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Adaptive cooling framework for Photovoltaic systems: A seasonal investigation under the terrestrial conditions of Sharjah, UAE

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Abstract. The increment of PV operating temperature has a significant impact on the overall efficiency, longevity, and degradation of PV systems. In this notion, researchers have sought to investigate different cooling methodologies to minimize the impact of abrupt operating temperatures. However, most investigations discuss the impact of the working base fluid in small periods without proposing methods for temperature regulation based on defined thresholds. In this study, an adaptive cooling framework is proposed through thermal and electrical modeling to examine the cooling effect on a 2.88 kW grid-connected PV system installed in Sharjah, UAE. An operating temperature threshold of 55°C is considered based on the annual average operating temperature, to facilitate adaptive cooling. The framework is modeled based on heat transfer thermodynamic laws and implemented on MATLAB using experimentally driven measurements collected from the above-mentioned system for December, March, June, and September. As a result, the proposed framework has presented notable merits in terms of electrical and thermal characteristics across the four different seasons. The highest heat extraction was observed in September, where a reduction of 25.36% was observed in PV operating temperature, showing the effectiveness of temperature regulation in harsh weather conditions. As a result, the electrical characteristics have improved significantly leading to an 8.79%, 6.39%, and 6.58% enhancement in maximum power output, maximum voltage, and electrical efficiency, respectively.

Introduction

The continuous depletion of conventional energy resources has led to the introduction of clean and renewable energy resources (RES) to tackle the escalating consequences of climate change [1–3] Solar energy has been popular amongst other RES due to its reliability, abundance, and zero-net fuel dependence, hence leading the way for the development of photovoltaic (PV) systems for clean electricity generation [4].

PV modules generate electrical energy based on two environmental factors, solar irradiance, and ambient temperature [5]. Typically, there is a direct proportionality for power with respect to solar irradiance [6], while there is an indirect proportionality with respect to the ambient temperature [7]. The PV cell performance is heavily dependent on environmental conditions, specifically operating temperature [8]. The increment of the PV module operating temperature dramatically reduces the overall efficiency of the PV panel. In this notion, cooling of PV modules is essential to sustain the PV system's longevity and performance. The extraction of dissipated heat from PV modules is critical to enhancing the operation of the PV cell [9]. The employment of water as a working base fluid has been a popular and viable cooling technique amongst other available techniques due to its feasibility on different system levels [10].

Several studies in the literature have reported the enhancement in PV module performance through the significant reduction in PV module operating temperature. A study reported by [11], investigated the impact of temperature of the PV cell on its performance through a range of 25°C – 60°C while maintaining a constant solar irradiance exposure. A laboratory-based experiment also conducted in [12], investigated the impact of operating temperature from a range of 25°C – 55°C while maintaining a 1000 W/m^2 solar irradiance. A simulation study reported by [13], combined artificial neural networks (ANN) and capabilities of reduced module operating temperature. The study demonstrated that with a reduction of 10°C in module operating temperature, the number of PV modules can be reduced by 12 % while supplying the same electrical capacity. An experimental study reported in [14], investigated the impact of water as a working base fluid for front surface heat extraction on a large-scale PV system. The study reported an increase of 9.76% in output power generation and a maximum efficiency of up to 13.47% while generating a thermal difference of 2.3°C. A study investigated under both laboratory and experimental conditions is reported in [15]. The validation of the effectiveness of water as a working base fluid was observed as a reduction of 24 K in PV module operating temperature was observed. As a result, the output power was enhanced by 10% as compared to the uncooled PV module. The employment of water as the cooling technique was experimentally investigated during July as reported in [16]. The study reported that a 10% increase in PV output power was observed due to the reduction of 20% in PV surface temperature, thus improving the PV module conversion efficiency by 14%. Additionally, the optimization of the water cooling process during the harsh climatic conditions in the UAE is reported [17]. The experimental investigation proposes an adaptive technique based on a defined 55°C temperature threshold to facilitate automated front surface cooling. As a result, a decrement of 17.3°C in PV module operating temperature was observed with an extracted heat of 15.41°C. In this notion, the output power and output voltage increased by 39.21% and 16.31%, respectively achieving a 12.5% electrical conversion efficiency. Another study reported the employment of automated timers for the automatic pumping of water for the cooling process as reported in [18]. Under summer conditions of the UAE, the experimental study is conducted to reveal the performance of a timed cooling operation on PV module performance. As a result, the average output power increased by 1.6 %, while decreasing the operating temperature by 6% on average. Additionally, the investigation of a small-scale controlled water spraying system was investigated by [19]. The self-cleaning methodology observed an improved electrical efficiency of 2.53% and an overall system efficiency of 83.3%.

The scientific literature explored the significant impact of deploying water as a working base fluid to enhance the performance of PV systems, especially in harsh and arid weather conditions. However, most investigations report the operation of water as a working base fluid for a specific day of the year, while the performance may vary throughout the entire year. The concept of investigating water as a working base fluid for different seasons of the year as well under defined temperature thresholds needs to be highlighted, to optimize the cooling procedure.

In this notion, this study presents a modeling approach to characterize the thermal properties of water as a working base fluid, illustrating the cooling effect and its impact on the PV module's electrical and thermal properties. The developed model is based on a 55°C temperature threshold, which operates as a gradient for facilitating an adaptive cooling effect, to optimize the cooling process when operating temperature is critical. Moreover, the study considers a 2.88 kW grid-connected PV system as a practical case study installed in Sharjah, United Arab Emirates, to model the impact of adaptive front surface cooling across four different seasons based on experimental measurements retrieved from the system, presenting variable weather conditions.

Dependence of electrical performance on thermal parameters

Environmental parameters have a prominent impact on the electrical conversion efficiency of PV systems, and their irregularity leads to deviation and instability in their overall performance. The United Arab Emirates is blessed with large exposure to solar irradiance of an average of 2285 kWh/m^2 annually, presenting the promise of PV system deployment [20]. However, 20% of sunlight is converted and generated into electricity, while the remainder is dissipated as waste heat leading to degradation in PV system performance and lifespan. PV cell technologies are defined with a power temperature coefficient (**β**), that demonstrates a degradation rate in %/°C with every 1°C above the standard testing conditions (STC) i.e., 25°C.

The dramatic impact of temperature can be observed during the summer periods, when the PV module operating temperature may reach up to 70°C. Such abrupt operating temperature leads to a significant reduction in output power generation. A comparison between summer and winter temperature profiles for July and December, respectively as illustrated in Fig. 1.

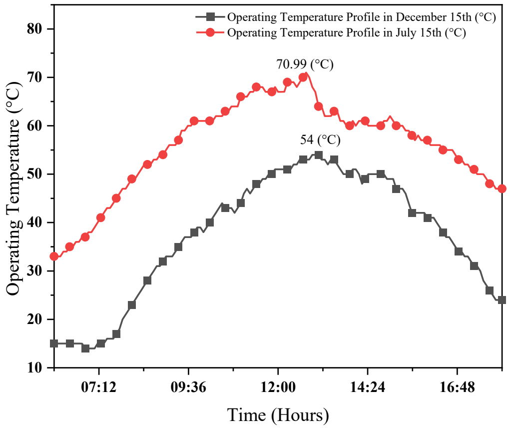


Fig. 1. PV module operating temperature profile comparison between summer and winter seasons for July 15th and December 15th.

In this notion, critical electrical parameters have been defined based on theoretical and mathematical interpretations as reported in [21], demonstrating the impact of temperature on maximum power output, maximum voltage output, and the electrical conversion efficiency for PV modules.

The maximum power output (P_{mpp}) at a single interval is demonstrated by Eq. 1 as follows:

$$P_{mpp} = P_{STC} \times \frac{G}{G_{STC}} \times \left[1+\beta_{STC}\left(T_{PV} - T_{STC}\right)\right] \tag{1}$$

where P_{STC} is the power prescribed by the manufacturer at standard testing conditions (STC), G is the solar irradiance measured at actual conditions, G_{STC} is the solar irradiance at STC conditions, which coincides to 1000 W/m^2, β_{STC} represents the power temperature coefficient that typically represents a negative decrement in power by %/1°C as the operating PV temperature surpasses the prescribed STC conditions, i.e., 25°C. This metric is usually mentioned by the PV manufacturer and is dependent on the T_{PV} representing the measured operating PV module temperature and T_{STC} is the operating PV module temperature at STC conditions, which coincides to 25°C. The power temperature coefficient typically varies between various PV technologies as previously discussed in Table 1.

Similarly, the maximum voltage output (V_{mpp}) at a single interval is demonstrated by Eq. 2 as follows:

$$V_{mpp} = V_{STC} \times \frac{G}{G_{STC}} \times \left[1+\gamma_{STC}\left(T_{PV} - T_{STC}\right)\right] \tag{2}$$

where V_{STC} is the voltage prescribed by the manufacturer at STC conditions, which coincides with the open circuit voltage (V_{oc}), γ_{STC} represents the V_{oc} temperature coefficient that typically represents a negative decrement in voltage by %/1°C as the operating PV temperature surpasses the prescribed STC conditions, i.e., 25°C.

Furthermore, the electrical conversion efficiency (η) at a single interval is demonstrated by Eq. 3 as follows

$$\eta = \eta_{STC} \times \left[1 + \beta_{STC}\left(T_{PV} - T_{STC}\right)\right] \tag{3}$$

where η is the electrical efficiency prescribed by the manufacturer at STC conditions.

Research Methodology

Experimental State-of-the-art

A 2.88 kW grid-connected PV system is established at the University of Sharjah main campus on the rooftop of the W-12 building (Lat. 25.34° N; Long. 55.42° E) as illustrated in Fig. 2. The system operates through a real-time data acquisition system, for instantaneous access of system data [22]. The system was previously discussed for its operation both in small and large periods, showing superior data recording capability and complete infrastructure [23]. In addition, the system operates as a complete grid-connected PV system, injecting AC electrical energy to the 3-phase local utility grid. Moreover, the on-grid PV system records electrical and environmental parameters at 5-minute intervals.

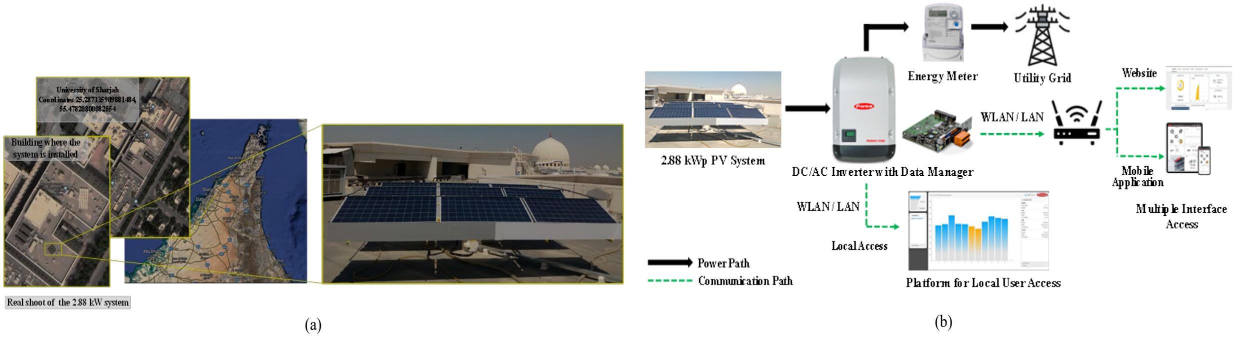


Fig. 2. Demonstration of (a) Established on-grid PV system (b) Power and Communication Loop

Adaptive Cooling Framework model

Based on the previously discussed state-of-the-art, a model is proposed and simulated through MATLAB, to depict the characteristics of water as a working base fluid based on the annual measured data retrieved from the real-time data acquisition hub. Water is selected as a working fluid due to its exceptional heat transfer characteristics and feasible implementation. The constant thermophysical properties are considered to show a uniform effect across all months, except with the change in inlet water temperature as per the given month. The months selected for data variability are December, March, June, and September demonstrating the variability in PV module operating temperature, validating the impact of the proposed temperature regulation technique.

The thermal modeling of water as a working base fluid is defined based on a set of thermodynamic laws, to depict the behavior of water. The heat absorption energy (Q) is defined by Eq. 4 as follows:

$$Q = m \times c \times \Delta T = m \times c \times \left(T_{PV} - T_{in}\right) \tag{4}$$

Where m is the mass of the water in kg, c is the specific heat of the water in J/kg.k, and ΔT is the temperature difference between the operating temperature and the water temperature in the Inlet tank assumed by its respective weather conditions.

The mass of water (m) is computed based on Eq. 5 as follows:

$$m = \rho \times A \times d \tag{5}$$

Where ρ is the density of water in kg/m^3, A is the surface area of the PV system in m^2, and d is the thickness of the water film in millimeters (mm).

Therefore, the temperature reduction ($T_{reduction}$) is computed through Newton's law of cooling as depicted in Eq. 6 as follows:

$$T_{reduction} = \frac{Q}{h \times A \times t} \tag{6}$$

Where h represents the convective heat transfer coefficient in W/m^2.K, and t represents the time in seconds over which cooling occurs. The value considered is 250 W/m^2.K since it is typical for harsh weather conditions such as the UAE, where it typically ranges from 50 – 300 W/m^2.K.

In this notion, the thermal model proposed will simulate the cooling effect under a temperature threshold of 55°C, which is selected based on the annual average temperature. The parameters of the thermal model are selected and presented in Table 1, which is based on the experimental conditions and location of Sharjah, UAE.

Table 1. Selected thermal parameters for the proposed adaptive cooling framework

Description	**Value**
Specific Heat [J/kg.K]	4186
Density [kg/m^3]	1000
Convective heat transfer coefficient [W/m^2/k]	250
Surface Area of PV system [m^2]	18.5
Thickness of water film [mm]	1
Time over which cooling occurs [s]	19.55
Average water temperature for cooling per month [°C]	December: 24.5 March: 32.5 June: 34.5 September: 34.5

Results and Discussion

The experimental data measured from the on-grid PV system is considered across an entire day from 6 AM to 6 PM during four distinct months. In principle, the thermodynamic laws discussed are implemented using MATLAB to assess the performance of the PV system across four distinct months both electrically and thermally, through the MATLAB script development.

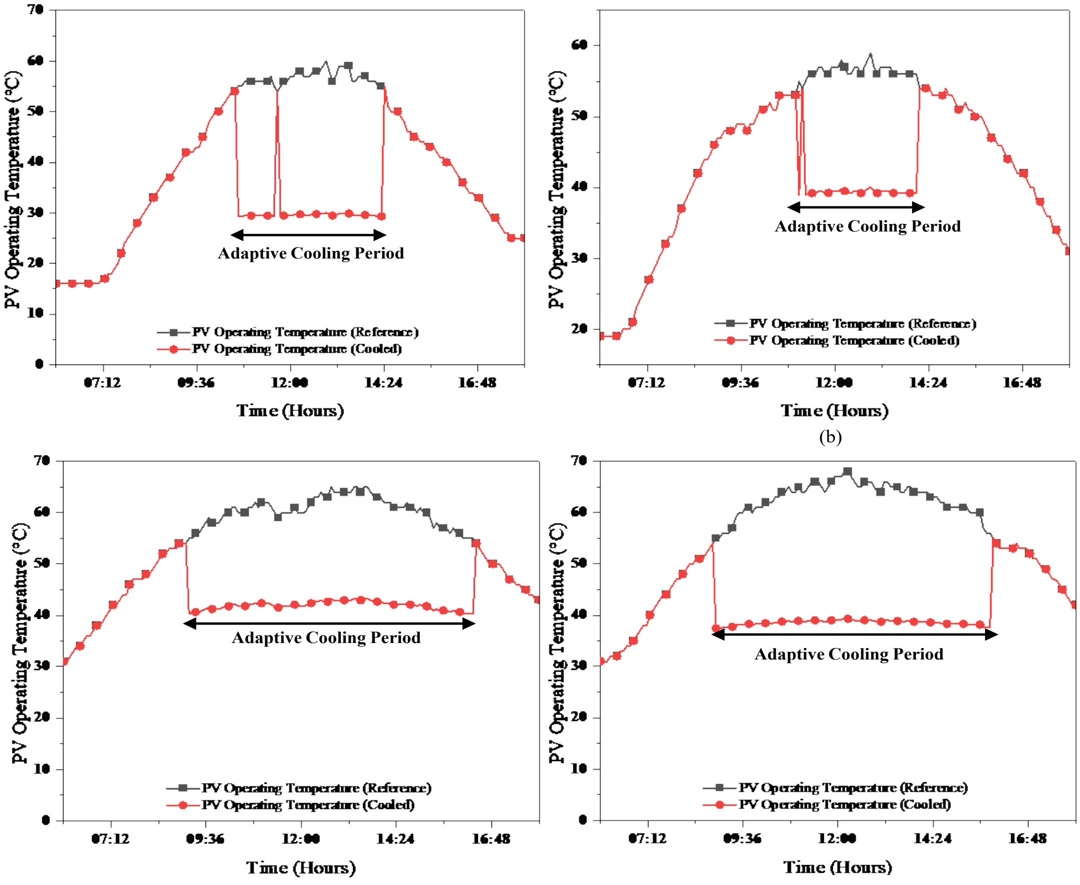
The PV module operating temperature is the primary figure of merit to be assessed based on the proposed framework. Based on the computations discussed above, longer periods of cooling are required during June and September as compared to December and March. Thus, an average PV operating temperature reduction of 20.43% and 25.35% is observed during June and September, respectively. The reduction in operating temperature is illustrated in Fig 3 and a summary of the temperature reduction is presented in Table 2, presenting the notable heat extraction during all four seasons using the above-mentioned thermodynamic laws.

Moreover, the relative decrease in operating temperature has led to an increment in the maximum power point. The maximum power output as computed in Eq. 1, presents an average increment of 6.3% and 8.8% in June and September, respectively, as demonstrated in Fig. 4.

The relative enhancement is also observed across other parameters such as the maximum operating voltage and electrical conversion efficiency as computed by Eqs. (2)-(3), presenting the adaptability of temperature regulation across different seasons for maintaining PV system lifetime and longevity. Thus, the proposed adaptive cooling framework proves viability when implemented practically on large-scale PV systems. The performance assessment of the proposed adaptive cooling framework is presented in Table 3, providing improved electrical performance across all seasons of the year, and maintaining high electrical efficiency at longer periods.

Table 2. Summary of operating temperature assessment based on proposed adaptive cooling framework for large-scale on-grid PV system

Description	**Period of Adaptive Cooling [Hours]**	**Operating Temperature [°C]**		
		Uncooled Average	*Cooled Average*	***Average Decrement***
December	10:40 AM – 2:20 PM	41.05	32.78	**20.13%**
March	11:05 AM– 2:05 PM	45.24	40.98	**9.41%**
June	9:10 AM – 4:20 PM	54.24	43.16	**20.43%**
September	8:55 AM – 3:50 PM	55.32	41.29	**25.36%**



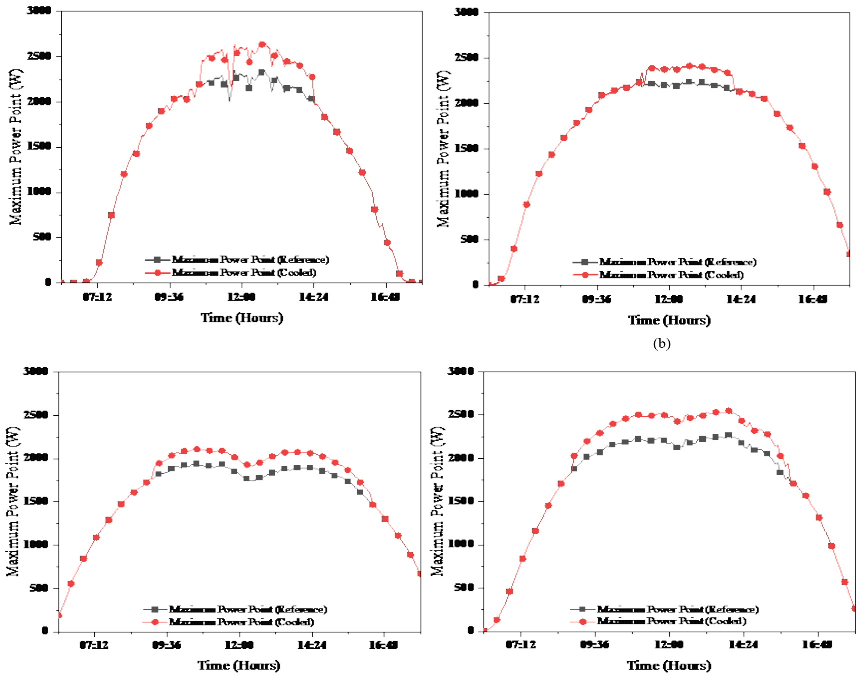
(b)

(d)

Fig. 3. Comparative assessment of operating temperature reduction during adaptive cooling process for large-scale on-grid PV system during selected days from (a) December (b) March (c) June (d) September

Table 3. Summary of electrical characteristics based on proposed adaptive cooling framework for large-scale on-grid PV system

Description	**Maximum Power Point [W]**			**Maximum Operating Voltage [V]**			**Electrical Conversion Efficiency [%]**		
	Uncooled Average	*Cooled Average*	***Average Increment***	*Uncooled Average*	*Cooled Average*	***Average Increment***	*Uncooled Average*	*Cooled Average*	***Average Increment***
December	1411.73	1497.88	**6.10%**	168.12	175.67	**4.49%**	15.42%	15.96%	**3.50%**
March	1656.48	1700.73	**2.67%**	197.39	201.26	**1.96%**	15.21%	15.41%	**1.31%**
June	1553.70	1651.51	**6.30%**	186.71	195.29	**4.59%**	14.51%	15.26%	**5.17%**
September	1661.28	1807.34	**8.79%**	200.35	213.16	**6.39%**	14.44%	15.39%	**6.58%**



(b)

(d)

Fig. 4. Comparative assessment of M_{PP} during adaptive cooling process for large-scale on-grid PV system during selected days from (a) December (b) March (c) June (d) September

Summary

This paper proposed a modeling framework for facilitating adaptive cooling for photovoltaic systems, for enhancing system efficiency and longevity. The proposed framework was implemented using MATLAB and experimentally driven environmental conditions, to simulate the thermal and electrical characteristics of a 2.88 kW grid-connected PV system in Sharjah, UAE. A temperature regulating threshold of 55°C was considered, to simulate the system characteristics for December, March, June, and September, providing a wide range of variability in PV module operating temperatures. The highest operating temperature reduction was observed in September with 25.36%, showing the effectiveness of temperature regulation in harsh weather conditions. As a result, the electrical characteristics have improved significantly leading to an 8.79%, 6.39%, and 6.58% enhancement in maximum power output, maximum voltage, and electrical efficiency, respectively. As a future work, the temperature threshold response time will be validated under experimental conditions and incorporation of advanced hardware. Additionally, the utilization of machine learning techniques to optimize the necessary thermal parameters will be investigated for improved energy efficiency and usage.

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