback period of the converter system, as it incurs a significant added cost every five years compared to the other systems. Despite the set interest rate, the proposed system's benefits are highlighted in the cash return at the end of the period. Fig. 21-b presents the average energy production in kWh per system per annum.

Table 5 provides a comprehensive comparison between the ideal system, MPPT converter system, proposed system, and fixed system. The table also includes the yearly carbon savings, assuming an average carbon intensity of 0.435 Kg CO₂/kWh [38] generated from the electricity in Jordan and excluding the embodied carbon generated from the production of PV modules and electronics. The relative efficiency in the table is calculated by comparing each system's efficiency to the maximum theoretical efficiency that can be extracted from the four PV modules. The proposed system has a drop in efficiency of around 7 % when compared to a drop of 3 % for the converter system. However, the installation of the switching circuit provides a significant benefit, with a 11 % increase in efficiency compared to a simple directly connected fixed load system. Additionally, it offers an additional 11.5 % in carbon savings from the Jordanian grid, with only a 3.8 % drop compared to the converter system (see Table 6).

Table 3

The estimated costs for the three systems (Jordan) [\$: United States Dollar, as in 2024].

System	PV Modules (\$)	Heating Elements (\$)	MPPT (\$) Technology	Installation Cost (\$)	Total (\$)
Converter	560	15	650	327	1,552
Proposed		30	70	198	858
Optimal Fixed Load (5.5 Ω)		15		177	752

Table 4

Electricity tariffs in Jordan [30].

Consumption range from (kWh)	to (kWh)	Cost JOD/kWh	Cost \$/kWh
1	300	0.050	0.070
301	600	0.100	0.14
More than 600		0.200	0.28

JOD: Jordanian Dinar, \$: United States Dollar.

4.2. Egypt and UK scenarios

For example, Egypt's solar production is 4600 W/m²/day, resulting in similar resistor values to those used in Jordan where k_i will be close to 1. However, for Britain, where solar production is 1800 W/m²/day, the optimal resistor values would be approximately 27 Ω and 13 Ω for R_1 and R_2 respectively.

In order to compare the results in Jordan with other countries with cheaper cost of energy and lower levels of solar energy, Egypt and UK were selected respectively, see Fig. 22 and Fig. 23.

The data used for analysis is outlined in Appendix A and Appendix B for Egypt and the UK respectively. The payback for Egypt for the proposed novel system is about 6–7 years, while the converter system needs about 11 years to break even, see Fig. 20-a. Fig. 20-b presents the energy produced in Egypt for each system which is very close to Jordan levels. However, the cost of electricity has made significant difference in the payback period. For the UK, due to the high prices of energy, the payback period of the proposed system is about 3 years only, see Fig. 20-a. The converter system needs circa 4 years in the UK. The total energy produced annually for the system is much less than the energy in the scenario of Jordan and Egypt, see Fig. 21-b.

Referring to Fig. 23, it is clear that using the values of the resistors suitable for Jordan in the UK results in circa 7.1 % less energy output that the ideal MPPT, compared to only 4.6 % reduction when resistors are adjusted and optimised as shown in Fig. 24. Thus, changing resistor values for each region offers only marginal performance improvements while significantly could increase manufacturing cost due to the bespoke design and manufacturing. This could make the approach impractical for large-scale production. However, modular design for specific regions might be a compromise.

Fig. 25 presents the analysis of the changes of energy prices and their effect of the expected payback period. Current case study prices where modified within ± 50 % of current energy prices in each country. The results show that increasing the energy prices by 50 %, while keeping all other variables constant, causes a change in the payback period to be 1.5 years, 2 years and 4 years for Jordan, UK and Egypt respectively.

5. Conclusion

The novel Near-MPPT control system to maximise efficiency and reduce cost of PV systems has been proposed. While the proposed system produces slightly less energy than a conventional PV system equipped with a DC-DC converter and MPPT P&O algorithm, it offers significant cost and water savings and carbon reductions. The estimated payback period for the full proposed system is less than 3 years for Jordan, making it an attractive option for families looking to reduce their energy costs. More importantly, when compared to standard Solar Vacuum Tubes (SVT) heating systems, the proposed PV heating system is found to have a better water savings in both winter and summer. The experimental work has estimated water savings in winter to be 83.7 % when compared to a solar thermal system. Additionally, the proposed system can be a suitable replacement for the commonly used but high-maintenance solar vacuum tube thermal heating systems and provide a better flexibility for combined heating and electricity generation if needed, hence providing a better flexibility to the user at lower cost. The paper also suggested a generic methodology to select optimum resistors

Table 5

A comprehensive comparison between the three systems in terms energy saved, carbon saving, efficiency, costs, and payback period (Amman, Jordan).

System type	Yearly Energy Saved from the Grid (kWh/year)	Relative efficiency (%)	Cost to buy (Price indication only) (USD)	Payback Period Per Household (Based on Grid cost of kWh to compensate for the losses) (years)	Carbon Savings by the grid in Jordan (kgCO ₂ /year)
Ideal	4.27x10 ³	100			
Converter	4.14x10 ³	97	1152	4 and 7 months	1800
Proposed	3.98x10 ³	93.2	858	2 and 9 months	1731
Optimal Fixed Load (5.5 Ω)	3.50x10 ³	82	767	3 and 1 month	1522

Table 6

Comparison between PV water heating and Solar Vacuum Tubes (SVT) thermal heating system in relation to general features and experimental results in Jordan.

System Type	Flexibility of heating and electricity	Power (Wp)	Cost of Hardware (USD)	Installation Cost (USD)	Area (m ²)	Retrofitting	Water Loss (Litres)	Thermal Insulation Need
SVT (20-tubes)	No	2850	700	300	5.7	Difficult	2838	High
Proposed system PV Heating (4-panels)	Yes	1820 Wp	660	198	8	Easy	645	Not-Needed

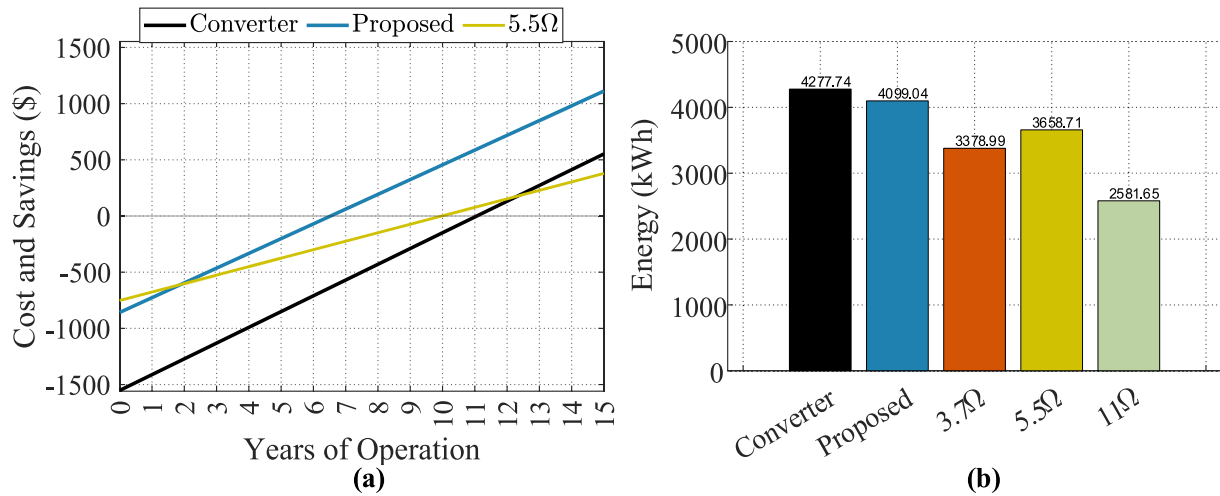


Fig. 22. Accumulative savings in USD for the three systems (Cairo, Egypt.) (a); and the annual energy produced per system (b).

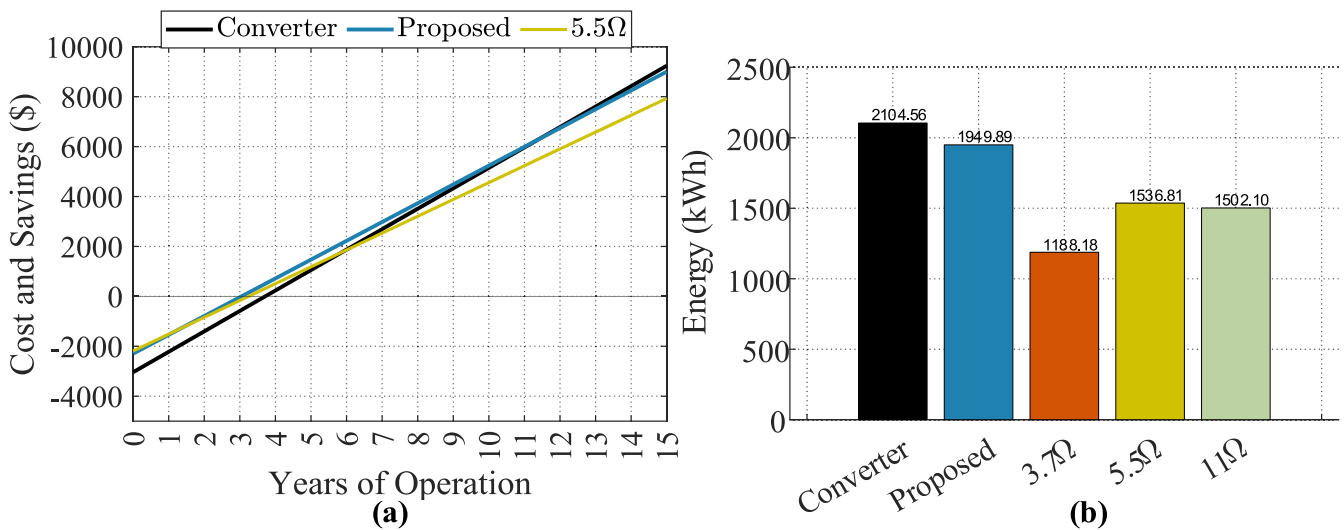


Fig. 23. Accumulative savings in USD for the three systems (Nottingham, UK) (a); and the annual energy produced per system (b).

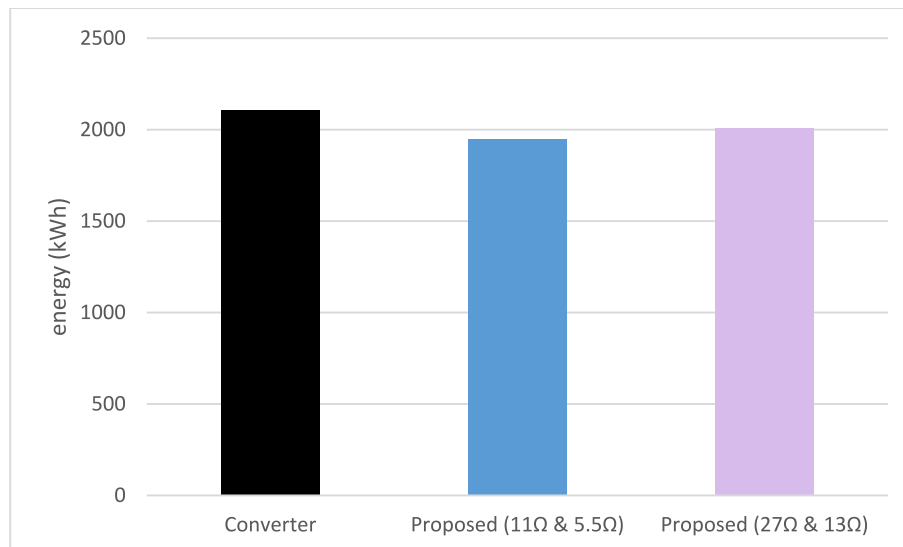


Fig. 24. Energy produced for the UK (Nottingham) by the ideal MPPT converter, proposed fixed resistor values and optimised resistor values.

Sensitivity of the payback period to variations in energy prices

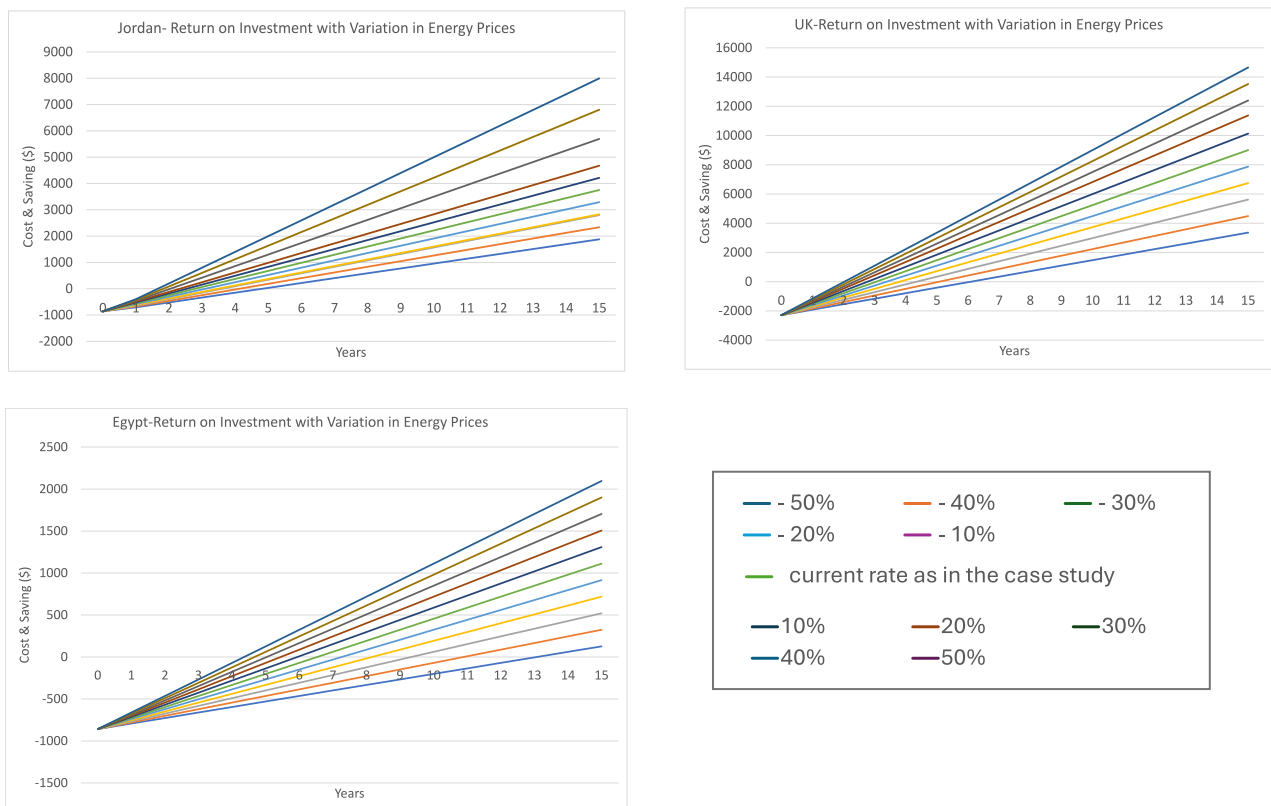


Fig. 25. The sensitivity of the payback period on changes of electricity prices.

for optimised Near-MPPT performance. This paper has proposed a novel low-cost PV water heating system with a novel low-cost switching circuit connected to two different rated switch elements to track near maximum power point (Near-MPPT) with cost savings between 24.5 % and 44.7 %. The hourly irradiation data for a location in Amman, Jordan, is obtained; and four median values are selected. Since the heating elements are simply modelled by a lumped resistor element, the suitable equivalent resistances that yield the most energy are calculated from the median irradiation data points. Using three electromechanical switches

and one semiconductor, four different equivalent resistance configurations have been possible with low losses and DC voltage disconnection/connection capability. The switching circuit is enabled by a control algorithm that switches between the configuration based on the threshold points, which extracts the highest power from the PV arrays at a given solar irradiation. In order to validate the proposed system, simulations have been conducted with high-fidelity PV array models. Compared to a conventional PV system with a DC-DC converter equipped with a MPPT P&O algorithm, the proposed system produced an average of about 3.8

% less energy. However, the proposed system produces about 13.7 % more energy than the directly connected system to a fixed load of 5.5Ω heating element. Finally, the proposed system's economic feasibility and potential carbon savings were evaluated. Based on cost estimates, the payback period for the proposed system is approximately 2 years and 9 months, compared to 4 years and 7 months for a similar system with a conventional MPPT DC-DC converter. This makes the proposed system an attractive option for Jordanian families looking to reduce their water heating energy burden, and it could serve as a suitable replacement for the commonly used, but high-maintenance vacuum tube water heating systems. Additionally, the proposed system can be a good option for reducing carbon emissions from the Jordanian grid, potentially reducing CO₂ emissions by about 1731 kg/year. Overall, the proposed system provides a cost-effective, efficient, and environmentally friendly solution for heating water using solar energy in Jordan. The configuration was also tested in Egypt and UK, and the payback period was found to be more sensitive to energy prices where the payback period for the proposed system was approximately for 6.5 years and 3 years for Egypt and the UK respectively. Any increase in energy prices would make the expected payback period shorter.

CRedit authorship contribution statement

Bashar Al-Haj Moh'd: Writing – review & editing, Writing – original

Appendix A. Egypt solar energy and cost case study

Table A1
Electricity tariffs (Egypt) [RA1].

From [kWh]	To [kWh]	E-pound/kWh	USD/kWh
1	50	0.58	0.01856
51	100	0.68	0.02176
101	200	0.83	0.02656
201	350	1.25	0.04
351	650	1.4	0.0448
More than 600		1.5	0.0464

[RA1] Egypt electricity tariff, Egypt applies new prices of electricity segments for 2024 - Egypt Independent, accessed on January 4, 2024.

EGP: Egyptian Pound, \$: United States Dollar.

Table A2
Estimated costs for the three systems (Egypt).

System	PV Modules (\$)	Heating Elements(\$)	MPPT (\$)	Installation Cost (\$)	Total(\$)
Converter	560	15	650	327	1,552
Proposed		30	70	198	858
Optimal Fixed Load (5.5 Ω)		15	0	177	752

Table A3
Energy produced in kWh (Cairo, Egypt).

	Yearly Produced [kWh]	Monthly Produced [kWh]	Price [USD]	AVG [USD/kWh]
Converter	4277.740	356.478	5.180	0.014530648
Proposed	4099.040	341.587	5.118	0.014979497
Optimal Fixed Load (5.5 Ω)	3658.710	304.893	4.464	0.01463857

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix B. UK solar energy and cost case study

Table B1
Electricity tariffs in UK [RB1].

Category	£/kWh	USD/kWh
Day time	0.30	0.392
Night 1am to 6am	0.18947	0.2349428

[RB1] British Gas (Jan 2024),
<https://www.britishgas.co.uk/energy/price-cap.html>, accessed on 2 Feb 2024.

Table B2
Estimated costs for the three systems (UK).

System	PV Modules (\$)	Heating Elements (\$)	MPPT (\$)	Installation Cost 30 %(\$)	Total (\$)
Converter	860	30	850	1300	3040
Proposed		65	70	1300	2295
Optimal Fixed Load (5.5 Ω)		30	—	1300	2190

Table B3
Energy produced in kWh (Nottingham, UK).

	Yearly Produced [kWh]	Monthly Produced [kWh]	Price [USD]	AVG [USD/kWh]
Converter	2104.560	175.380	98.683	0.5625632
Proposed	1949.890	162.491	91.417	0.563
Optimal Fixed Load (5.5 Ω)	1536.810	128.068	72.055	0.563

Appendix C.: Three resistors near-MPPT configuration

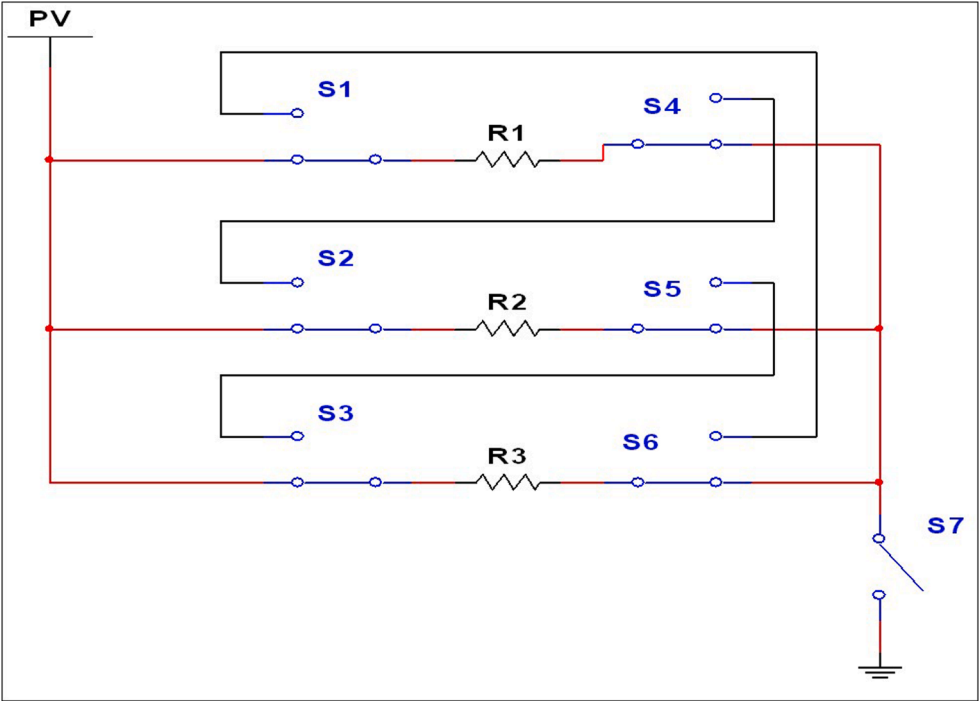


Fig. c. A schematic diagram of using 3 resistors for Near-MPPT system.

Table c

The lookup table of the relay switches and the related configuration*.

#	S1	S2	S3	S4	S5	S6	Configuration	Ranking	Description
1	ON	ON	ON	ON	ON	ON	R1//R2//R3	1	Lowest resistance, Highest power
2	ON	ON	ON	ON	ON	OFF	R1//R2	2	
3	ON	OFF	ON	ON	OFF	ON	R1//R3	3	
4	OFF	ON	ON	OFF	ON	ON	R2//R3	4	
5	ON	x	x	ON	OFF	OFF	R1	5	
6	x	ON	x	OFF	ON	OFF	R2	6	
7	x	x	ON	OFF	OFF	ON	R3	7	
8	ON	ON	OFF	ON	OFF	ON	R1//(R2 + R3)	8	Highest resistance, Lowest power
9	OFF	ON	ON	ON	ON	OFF	R2//(R1 + R3)	9	
10	ON	OFF	ON	OFF	ON	ON	(R1 + R2)//R3	10	
11	ON	OFF	OFF	OFF	ON	x	R1 + R2	11	
12	OFF	OFF	ON	ON	x	OFF	R1 + R3	12	
13	OFF	ON	OFF	x	OFF	ON	R2 + R3	13	

*Assume $R1 < R2 < R3$ where $//$: means parallel.

+: means series connection x: don't care.

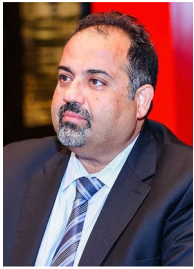
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