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ORIGINAL PAPER

Rapid evaluation of the design and manufacture of cooling systems of photovoltaic solar panels

Eisa Almeshaiei[1] · Amin Al-Habaibeh[2] · Nicholas Mina[2] · Shatirah Akib[2]

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Abstract

A new methodology is presented in this paper to encourage the growth of renewable energy technologies in hot and arid countries. PV solar panels are characterized by a decrease in efficiency with the increase in temperatures. This means in hot sunny countries, the actual output will decrease, affecting the power output despite the high availability of sun irradiation. In order to address this issue, a new methodology has been developed and presented in this paper to support system's designers and manufacturers; which allows rapid testing and assessment of the design in consistent way within a short period of time. The approach, named Rapid Evaluation of Solar panels Cooling (RESC), is novel as it combines rapid laboratory testing, with in-situ experimental data to evaluate the cooling technologies that are integrated into solar panels. Modular and scalable designs of passive (chimney effect) and active (fan) cooling methods were tested. The results show that the suggested approach is successful in comparing between the cooling technologies to assess their performance and the payback period within a short period of time. Carbon savings are also calculated for the suggested cooling technologies. The results show that the best energy performance was found to be for the fan-cooled system with overall 12.3% improvement in annual energy output. However, when compared to the payback period on financial investment, the passive cooling is found to more appealing. The key advantage of cooling technologies is found to be in producing an additional significant level of power during summer days when the surface temperature of the panel is at 70 °C or above. Hence, in such conditions, the cooling process could result in an increase in power output of about 53.15% relative to the uncooled standard panels.

Keywords Photovoltaic · Cooling · Solar energy · Renewable energy

List of symbols

P_m	Power at maximum level of solar cell or panel
I_m	Current at maximum power point
V_m	Voltage at maximum power point
FF	Fill factor
I_{SC}	Short circuit current
V_{OC}	Open circuit voltage
β_{ref}	Temperature coefficient
T_o	The elevated temperature at which the PV efficiency is zero
η_{Tref}	Solar module's electrical efficiency at the reference temperature T_{ref}
η	Solar module's electrical efficiency
T	Temperature in degree centigrade
T_c	Solar cell temperature
Ta	Ambient temperature
Vw	Local wind speed
T_{ref}	The reference temperature T_{ref}
γ	Solar radiation coefficient
$\Phi(t)$	Solar irradiation flux
C_{Fs}	Standard correction factor with no cooling ($C_{Fs} = 1$)
C_{Fp}	Correction factor for passive cooled panel
C_{Ff}	Correction factor for fan cooled panel

✉ Amin Al-Habaibeh
Amin.Al-Habaibeh@ntu.ac.uk

[1] Manufacturing Department, College of Technological Studies, The Public Authority for Applied Education and Training, Kuwait City, Kuwait

[2] Product Innovation Centre, School of Architecture, Design and the Built Environment, Nottingham Trent University, Nottingham, UK

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1 Introduction

The strategy of COP26, The 26th United Nations Climate Change Conference of the Parties, is driving countries on global levels towards net zero carbon emission. Hence attracting more interest in renewable and affordable energy; where solar is considered to be one of the most common types to use, particularly in sunny regions such as Gulf countries [1–3]. Renewable energy is becoming a necessity to reduce carbon emission and pollution, hence limiting global warming. There has already been significant global capital and personnel investments in solar energy, as a result, the global solar installation capacities increased significantly from 5.8 GW in 2006 to 301.5 GW in 2016 [4]. Photovoltaic solar energy is one of the most common solar technologies for electricity generation and the easiest to install, as an independent installation or via connection to the grid. The PV principle of operation is based on the properties of the semiconductor materials, which emits electrons by absorbing energy from the solar irradiation, and its efficiency of conversion is the proportion of solar energy that a photovoltaic cell converts into electricity [5]. The integration of photovoltaic roof-mounted systems in low-voltage distribution networks has become a significant international trend, supported by falling photovoltaic prices [6]. The technological problems associated with incorporating photovoltaic low-power systems into low-voltage grids have clearly illustrated and addressed by Bayer et al. [7]. Photovoltaic power producers try to maximise their profits by feeding as much electricity onto the grid as possible. Two main elements must be satisfied for a photovoltaic system to be profitable: reliability and performance. The exact estimation of the photovoltaic system's production is crucial for future evaluations of new installations of photovoltaic systems. Due to the lower prices of photovoltaic technology, photovoltaic roofing systems have become an emerging trend in the international arena [8]. Today's PV solar technologies are the product of decades of improvements in performance and cost. Each type of solar PV technology is based on different architectures and materials and has its advantages. The analysis and comparison between different technologies under certain conditions can help developing the most efficient and advantageous solar system. Different technologies are available on the market due to various photovoltaic applications, with a wide range of efficiencies and costs. A lower output device is usually cheaper, but producing the needed energy requires a wider area, which increases the cost of land and maintenance [9].

Photovoltaic solar panel technologies can be divided into three generations [10], as follows:

- First generation: Gallium arsenide (GaAs), and crystalline silicon (c-Si) such as multicrystalline (multi-Si) silicon and monocrystalline (mono-Si) silicon;
- Second generation (thin films): amorpheous silicon (a-Si), CdTe, or copper indium gallium (di) selenide (CIS/CIGS);
- Third generation: dye-sensitized, organic and multi-junction

In addition to cell's temperature, non-uniform cell temperature and irregular illumination across the cell also affect the efficiency and overall device performance [11, 12]. The main challenges for installing photovoltaic energy systems are income/cost ratio and ecological problems [13]. According to Chander et al. [144], the overall performance of solar cells depends on the environmental parameters such as light intensity, tracking angle and cell temperature, etc. According to NREL, USA National Renewable Energy Laboratory [15], the cell efficiencies of PV panels in research range between 13 and 47.1%. The expected efficiency of commercially available PV panels is expected to reach 48% by 2050 [16]. As a result, the efficiency of the panel decreases as the open-circuit voltage and fill factor (FF) decreases as the temperature increases [17, 18]. Hence, one of the limitations of PV solar panels systems, is the reduction in efficiency due to the increase in temperature [19]. Subsequently providing a challenge in hot countries, particularly during midday summer heat. Because of these reasons, the drop in efficiency due to heat reduces the system's overall performance and leads to an increase in cost per unit. To gain optimum and best performance in solar cells, innovative cooling techniques should be investigated to maintain the solar cell's temperature in a reasonable operating state; which should provide an enhanced performance in terms of energy, payback on investment and reduction in carbon emission. According to Bahaidarah et al. [20], there is still a lack of awareness of economic and ecological issues for PV cooling systems. Only a few studies have concentrated on this area, see for example Baloch et al. [21] and Cucchiella and D'Adamo [22],while most photovoltaic cooling systems studies have only tackled technical aspects [23].

To address this challenge, this paper addresses the regulation of PV solar panel temperatures in hot arid countries via cooling to maintain reasonable levels of output. It also introduce a novel rapid method of assessment of the designs to allow rapid introduction to the market. In relation to this, there are still many challenges to be addressed. For example, Kandeal et al. [24] have presented a comprehensive literature review of the different cooling methods of photovoltaic systems to enhance efficiency. The paper concluded that enhancing PV efficiency via cooling methods is still in its infancy and further work is still needed in this area. Also there was no rapid assessment method found in literature to rapidly assess the cooling designs. A water cooling system for solar panels was also suggested in Brazil [25]; the methodology included two levels of irradiation: high and low. The use of the water cooling at a high level of irradiation resulted in a

12.26% relative increase in power. In Salameh et al. [26] a review of photovoltaic technology and the cooling methods are presented. One of the key findings is that water cooling is more effective than air due to the higher thermal capacity of water but it lacks the simplicity and sustainability in design. Other water flow cooling for solar panels is suggested by Shahverdian et al. [27] where results better performance with water cooling, but water consumption and the energy associated with its use should be taken into consideration. Therefore, in this paper air cooling will be the focus of the suggested cooling system in this paper due to the hot and arid areas of the suggested markets, which has lack of natural water resources.

Table 1 presents some key technologies available in literature that have been used or could be used for air cooling of solar panels. In this section each technology will be briefly discussed and the choice of technology to take forward will be assessed. Water cooling is not considered in this study as the Gulf region is an arid region to use water for such applications.

In relation to Passive cooling using stack ventilation and Bernoulli's principle [28], the concept is based on the fact that hot air is lighter than cold air due to the difference in density and hence hot air rises and is replaced by cooler air. And this creates air circulation (Chimney effect) which provides a cooling process of surfaces. The same concept is used in power stations' cooling towers. This technology has the advantage of being simple, reliable, low maintenance and with no electric parts or electricity consumption. However, its performance will depend on the environmental conditions and some design factors. Therefore, this principle is selected in this paper for evaluation. For fan cooling, according to Dwivedi et al. [29], it is a simple technology which only consumes electricity in the powering of the fan which does not need significant power, but it has the advantage of being controlled via speed controller to optimize energy versus cooling effect. Fan technology will be assessed in this paper due to its potential. Active cooling air conditioning consumes much more electricity and more complex in relation to maintenance [30] and the demand for electricity is high relative to the energy savings, hence it might not be suitable in most applications. Evaporation cooling [31] is based on the heat exchange of latent heat by changing water to vapour and hence absorbing heat from the surrounding environment causing the cooling process. This technology is normally not suitable in hot arid countries as humidity is normally low and water is scarce and expensive commodity to be provided for cooling applications. Heat sinks [32] work via conduction and transfer of heat by increasing the surface for heat exchange. However, the process of convection might not be efficient without air circulation and hence this method could be considered an add-on feature for the other methods if needed.

From the above discussion, it is evident that the temperature of PV panels plays an important role in affecting their efficiency; and cooling of panels would maintain or enhance this efficiency. Passive cooling and fan cooling could be considered the simplest, most reliable and lowest in cost. Hence, this paper presents a novel modular and scalable cooling system design for cooling PV panels. However, one of the challenges is the way to assess and evaluate the design of cooling systems in a rapid way prior to mass production. The full experimental work will need a full season of assessment in summer and this is costly from financial and time point of view and does not help in rapidly producing a product to the market. To address this challenge and in order to assess the cooling technology, a combined empirical and simulation work is presented to understand the performance of the two selected cooling. The experimental work data is integrated with data from Photovoltaic Geographical Information System [33]; which is a database for PV performance, solar radiation and typical metrological year (TMY). The database will be used to assess the standard solar panel performance. But for cooling application, a relative efficiency output will be needed for the same solar radiation but at different temperatures; hence the need of the new approach. Therefore, the suggested approach in this paper integrates emulation and empirical testing to provide a cutting edge and rapid technique to support manufacturers of the cooling systems to rapidly introduce new novel products to the market with significant confidence and well understood system performance. The suggested methodology can also be used to convince customers and investors to use the technology.

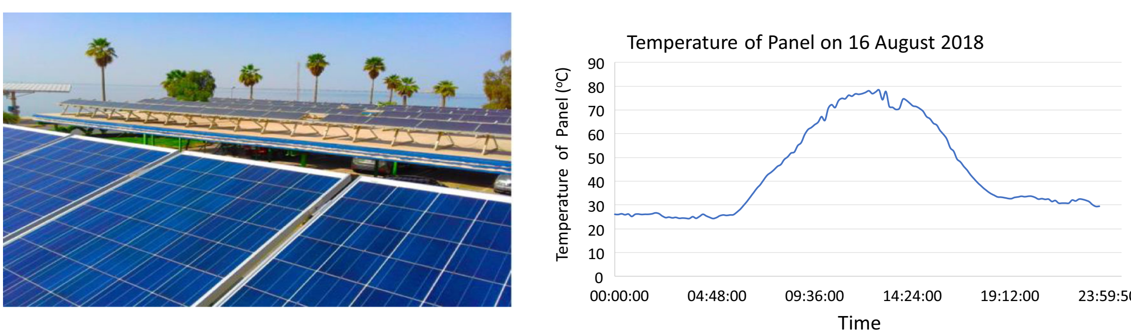
2 Methodology

The focus of this research work is on enhancing the power output of solar panels in hot arid countries. The focus of this study is on Kuwait, as a hot arid country, with the use of fixed load stand-alone PV systems. This is because it is a simpler system to integrate to home environment to power specific devices off-the-grid via batteries such as lights, water pumps, electric doors, etc. Temperatures in Kuwait could reach extremely high levels. Figure 1a presents the location in Kuwait where the surface temperature of a photovoltaic panel was measured during a typical summer day in August 2018. Figure 1b presents the temperature readings of the surface of a panel where a thermocouple was attached to the back surface of the PV panel. Although air temperature does not exceed 50 °C in most situations, the surface temperature due to the direct sun has reached much higher levels in this case, about 79 °C.

Polycrystalline technology will be proposed and tested in this research work as suggested by the manufacturers. When testing the Polycrystalline panels under an optimum fixed

Table 1 Cooling technologies and their strength and weaknesses

Method of cooling		Strengths	Weaknesses	References
Passive cooling	Stack ventilation and Bernoulli's principle	Uses natural elements No operating costs No emissions or energy consumption No mechanical parts	No temperature control Exterior temperature. impacts effectiveness and performance Surroundings can create obstructions and affect the process effectiveness	[28]
Active cooling	Fan cooling	Simple design with possibility to control fan speed for different cooling rates Consumes limited electricity	Consumes electricity for the solar panels or other sources	[29]
	Air-condition	Decreases internal temperatures at an effective rate Temperature control feature	High energy consuming method High contribute to carbon emissions if fossil fuel is used Energy demanding an hence reduce the actual system output if solar panels are used	[30]
Evaporation cooling		Utilises evaporation method without the use of energy or by using limited energy	Relies on humidity levels being low	[31]
Heat sinks		Natural method of cooling No energy required	Cost of heat sink reflects on performance	[30]



(a) (b)

Fig. 1 The location of temperature testing in Kuwait showing Polycrystalline panels (**a**) and an example of a solar panel temperature levels in summer (**b**)

load, Fig. 2 presents the relationship between the efficiency (%) relative to 25 °C reference during lab testing. It is evident that at 70 °C, the power output reaches about 40% relative to the output at 25 °C. If we assume 15% efficiency W/m^2, this makes the efficiency at 70 °C to be only 6% W/m^2. This indicates the importance of reducing the temperature of solar panels in hot countries in order to enhance the electricity output in summer time in the middle of the day, where more of the electricity demand is needed due to the requirements for air conditioning.

As discussed above, the use of manufacturer's specifications to assess the performance of PV panels with the integrated cooling systems is difficult as the standard procedures will not be practical with the panels are integrated as part of a cooling product. The other problem is the estimation of annual performance with a high level of confidence at different locations without having to wait a full year or season to assess the actual performance. The weather conditions changes and an accurate estimation is needed for the manufacturers of cooling systems to provide evidence of the value of the cooling system in terms of financial, energy and carbon emission savings to justify the productions of a new design. Figure 3 presents the suggested novel methodology to assess the performance of the cooling systems. The process starts with a standard solar panel, stage (a), that the manufacturer is familiar with and its performance; see for example Almeshaiei et al. [34]. The cooling system is then designed and a prototype is manufactured as in stage (b). Empirical

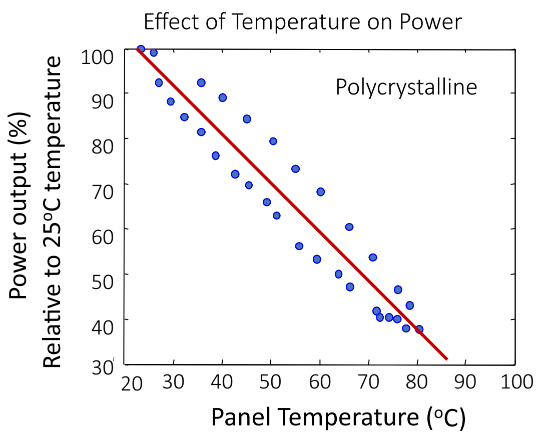


Fig. 2 Lab testing showing the reduction in PV power output of a polycrystalline panel due to the increase in temperature

Table 2 The specifications of the used Polycrystalline solar panel (commercially available), test conditions under 1000 W/m^2 of solar energy and 25 °C

Specifications	Value
Power rating	100 W
Type	Polycrystalline
Dimensions	1005 × 670 × 35 mm
Cell efficiency	21.00%
Optimum operating voltage (Vmp)	19.55 V
Optimum operating current (Imp)	5.12 A
Open circuit voltage (Voc)	23.15 V
Open circuit current (Isc)	5.45 A
Max temperature	+ 85 °C
Min temperature	− 40 °C

lab testing will be conducted for the prototype (stage (c)). In stage (d), the potential location of the market segment of the technology is decided upon,and in this case a typical standard (uncooled) solar panel output can be obtained using historical data or PVGIS [33] database. The standard (uncooled) panel power output (stage (e1) is estimated experimentally or via the use of PVGIS [33]. In stage (e2) the surface temperature of a standard panel can be obtained experimentally, as presented in this paper, or mathematically via weather data and sun irradiation as presented by Solaimanian and Kennedy [35].

In this case study, in Kuwait with ambient temperature reaching 50 °C in summer, the standard (uncooled) panel temperature was available from a previous testing and was used in this occasion. Otherwise; temperature of panels can be estimated using [35] where heat transfer equations were suggested with suitable modifications for PV solar panels and heat transfer. Following that, calibration equations can be obtained from the lab testing and the temperature and energy data estimation (stage (f)). In this way, the actual cooling system design is compared with the standard panel in the lab environment; and then the expected output in the chosen location can be estimated by comparing the performance of the cooled with the standard panel. Based on the output, the expected energy and carbon savings from using the cooling components will be evaluated; allowing the manufacturer to make an educated judgment regarding the benefits to customers and hence the expected added value in terms of cost, carbon and energy savings during the Life cycle Assessment of the Product.

3 The design configuration of the proposed cooling systems

Based on the literature review, fan cooling and passive cooling are the technologies that will be designed and assessed in this paper due to their simplicity, low cost and ease of use. Figure 4 presents the standard panel in comparison to the other two cooling methods, namely fan cooling, Fig. 4b1, and passive cooling, Fig. 4c1. The cooling designs are based on cooling the back surface of the panels as front cooling will require glass installation which could create green-house effect if air circulation is not effective.

Figure 4b2, c2 present CAD models of the designs showing the final product. The novel design is modular and scalable for different panel sizes. Air circulation is presented in red and blue arrows. Figure 5 presents the main individual components to achieve both designs. The innovation in design comes here using plastic formed panels to create the chamber that will allow air circulation in both technologies. The design is based on minimum-number of components to reduce costs combined with modular design where the passive or active cooling could be used depending on future performance and evaluation. A 100 W Polycrystalline PV Solar panel is used for this research work. The details of the solar panel used in shown in Table 2. The panel is chosen due to its moderate cost, reasonable efficiency and commonly used by local installers.

4 Temperature dependent electrical efficiency of PV module

Modelling thermal performance has been well documented by [36]. And several models have been documented in relation to electrical efficiency and temperature [37]. The surface temperature of PV panels plays a key role in the photovoltaic conversion process (electrical efficiency). Michael et al. [38] has presented a paper on a novel photovoltaic module for photovoltaic thermal applications and the work empirically

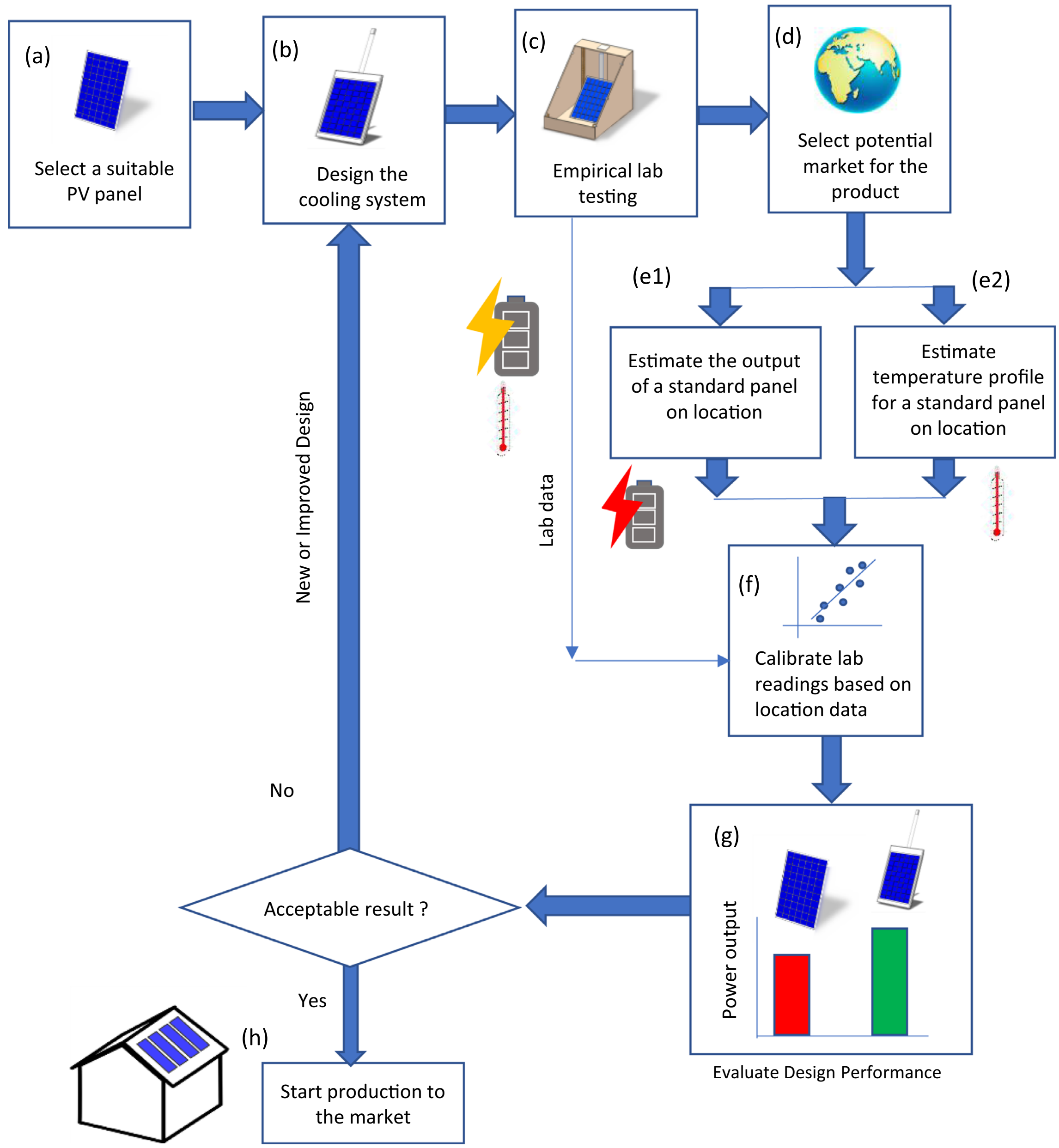


Fig. 3 The novel developed methodology, Rapid Evaluation of Solar panels Cooling (RESC), to support systems manufacturers

has been done to estimate the benefits. The correlation models in literature for cell temperature, as will be discussed later in this section, apply basic environmental variables and do not take into consideration complex system approach [39] or specially designed products. Since the available equations have been developed with a specific mounting geometry or system integration level in mind, it is critical for cooling systems design to use empirical approach for evaluation. In one hand, pure simulation will include normally assumptions that is difficult alone to guarantee accurate results due to the unknown accuracy of the assumptions used and the difficulty of convincing investors and manufacturers to invest based on only a simulation exercise. On the other hand, lengthy empirical approach, although being very accurate, could be time and money consuming for a rapid production process by manufacturers.

According to [37], there are many equations that express the PV cell temperature (Tc) as a function of weather variables such as the ambient temperature (Ta), local wind speed (Vw) and solar radiation (Φ(t)).

The effect of temperature on the electrical efficiency of a PV panel can be obtained by using the following equation: [37]:

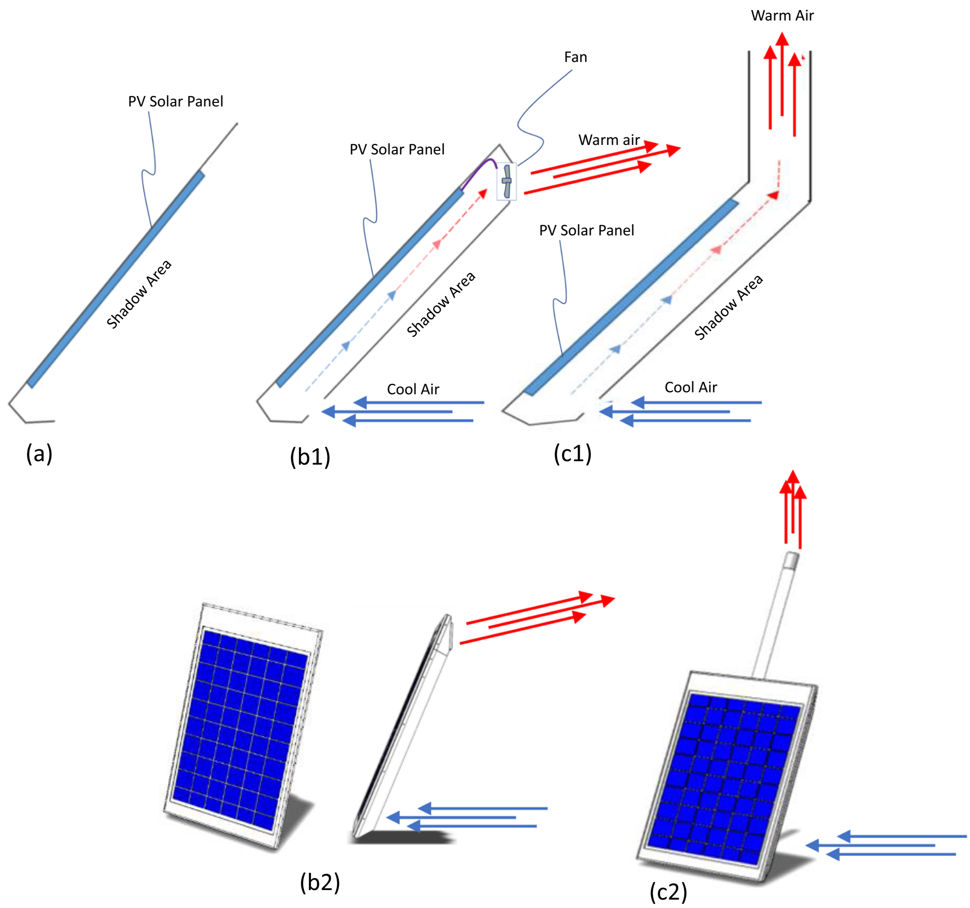


Fig. 4 The three systems that will be compared; no cooling (**a**), fan cooling (**b**) and passive cooling (**c**)

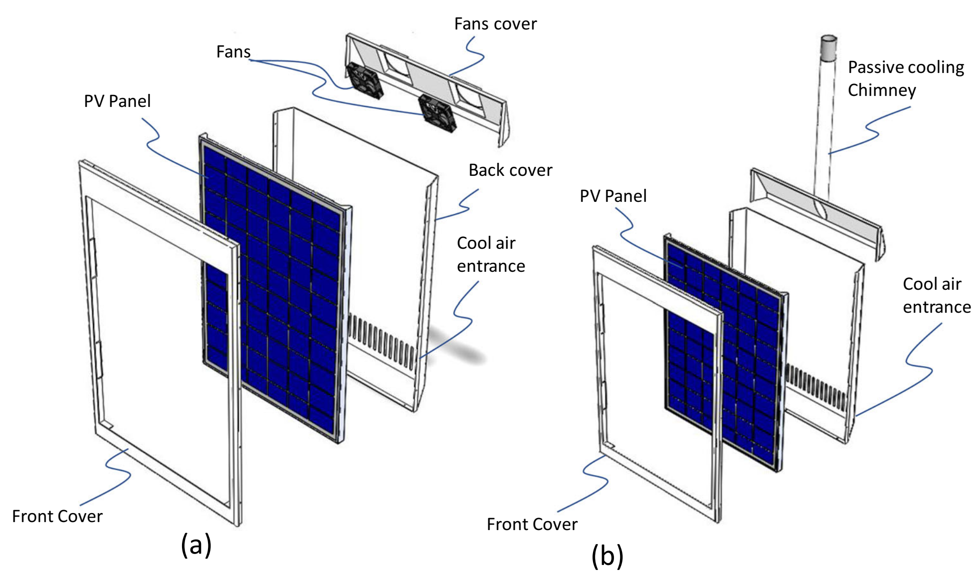


Fig. 5 The modular and scalable design components of fan cooled (**a**) and passive cooling (**b**) PV panels

$$P_m = I_m V_m = (FF) I_{SC} V_{OC} \tag{1}$$

where FF is the fill factor, Isc is short circuit current, Voc is open circuit voltage and subscript m refers to the maximum power point in the modules I–V curve.

The open circuit voltage and the fill factor decrease with temperature [19]. The effect on solar panel efficiency, η, can be expressed as a linear relation by Eq. (2) as described by Dubey et al. [37]:

$$\eta = \eta_{Tref} 1 - \beta_{ref}\left(T_c - T_{ref}\right) + \gamma log_{10} \Phi(t), \tag{2}$$

where η_{Tref} module's electrical efficiency at the reference temperature T_{ref} and at solar radiation flux $\Phi(t)$ on module irradiation solar power of 1000 W/m^2. The temperature coefficient, β_{ref}, and the solar radiation coefficient, γ, are mainly material properties of the solar panel. The terms η_{Tref} and β_{ref} are normally given by the PV manufacturer. However, they can be estimated from flash tests in which the module's electrical output is measured at two different temperatures for a given solar irradiation flux [40]. The term $\gamma log_{10} \Phi(t)$ is normally too small for polycrystalline solar panels and hence Eq. (2) becomes:

$$\eta = \eta_{Tref} 1 - \beta_{ref}\left(T_c - T_{ref}\right); \tag{3}$$

where

$$\beta_{ref} = \frac{1}{T_o - T_{ref}}. \tag{4}$$

where T_o is the elevated temperature at which the PV efficiency is zero (circa 270 °C for polycrystalline) based on Evans and Florschuetz [41].

The above equations allow the calculations of the efficiency of solar panels, and reference [37] highlights a wide range of equation to calculate that. But one of the challenges that the equations fall short of is providing information when the solar panel is integrated to a cooling system to form a new product with different characteristics and thermal response. In this case, the solar panels and the cooling structures will need to be tested to provide accurate information at different temperature levels, which might not follow the same characteristic as simple PV panels.

5 The design of the test rig

In order to evaluate the designed cooling systems, a controlled environment was needed to compare like-for-like, as real environment would not allow exact control of temperature and measures. This will also allow a rapid testing of the panels using a combined lab data with in-situ real data. To allow this, a special test rig has been designed with the concept shown in Fig. 6. A chamber with glass pane is designed which allows a controlled light intensity and temperature control. An electric heater is used to allow the emulation of air temperature on the surface of the panel. A ventilation is used to allow balancing the pressure during air circulation. Figure 7 presents the detailed design and the components used to construct the test rig. Figure 8 presents the actual test rig with a standard solar panel (Fig. 8a) and the lights used (Fig. 8b). The test rig is designed to allow access into the rig via back door opening flap. An electric heater is located in the front to increase surface temperature of objects inside as well as internal air. Electric lights are positioned externally to provide the necessary emulation for solar irradiation. Glass front angled parallel to solar panel for optimum angle performance. Shape of test-rig provides the necessary height for testing the suggested designs of cooling methods. The average irradiance level on the panel is estimated to be 150 W, which is kept constant.

In order to select the optimum load resistor that produces the maximum power; a load sweep at 25 °C and experimental irradiance level has been conducted. The resistive load is kept fixed during the experimental work to simulate the fixed resistive load on the system. All tests were done under the same conditions for comparability. The efficiency in this case is a relative comparison based on the temperature under fixed resistive load as will be discussed in the following section.

6 Results and discussion

Figure 9 presents the experimental results between the three products: the standard panel, fan cooled panel and passive cooled panel.

At 25 °C the three panels perform at the same level. However, with the increase in temperature the standard uncooled panel starts to show a massive drop in performance. The cooled panels show much better performance with the fan cooled panel resents a better performance when compared with passive cooled panel. Figure 9 provides evidence for the success of the concepts. Table 3 presents detailed figures and percentage of relative efficiency improvement when compared to the performance at 25 °C.

As indicated in Table 3, the passive cooling has an improvement of 27.4% over the uncooled standard panel, however, the fan cooled has an improvement of 32.1%. The 4.7% power difference between the fan cooled and passive cooled in watts will depend on the actual rating of the solar panel and the light. Given that each fan will consume part of the generated power, this will reduce the overall efficiency of the active-cooling product. In our case, two fans were used and each was consuming 0.5 W; this would mean that the net output for the fan-cooled panel would be reduced

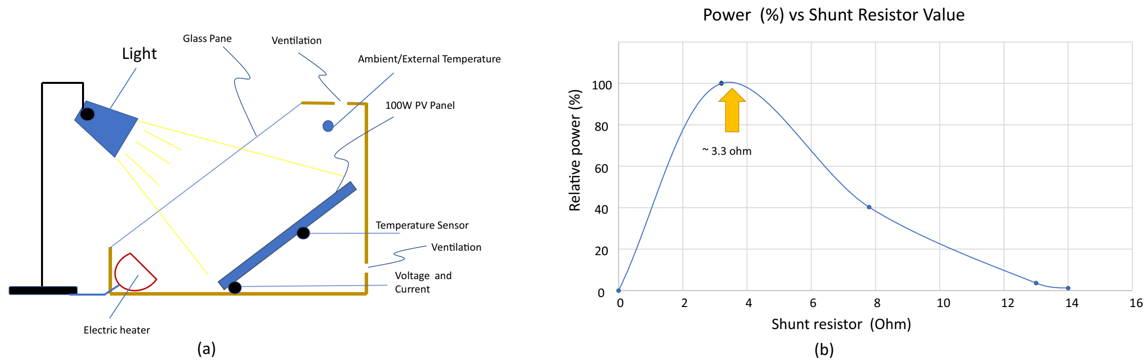


Fig. 6 The main concept of the test rig (**a**); and an example of the optimisation of the value of the fixed load shunt resistor at a constant light intensity (**b**)

Fig. 7 CAD model shows the detailed design of the proposed test-rig

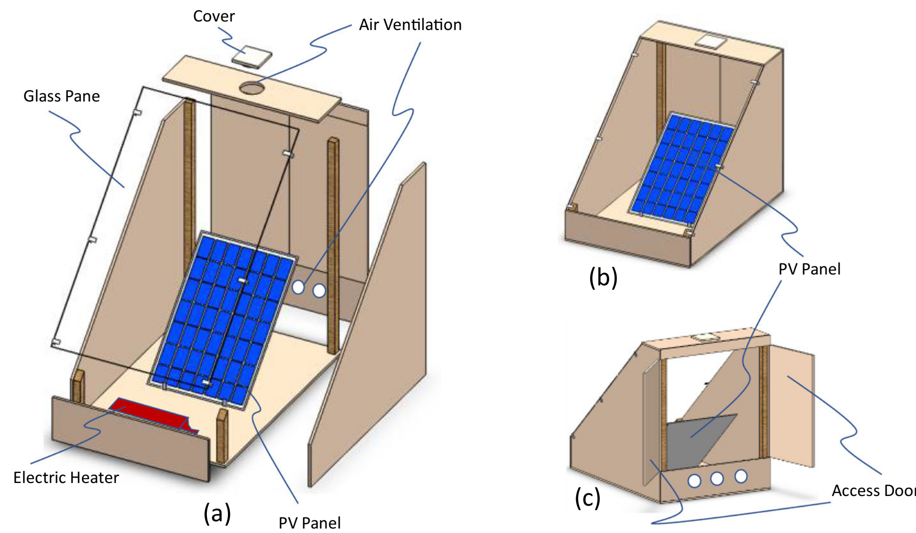
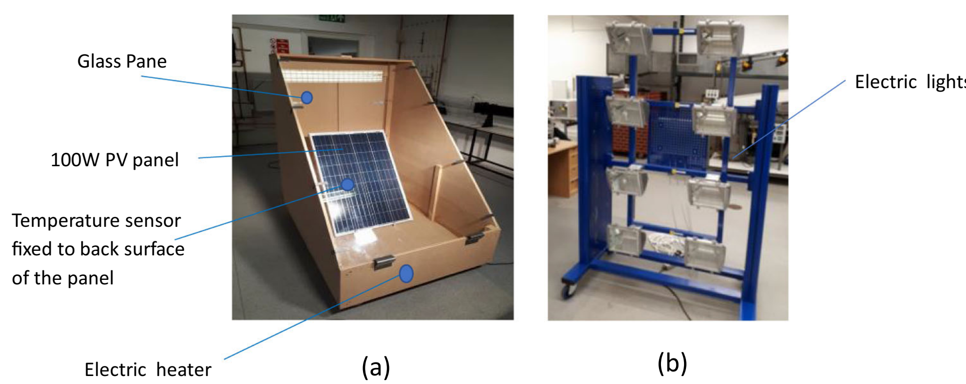


Fig. 8 The implemented test rig showing the standard panel and artificial lighting system



by 1 W. Hence energy generated vs energy consumed in the fans will be a critical point for the selection between the two technologies. Table 3 presented a comparison of the relative efficiency output relative to 25 °C temperature for a nominal 100 W panel at 70 °C for a constant irradiation level. However, as seen from Fig. 1, the temperature will fluctuate during the day and hence the relative efficiency improvement is expected to be less in winter and during mornings and evenings due to the low surface temperatures caused by lower air temperature. This will be discussed in detail in the next section.

6.1 Cost and carbon footprint of components

Table 4 presents the estimated cost and embodied carbon of components for each design. The embedded carbon to manufacture the components of the cooling systems are estimated based on material information from Alsabri and Al-Ghamdi

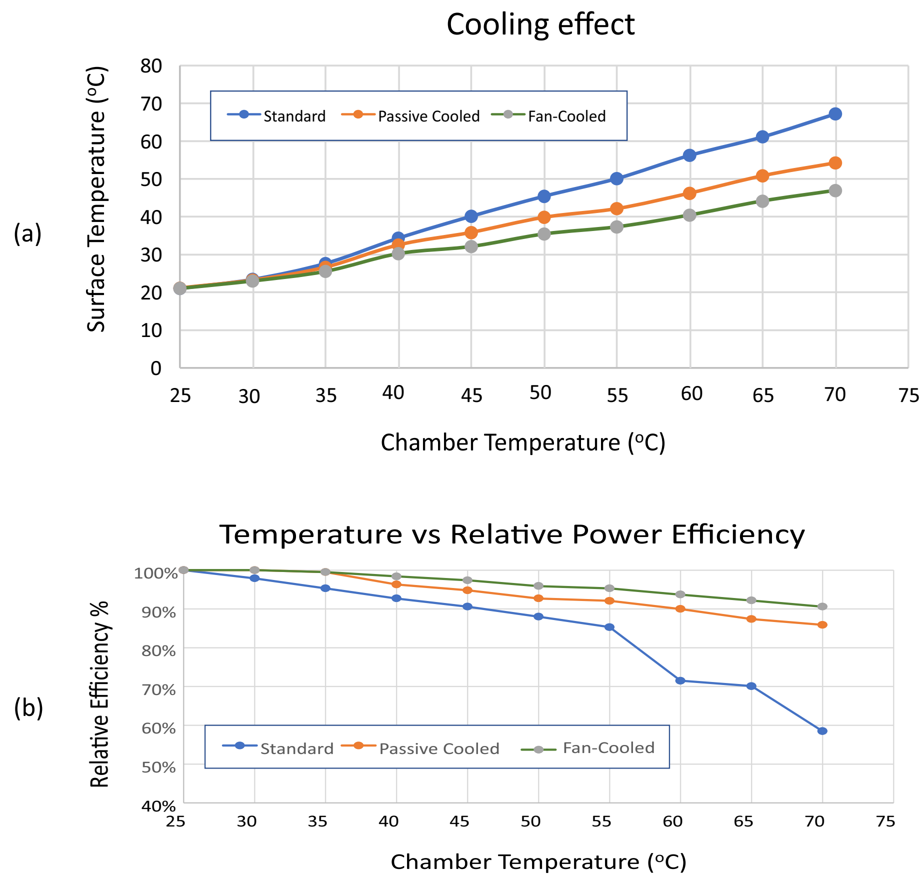


Fig. 9 The results when comparing between the three panels: standard, fan-cooled and passive cooled

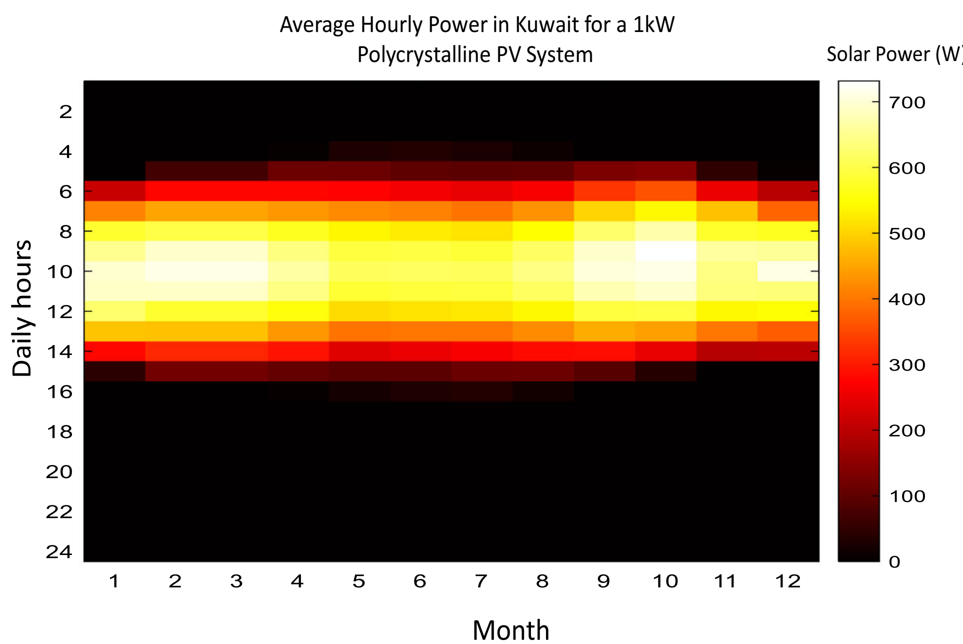


Fig. 10 Average daily electricity power output in Kuwait for a 45 degree facing south for a nominal 1 kW capacity (based on data from PVGIS [33])

Table 3 A relative comparison between cooling methods, light intensity is constant at circa irradiance level on the panel of 150 W per square meter

Chamber reference temperature (°C)	Standard panel (no cooling) Relative efficiency (%)	Passive cooling Relative efficiency (%)	Fan cooling Relative efficiency (%)
25	100%	100%	100%
30	97.90%	100%	100%
35	95.30%	99.50%	99.50%
40	92.70%	96.30%	98.40%
45	90.60%	94.80%	97.40%
50	88.00%	92.70%	95.90%
55	85.30%	92.10%	95.30%
60	71.50%	90.00%	93.70%
65	70.10%	87.40%	92.20%
70	58.50%	85.90%	90.60%
Maximum relative efficiency decrease between 25 and 70 °C	100–58.50 = 41.50%	100–85.90 = 14.10%	100–90.60 = 9.40%
Overall relative efficiency improvement @70 °C relative to nominal output	0% (benchmark)	85.9–58.5 = 27.4%	90.6–58.5 = 32.1%
Power consumed for improvement		0	1 W (two fans)
Expected net electricity power output @70 °C under STC conditions	58.50 W	85.90 W (**46.83%**)	89.6 (**53.15%**)

[42] and Berners-Lee [43]. Due to the cost of the fans, the cost of the fan-cooled system is found to be £32.51, while the passive cooled is found to be almost half of that at £16.12. The tooling costs for vacuum forming is expected to be similar for both designs due to the modularity of the design as shown in Fig. 5. Normally the capacity needed will be within the range of 1 kW to allow useful applications of the energy. Therefore, based on the suggested 100 W panel, there will be a need for 10 units to allow the production of the needed power. The cost of ten units are summarised in Table 4. Based on the 10 units capacity, the calculations of the payback period will be performed. Please note that a solar panel is rated by the amount of power it creates at Standard Test Conditions, or STC. These conditions include the intensity of the sun, 1000 W per square meter, the angle of the light hitting the panel directly and at the temperature of 25 °C.

6.2 Payback period

The estimated payback period is calculated by working out the potential KWh of the 1000 W solar panels (10 units) would produce in Kuwait. This was then compared against the potential production when using the cooling systems to evaluate the additional energy produced and money saved from the grid's cost. To achieve accurate calculations, the expected solar output in Kuwait is utilised using [33] database with the data of the laboratory experimental work and hourly experimental surface temperatures of panels in Kuwait at location 29° 20′ 12″ N 47° 54′ 17″ E. Figure 10 presents the average hourly electric power to be generated from a 1 kW capacity system at that location in Kuwait. The data is arranged to provide average hourly power production for each month. Note that between May and August there is a drop in power generated due to the increase in temperature as the database uses a standard Polycrystalline panel for the calculations. The calculations are based on 45° tilt angle with panels facing south.

Figure 11 presents the energy produced per month on average using the standard panel. The energy produced is between 140 kWh to just above 160 kWh, depending on the solar radiation and surface temperatures. Note as indicated in Fig. 11, there is significant drop in energy generated due to the increased ambient temperatures. In order to allow the evaluation of the cooling effect of the two technologies on the solar panel in Kuwait over a year, Fig. 12 presents the surface temperature of the panel which was tested in Kuwait between 2018 and 2019. Similar to the data in Fig. 1, the average hourly daily temperature is presented for each month. Months of January, February, July, August, October, November and December were captured experimentally, the rest of the data was interpolated using average air temperatures and the captured temperatures of the panel's surface.

Figures 10 and 12, when combined with the data of the laboratory results of Table 3, will allow the calibration of product relative efficiency to calculate the expected improvement based on the cooling processes. To ease the calculations,

Table 4 Estimated costs of components and carbon emission

Fan cooling system					Passive cooling system				
Part	Manufacturing method	Quantity per unit	Total cost per unit	Embodied carbon kg	Part	Manufacturing method	Quantity per unit	Total cost per unit	Embodied carbon kg
Front face	Injection moulding	1	£2.62	4.37	Front face	Injection moulding	1	£2.62	4.37
Inlet unit	Vacuum formed	1	£7.44	14.30	Inlet unit	Vacuum formed	1	£7.44	14.30
Fan unit	Vacuum formed	1	£3.77	5.08	Chimney unit	Vacuum formed	1	£3.77	5.08
Additional components					Additional components				
Part		Quantity per unit	Total cost		Part		Quantity per unit	Total cost	
Fan and accessories		2	£17.52	1.23	Pipe and accessories		1	£1.13	1.53
Nylon M3 × 10 mm screws		20	£1.16	2.13	Nylon M3 × 10 mm screws		20	£1.16	2.13
Total components cost per unit			£32.51	27.10	Total components cost per unit			£16.12	27.40
Cost of 10 units (1000 W capacity)			£325.1	271.00	Cost of 10 units (1000 W capacity)			£161.2	274.00

Table 5 Correction factors based on temperatures

Panel surface temperature (°C)	Standard panel (no cooling)		Passive cooling		Fan cooling	
	Relative efficiency (%)	Correction factor (*CFs*) For PVGIS	Relative efficiency (%)	Correction factor (*CFp*) For PVGIS	Relative efficiency (%)	Correction factor (*CFf*) For PVGIS
25	100%	1	100%	1.00	100%	1.00
30	97.90%	1	100%	1.02	100%	1.02
35	95.30%	1	99.50%	1.04	99.50%	1.04
40	92.70%	1	96.30%	1.03	98.40%	1.06
45	90.60%	1	94.80%	1.04	97.40%	1.07
50	88.00%	1	92.70%	1.05	95.90%	1.08
55	85.30%	1	92.10%	1.07	95.30%	1.11
60	71.50%	1	90.00%	1.25	93.70%	1.31
65	70.10%	1	87.40%	1.24	92.20%	1.31
70	58.50%	1	85.90%	1.46	90.60%	1.54

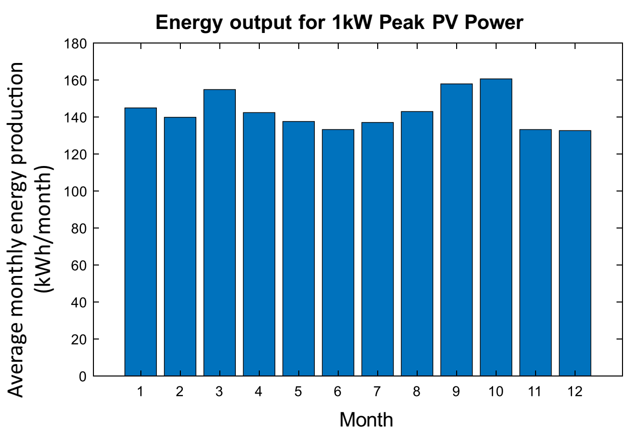


Fig. 11 Average monthly energy production for a 1 kW power output capacity panels (10 units of 100w), (45 degree facing south). (based on data from PVGIS [33])

Table 5 presents a new term, namely the correction factor (CF), which will be applied to evaluate the expected addition power output due to the cooling effect. Table 5 is used to provide the calibration equations which will help to produce accurate electric power output from the cooled solar systems.

For a standard panel, the correction factor equals to 1 regardless of the temperature, as it used as the reference (3rd column of Table 5). For the cooled panels, and at each panel temperature, the correction factor is developed based on the expected relative efficiency (columns 5 and 7 of Table 5).

Hence the correction factor (CF) at a given temperature is defined as:

$$CF = \frac{Relative\ efficiency\ of\ the\ cooled\ PV\ panel}{Relative\ efficiency\ of\ the\ standard\ uncooled\ PV\ panel}. \tag{5}$$

Figure 10 presents the expected standard uncooled panel at location in Kuwait; and hence the calibration equation for the standard uncooled panel will be:

$$CF_s = 1; \tag{6}$$

where CF_s is the correction factor equation to calibrated the expected electric power output for the standard solar panel.

Based on Table 5, for passive cooling, the correction factor (CF_p) can be calculated (based on columns 1 and 5) as:

$$CF_p = 0.000346T^2 - 0.024468T + 1.433959; \tag{7}$$

where T is the temperature of the surface of the panel in ^{o}C which is obtained from Fig. 12.

Similarly, for Fan Cooling the Correction Factor can be calculated (based on columns 1 and 7 of Table 5) as:

$$CF_f = 0.000365T^2 - 0.024454T + 1.418744; \tag{8}$$

where T is the temperature of the surface of the panel in ^{o}C which is obtained from Fig. 12.

Based on the data of Fig. 10, Fig. 12 and the three equations above (Eqs. 6, 7, 8), Fig. 13 presents the expected power output of the three types of panels, namely standard with no cooling, passive cooling and fan cooling. Figure 14 presents the monthly average energy generated. Note the increase in energy levels in the months between May and August due to the cooling process. The overall energy produced in a year is summarised in Fig. 15. This does not include the energy consumed by the fans for the fan cooled scenario; but Table 6 includes the full calculations of the payback period including the energy consumed by the fans.

Considering that the electricity price in Kuwait per kWh is about \$0.033 kWh (circa £0.0244) as estimated from Global

Petrol Prices [44], it is clear that the payback period at current energy prices is not an encouraging levels at more than 40 and 80 years for the passive and fan cooling respectively, see Table 6. However, the advantage of this cooling technology is adding a significant level of power during summer days when the surface temperature is at 70 °C or above, which could reach an increase in power output of 53.15% as shown in Table 3. Moreover, future electricity prices in Kuwait are expected to increase based on Fattouh and Mahadeva [45]. For example, based on UK prices (£0.172 per kWh), this payback period will be about 5.7 years and 11.5 years for passive and fan cooled systems respectively.

Assuming 632 g CO_2 per 1 kWh for Kuwait's grid as estimated from Global Economy (2021) [46] and Al-Mutairi et al. [47], the Carbon payback period seems more reasonable of less than 3 years. Table 6 presents the payback period for the embedded carbons for the additional components.

Interestingly, from Fig. 15, it can be seen that the improvement relative to the uncooled panel of annual average is about

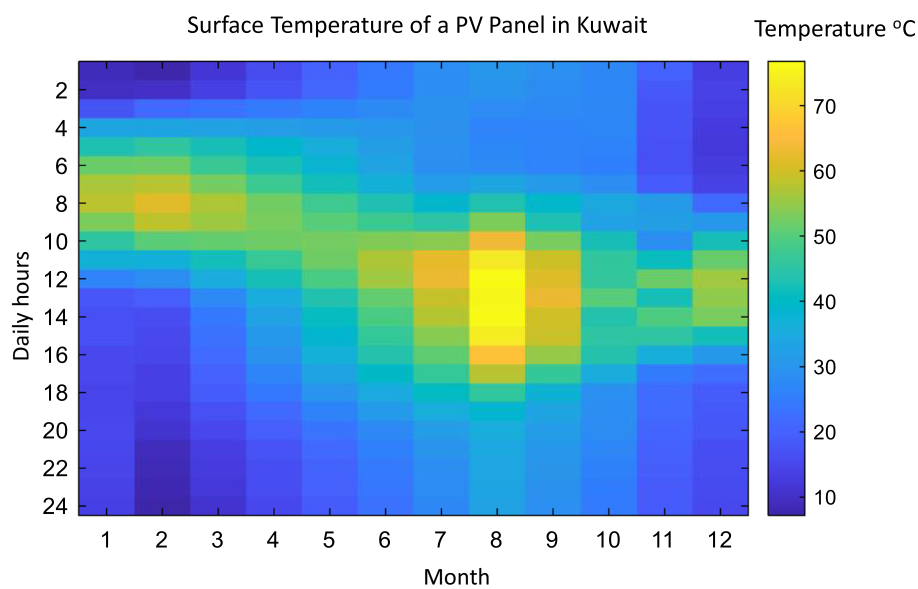


Fig. 12 A typical hourly average surface temperature of a PV panel in Kuwait

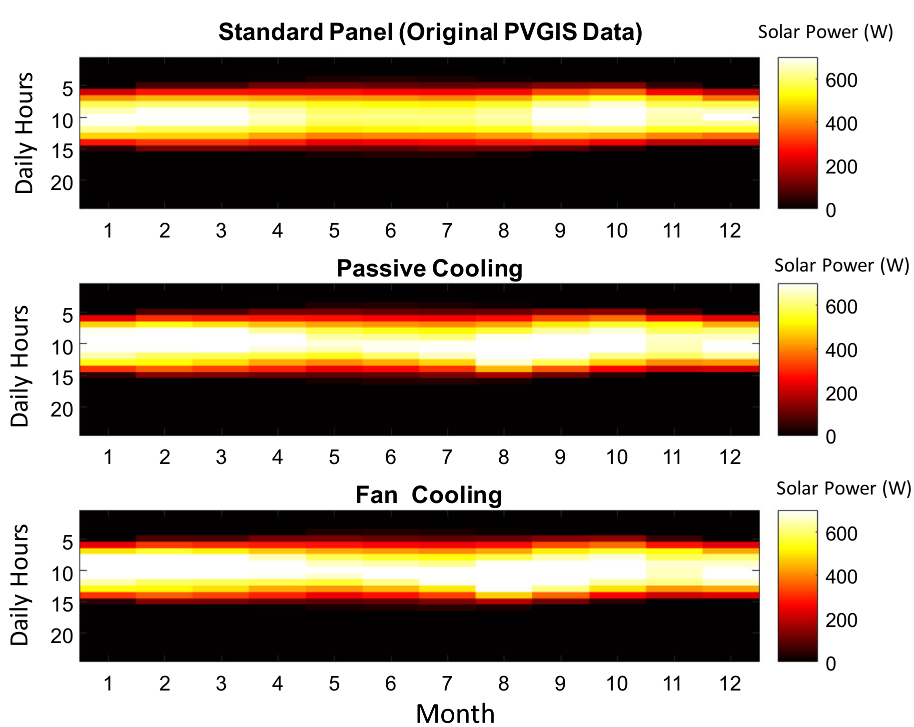


Fig. 13 Average daily electricity power output in Kuwait for a 45 degree facing south for a nominal 1 kW capacity with standard panel, passive cooling and fan cooling

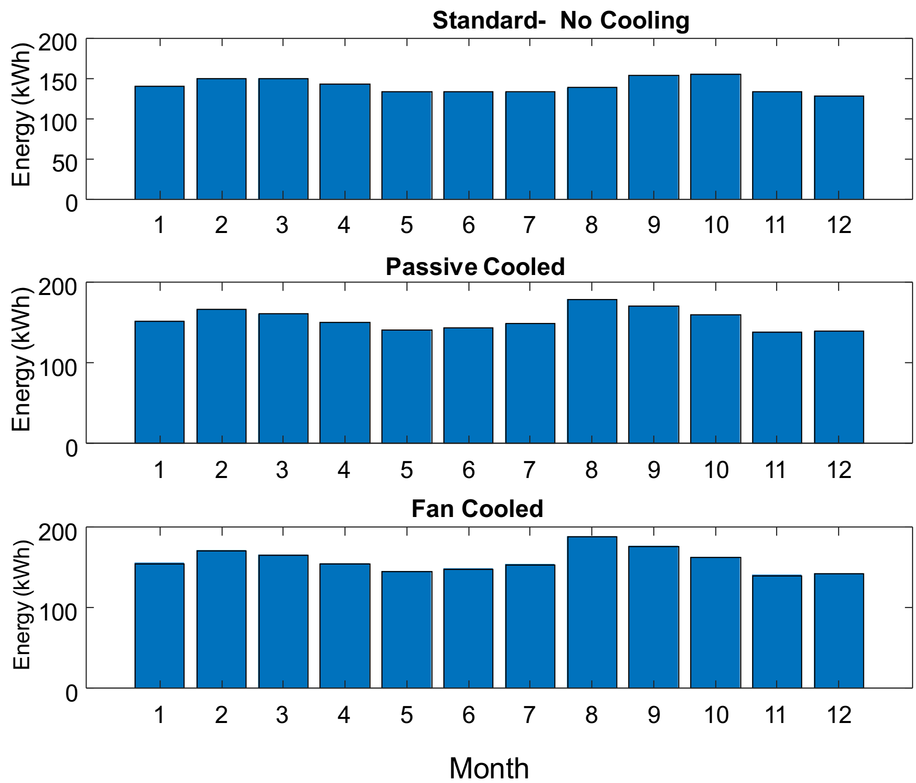


Fig. 14 Average monthly energy production for a nominal 1 kW power output capacity panels (45 degree facing south) for the standard, passive cooled and fan cooled panels

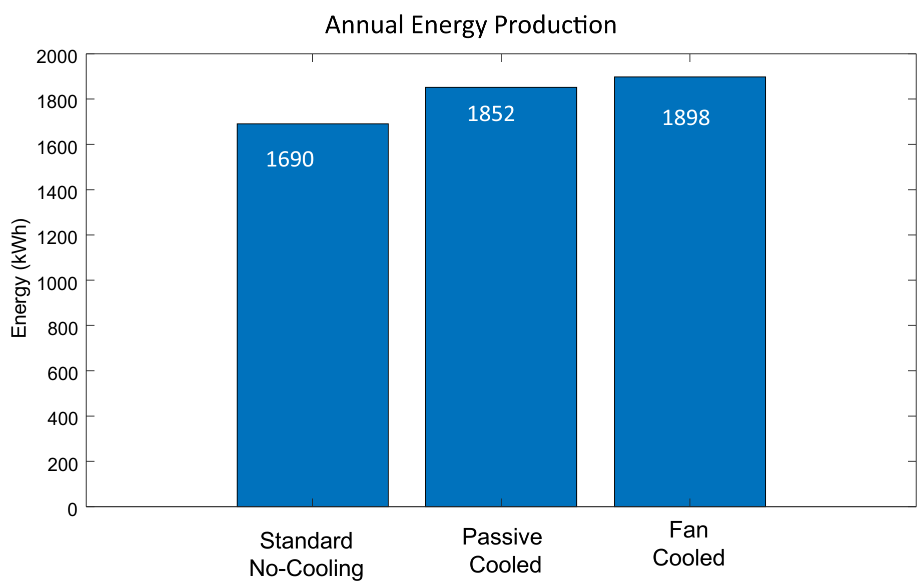


Fig. 15 The amount of energy produced in kWh per annum for the three systems, standard, passive cooled and fan cooled

9.58% and 12.3% for passive and fan cooled panels respectively. Such values are similar in range to the 12.26% relative increase reported by Zilli et al. (2018). In addition to the energy aspects, the economic and ecological issues have been articulated to address the knowledge gap as highlighted by Bahaidarah et al. [20]; and it seems the carbon saving, as seen in Table 6, are more attractive than the return on investment in this case study.

7 Conclusion

This paper has presented a new modular passive and active cooling systems and the associated test-rig to enable the implementation of the experimental work. The designs are scalable to allow a simple market introduction for a wide range of sizes. Nevertheless, the key novelty in this paper is in the proposed approach for the rapid assessment of new designs for cooling PV solar panels, named Rapid Evaluation

Table 6 Payback period calculations

	Additional energy produced per annum kWh	Energy of cooling accessories kWh	Net additional energy per annum kWh	Cost per 10 units £	Price per kWh (Kuwait) £	Financial savings per annum	£ Payback period (years) *Based on current Kuwait electricity prices*	Carbon payback period (years)
Passive cooled	1852–1690 = 162.00	0	162.00	£161.20	£0.0244	£8.10	40.72	274/102.38 = 2.67 years
Fan cooled	1898–1690 = 208.00	43.00	165.00	£325.10	£0.0244	£8.25	80.75	271/102.38 = 2.64 years

of Solar panels Cooling (RESC). It is related to international collaboration between the UK and Kuwait. To assess the design of the cooling system and life cycle analysis, there is a need to evaluate the annual performance rapidly within short period of time to allow rapid product development and assessment for the technology of choice and reduce the investment's risk. The suggested approach integrates data from three sources: lab testing of the cooling technologies using a bespoke test-rig, experimental data in-situ for the expected surface temperatures of panels and the expected performance of a standard solar panel of the same type from available databases such as PVGIS [33]. The database includes the expected performance in-situ of the standard solar panel. By combining the in-situ surface temperatures of a standard solar panel with the lab testing of the cooling technologies at different temperatures, this allows a comparative evaluation and an estimation of the additional electricity and the payback period in terms of embodied carbon and financial investment. Certainly there may be variability in the parameters that control the cooling process and the environmental parameters on site, but the paper has provided evidence of the success of this novel approach and that the suggested technologies are suitable, particularly to generate additional electricity at high temperatures when the demand is huge causing scheduled electricity power cut in some occasions. The cooling process could provide an additional 53.15% of power during periods of extreme hot temperatures. The results also show that passive cooling is slightly less efficient than fan cooling; but the passive cooling is expected to be more reliable and cheaper to fabricate due to the absence of the electric fans and the additional electric accessories. The suggested approach provides a systematic method to rapidly assess cooling systems of PV panels for swift introduction to market in hot arid counties and hence encourage the growth of renewable energy technologies.

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