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Enhancing Photovoltaic Panel Efficiency through Water-Cooling: A Parametric Comparative Evaluation of Energetic, Economic, and Environmental Benefits

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Abstract

The pressing need for more effective solar technology is highlighted by the global transition away from fossil fuels and toward renewable energy sources. Despite the enormous potential of photovoltaic (PV) panels, efficiency losses in high-temperature conditions limit their performance. The purpose of this study is to theoretically evaluate the energy, financial, and environmental advantages of different water-cooling techniques intended to improve the sustainability and operating efficiency of PV panels. In contrast to traditional research, this work quantifies increases in energy output, cost savings, and CO₂ emission reductions across various cooling configurations by a thorough parametric analysis inside a single theoretical framework. To simulate how various water-cooling methods affect PV panel performance, a mathematical parametric model was created. Energy production, cost savings, and carbon footprint reduction were among the key performance metrics computed and compared for PV applications in relation to the consumption ratio R , which is defined as the ratio of the actual building load to the maximum PV power output, or the amount of energy consumed by the house from the PV panels.

With an annual energy gain of 1354.10R kWh per panel, cost savings of 582.26R USD, and CO₂ emission reductions of 785.37R kg, jet water impingement cooling (JWPV) outperformed

the other technologies under evaluation. However, with energy gains of 1061.53R kWh, savings of 456.46R USD, and CO₂ reductions of 615.68R kg, evaporative cooling (EPV) produced the least amount of improvement. These results highlight how important efficient cooling is to improving PV panel performance and developing sustainable solar energy solutions.

Keywords: Photovoltaic Panels; Water Cooling Techniques; Energy Efficiency Enhancement; Sustainability in Solar Energy; CO₂ Emission Reduction; Jet Water Impingement Cooling.

Nomenclature:

CO₂: Carbon dioxide

R: Consumption Ratio

PV: Photovoltaic panel

LPM: Liters per minute

PVT: Thermal photovoltaic panel

CPV: Cooled photovoltaic panel

CCPV: Concentrated Cooled photovoltaic panel

USD: United States Dollar

IPV: Immersed Photovoltaic Panels

SPV: Spray Cooling Photovoltaic Panels

PVWT: Photovoltaic water Thermal Systems

FPV: Floating Photovoltaic Panels

MCPV: Micro Cooling Photovoltaic Panels

EWHE: Earth-Water Heat Exchanger

JWPV: Jet water photovoltaic panel

EPV: Evaporative photovoltaic panel

1. Introduction

Fossil fuels have long been the primary source of energy generation on a worldwide scale. These fossil fuels have become an environmental concern due to the destructive impact they have on the environment. As a result, the need for clean and renewable energy sources has recently surged over the world to help minimise the use of fossil fuels [1]. In addition, traditional fossil fuels are costly, contribute to climate change, and deplete the ozone layer by emitting greenhouse gases into the atmosphere. To reduce our dependency on fossil fuels and their negative environmental impact, renewable and sustainable energy options are becoming crucial [2].

In recent years, renewable energy sources have garnered increasing attention as the world seeks to address the growing concerns of climate change, environmental degradation, and the depletion of finite resources [3-4]. Among these renewable sources, solar energy has emerged as a key player in the global shift towards more sustainable energy systems [5-6]. PV panels have gained significant traction due to their ability to convert sunlight into electricity efficiently and their minimal environmental impact during operation [7-8]. As technology advances and production costs continue to decrease, PV systems become a more attractive alternative to traditional non-renewable energy sources. This growing emphasis on solar power reflects a broader commitment to reducing greenhouse gas emissions and achieving long-term energy sustainability [7-8].

However, several factors limit the energy output of PV systems, including wind, humidity, soil conditions, shading, and temperature [9]. Among these, temperature plays a particularly significant role in affecting the efficiency of PV panels. For every degree Celsius increase in the temperature of a photovoltaic panel above the standard test conditions, its efficiency decreases by approximately 0.5% [10]. This temperature-related decline in efficiency highlights the importance of managing thermal conditions to optimize the performance of PV systems in varying environmental settings.

So many cooling techniques are explored and used by researchers, as Kotla et.al [11] investigates the potential of using nanoparticles to improve the efficiency of Single Basin Solar Distiller (SBD), Praveenkumar et. al [1] studies experimentally the effect of a fanless CPU heat pipe on the performance of a PV module, in other study Praveenkumar et. al [12] uses a thermoelectric cooling mechanism to cool a PV panel under real weather conditions, also Praveenkumar et. al [13] proposed a passive cooling mechanism using designed

aluminum sheets mounted at the rear side of the PV module, Naseer T. Alwan et. al [14] developed an improved condensation-evaporation process that includes spraying a tiny layer of water over a heated absorber plate. Natural convection transports the resultant water vapour to an adjacent aluminium plate, Ephraim Bonah Agyekum et. al [15] investigated the effect of simultaneous dual-surface cooling on the performance output of a photovoltaic (PV) module. Sathish et. al [16] investigated a low-cost miniature salt-gradient solar pond, PraveenKumar et. al [2] intends to improve the efficiency of solar photovoltaic (PV) panels by combining inexpensive aluminium reflectors, aluminium heat sinks, and a phase change material (PCM) loaded with zinc oxide (ZnO) nanoparticles, PraveenKumar et. al [17] made an analysis between a reference PV panel, a photovoltaic thermal (PVT) system cooled with water, and a PVT system equipped with thermoelectric generators (TEGs) and nanofluid, Ravinder Kumar et. al [18] Experimental investigation into the performance enhancement of single- and double-effect solar stills employing silver balls and nanofluids for bioactivation, C. Suresh et. al [19] examines the use of nanofluids in solar distillation, with an emphasis on optimising their composition, optical characteristics, and thermal performance, Gali Sai et. al [20] evaluates the performance of double-slope solar stills (DS) improved with ZnO nanofluids derived from sugarcane juice (SZN) via spray pyrolysis, showing its potential to promote sustainable water desalination technology, Suvaranjan Sutar et. al [21] created A unique design with quadratic-shaped ribs attached to the absorber plate in various orientations and a transverse flow pattern consisting of one straight side and one curved side is subjected to compressive analysis using numerical methods.

Among the various cooling technologies that researchers are exploring, water-based cooling techniques, whether used as a standalone method or integrated with other cooling approaches, stand out as one of the most promising solutions. These water-cooling systems offer significant potential in enhancing the efficiency and performance of photovoltaic panels by effectively reducing temperature-related losses, making them a key area of focus in advancing solar energy technologies.

Water cooling for PV panels can be implemented through several innovative methods, each offering unique advantages in enhancing panel efficiency:

- Immersed Photovoltaic Panels (IPV) are directly submerged in water, providing effective cooling through thermal conduction.

- Floating Photovoltaic Panels (FPV) are positioned above a water surface, utilizing the water beneath to help dissipate heat, reducing the panels' temperature and improving their performance.
- Spray Cooling (SPV) involves spraying water onto the surface of the PV panels through strategically placed nozzles, allowing for direct heat dissipation.
- Earth-Water Heat Exchanger (EWHE) circulates water through pipes buried in the ground. This technique takes advantage of the temperature difference between the ground and ambient air to cool the PV panels effectively.
- Micro Cooling (MCPV) uses microchannels beneath the PV panels to circulate coolant, providing localized cooling and improving efficiency by reducing hot spots.
- Evaporative Cooling (EPV) utilizes the phase change of the coolant from liquid to vapor to leverage the cooling effect of evaporation to lower the temperature of the PV panel.
- Photovoltaic Thermal Systems (PVT) combines thermal collectors with photovoltaic modules, capturing electricity and thermal energy and improving the system's overall efficiency.
- Jet impingement enhances heat transfer by directing a high-speed fluid stream onto a target surface, significantly improving thermal performance. This technique is widely utilized for heating and cooling applications, offering exceptional efficiency across diverse temperature ranges.

These various water-cooling methods are illustrated in Fig. 1, each offering a distinct mechanism for enhancing the energy performance and longevity of PV panels through effective temperature management.

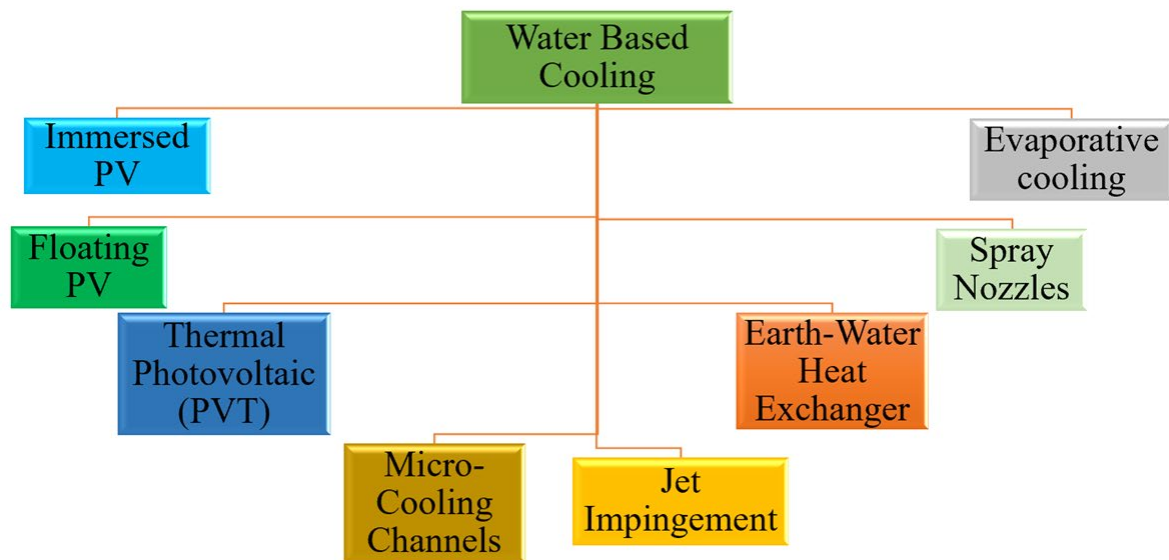


Fig. 1. Water cooling techniques.

An experimental study conducted by Mehrotra et al. [22] showed that immersing Polycrystalline PV panels in water increases the electrical efficiency by 17.8% at a depth of 1cm. Elminshawy et al. [23] reported a temperature reduction of about 15.10% and an increase in the electric generation of up to 20.76% when submerging partially the PV panel compared to land PV. Moreover, Bevilacqua et al. [24] introduced a PV panel with spray cooling on its back surface. The results showed that the electrical output increased by 7.8%, along with a 28.2% reduction in the cells' temperature. Bhatnagar et al. [25] conducted an experiment using V-shaped micro-cooling channels, analyzing the effects of varying flow rates on PV panel performance. The results indicated that increasing the water flow rate from 0.3 LPM to 0.6 LPM led to corresponding increases in maximum power output by 4.4%, 3.29%, 2.26%, and 1.71%, respectively. The panel temperature dropped by 12.7°C at 0.3 LPM, 9.5°C at 0.4 LPM, and 13.9% at 0.6 LPM.

Mansour et al. [26] investigated the effectiveness of evaporative cooling pads on two types of PV panels: CPV (cooled PV panel) and CCPV (concentrated cooled PV panel). The results demonstrated that the average daily power increment ratio (PIR) for CPV systems ranged from 4.7% to 7.4%. In contrast, depending on environmental conditions, CCPV systems achieved a higher PIR, varying between 6.7% and 12%. Husam et al. [27] used jet water impingement to cool and improve a thermal photovoltaic panel. The results showed that when the mass flow rate changes from 0.033 to 0.16kg/s at each solar radiation level, the PVT collector with jet

impingement achieved a maximum thermal efficiency of 72%, a PV efficiency of 11.35%, and an overall PVT efficiency of 81%. Finally, Jakhar et al. [28] explored a novel hybrid system, where an integrated photovoltaic thermal solar system (IPVTS) is combined with an EWHE to enhance energy efficiency and thermal regulation. The findings showed an increase in the experimental electrical efficiency of IPVTS integrated with EWHE by 1.02-1.41% compared to without cooling.

The reviewed literature, categorized based on methodology, climate conditions, study type, and key findings, is summarized in Table 1.

Table 1: A literature summary on some water-cooling techniques.

Cooling Type	Climate	Type	Results	Reference
Immersing Polycrystalline PV Panel	Bhopal-India	Experimental	Efficiency increased by 17.8% at an optimal depth of 1cm water immersion	[22]
Partially submerged floating photovoltaic (PSFPV)	Port Said, Egypt	Experimental	A Temperature reduction of about 15.10% and a more electric generation of up to 20.76% compared to land photovoltaic panels	[23]
Spray cooling on the back surface	University of Calabria, Italy	Numerical & Experimental	A performance comparison with a non-cooled PV panel revealed an average increase of 7.8% in electrical output during peak solar radiation hours, along with a 28.2% reduction in average cell temperature.	[24]
A PV panel equipped with V-shaped aluminum cooling channels on its back surface.	India	Experimental	When varying the flow rates between 0.3LPM, 0.4LPM, 0.5LPM, 0.6LPM an increase in the maximum power by 4.4 %, 3.29%, 2.26 %, 1.71 % respectively	[25]
Evaporative pads used on two types of PV panels Cooled PV and Concentrated PV	Egypt	Experimental	The average daily power increment ratio (PIR) varies between 4.7% and 7.4% for CPV systems, while CCPV systems exhibit a PIR ranging from 6.7% to 12%	[26]

Water Jet impingement designed to cool a PVT	Iraq	Numerical & Experimental	With jet collision cooling, the electrical efficiency is 11.35% (at 1000 W/m ²), and the thermal performance increased to 81% at 1000 W/m ²	[27]
Integrated photovoltaic thermal solar system (IPVTS) combined with an EWHE	Pilani, India	Experimental	The results showed that with EWHE cooling, the experimental electrical efficiency of IPVTS increased by 1.02– 1.41% compared to without cooling.	[28]

The table provides a comparative comparison of diverse water-based cooling methods for photovoltaic (PV) panels in various climates and experimental conditions. Among the methods, partial submersion (PSFPV) in Port Said, Egypt demonstrated the most significant improvement, yielding a 20.76% increase in electricity generation and a 15.10% drop in temperature. Submerging polycrystalline panels in Bhopal, India resulted in a 17.8% enhancement in efficiency at a depth of 1 cm. Water jet impingement in Iraq exhibited a notable enhancement in thermal efficiency to 81% and an increase in electrical efficiency to 11.35%. Spray cooling and V-shaped aluminium channels produced moderate electrical enhancements of 7.8% and 4.4%, respectively, whilst evaporative pads and IPVTS-EWHE systems exhibited diverse outcomes, with improvements between 4.7% and 12% and 1.02% to 1.41%, respectively. In general, methods that involve direct contact with water, such as immersion and jet impingement, typically result in greater efficiency improvements.

From the above literature, the following principal research gaps may be discerned:

- 1. Lack of Theoretical Parametric Studies:** Most of the current research focuses on experimental studies of water-cooling methods for photovoltaic panels, but there aren't many systematic theoretical parametric assessments assessing the effects of these methods on the environment, economy, and energy.
- 2. Limited Comparative Quantification among Cooling Techniques:** Prior research usually explores unique cooling strategies without presenting a consistent, similar quantification of CO₂ reductions, cost savings, and energy gains across various water-based cooling strategies.
- 3. Inadequate Integrated Assessments Connecting Environmental, Financial, and Energy Measures:** A gap in comprehensive decision-making tools for sustainable PV system design

stems from the dearth of studies that combine a holistic assessment that concurrently tackles energy performance, financial viability, and environmental advantages.

This study intends to assess the economic and environmental effects of water-based cooling techniques utilised for photovoltaic (PV) panels. Furthermore, it aims to assess the payback period linked to these cooling methods, offering insights into their viability and enduring advantages.

To fill the research gaps, the current work tackles the urgent need to increase solar panels' operational efficiency, especially in hot areas where performance is severely hampered by rising temperatures. It provides a new and methodical theoretical parametric assessment of several water-cooling methods, such as earth-water heat exchangers, evaporative cooling, spray cooling, and jet impingement. The study measures and contrasts the energetic (increases in energy output), economic (cost savings), and environmental (decreases in CO₂ emissions) effects of various methods by creating and utilizing a single mathematical framework. In contrast to conventional research, which mostly concentrates on experimental findings or individual cooling techniques, this work offers a distinct, multifaceted viewpoint that offers insightful information for improving PV cooling tactics and directing the construction of sustainable energy systems. With significant advantages in each of the three evaluation domains, the results show that the jet water impingement cooling technique is the most successful in improving PV performance. The following succinctly describes the work's main originality points:

1. **Innovative Micro-Level Theoretical Parametric Modelling:** creation of a standardized mathematical framework for measuring and contrasting the effectiveness of different water-cooling methods in terms of economic, environmental, and energetic parameters.
2. **Holistic Triple-Dimension Evaluation:** The study evaluates energy production enhancements, cost savings, and CO₂ emission reductions all at once, offering a comprehensive perspective that hasn't often been examined in tandem in earlier studies.
3. **Strategic Comparative Insights across Cooling Techniques:** Using theoretical projections, the best-performing cooling techniques—particularly jet water impingement—are identified and compared, providing practical advice for practical application in sustainable PV systems.

2. Governing equations

Solar energy is absorbed and converted into electrical power by PV cells. To accurately measure the intensity of solar radiation, a solar power meter should be positioned perpendicular to the surface of the PV panel, facing directly toward the sun. This ensures that the meter captures the maximum amount of incident solar energy. Meanwhile, the electrical output from the PV panel, which is supplied to the application, can be monitored using voltmeters to measure the voltage and ammeters to assess the current.

By simultaneously recording voltage and current, the power output of the PV panel can be accurately determined by [8]:

$$P_{out} = V_{out} \cdot I_{out} \quad (1)$$

where:

P_{out} : Output electric power of the PV panel (W)

V_{out} : Output voltage of the PV panel (V)

I_{out} : Output current of the PV panel (A)

The area of a PV panel varies depending on its type. In the case of monocrystalline PV panels, a significant portion of the panel's surface area effectively converts sunlight into electricity due to the high efficiency and uniformity of the cells. On the other hand, polycrystalline PV panels are composed of multiple individual cells, each with a specific width and length, leading to a slightly lower overall efficiency than monocrystalline panels. Although this study focuses on using a monocrystalline PV panel, for a more comprehensive analysis, it is also essential to consider the effective area of a polycrystalline PV panel. The effective area of a polycrystalline panel is given by [8]:

$$A_{eff} = N \cdot l \cdot w \quad (2)$$

where:

A_{eff} : is the effective area of the PV panel (m^2)

N: total number of cells found in the PV.

l : effective length of the cell (m)

w : effective width of the cell (m)

The input solar power is calculated by multiplying the solar insolation by the effective area of the PV panel. It is determined by [7-8]:

$$P_{in} = I \cdot A_{eff} \quad (3)$$

P_{in} : Power received from the sun by the PV (W)

I : Solar insolation (W/m^2)

Electrical efficiency refers to a PV panel's ability to convert incoming solar energy into usable electrical power. It is a critical metric that indicates how effectively a PV panel transforms sunlight into electricity. The electrical efficiency, $\eta_{electrical}$, of a PV panel can be calculated using the following formula [7-8]:

$$\eta_{electrical} = \frac{P_{out}}{P_{in}} \quad (4)$$

In this study, the relative efficiency compared to standard PV systems was utilized to calculate energy output, cost savings, and carbon dioxide reduction. It is measured as [7-8]:

$$\eta_{relative} = \frac{\eta_{cooled} - \eta_{non-cooled}}{\eta_{non-cooled}} \quad (5)$$

The output energy of a PV panel can be calculated based on the panel's electrical power production over a specific period, considering various factors such as solar irradiance, panel efficiency, and environmental conditions. The formula for calculating the output energy is [7-8]:

$$E = I_{day} \cdot A_{eff} \cdot \eta_{electrical} \cdot n \quad (6)$$

where:

E : is the output energy of the PV panel (kWh)

I_{day} : The average solar insolation per day ($\frac{kWh}{m^2 \times day}$)

n : Number of days in a month

The savings value is quantified by calculating the reduction in energy costs due to the use of the PV panel, which displaces the need for grid electricity or fossil fuel-based energy sources. This can be determined by comparing the cost of electricity produced by the PV system to the

cost of purchasing the same amount of electricity from conventional sources. The savings are typically expressed as [8]:

$$Savings = E \times C \quad (7)$$

where:

C: The price of each kWh

The CO_2 reduction value is quantified by calculating the amount of carbon dioxide emissions that are avoided using a PV panel, which replaces electricity generated from fossil fuel-based power plants. This value is determined by estimating the amount of CO_2 that would have been emitted to produce the equivalent amount of electricity from conventional energy sources. The CO_2 reduction can be calculated as [8]:

$$CO_2 (reduced) = E \times P \quad (8)$$

where:

$CO_2 (reduced)$: The amount of CO_2 reduced (kg).

P: The amount of CO_2 produced per 1 kWh of electricity $\frac{kg}{kWh}$

The payback period refers to the amount of time required for an investment to recover its initial cost through the savings or returns it generates. It is a key financial metric used to assess the feasibility and profitability of an investment. The payback period is calculated by [6-7]:

$$K = \frac{Cost}{Income} \quad (9)$$

Where:

K: the payback period (years)

Cost: is the initial investment in implementing the system.

Income: Annual Savings due to reduced energy costs or increased energy production.

The study employs various formulas to calculate energy enhancement, savings, CO_2 reduction, and the payback period for each system using Eqs. (6), (7), (8), (9), including both traditional PV panels and water-based cooling photovoltaic panels. These formulas outline the methodology used to determine each performance metric. While the equations for calculating the power output and efficiency of PV panels were referenced, they were not directly applied in the computation of the final metrics.

3. Methodology

This paper conducts a parametric analysis of various water-cooling techniques to evaluate their impact on the energy output of PV panels. The analysis further extends to calculating cost savings, CO₂ reduction, and the payback period for each cooling method. The process followed to determine the payback period is illustrated in Figure 2.

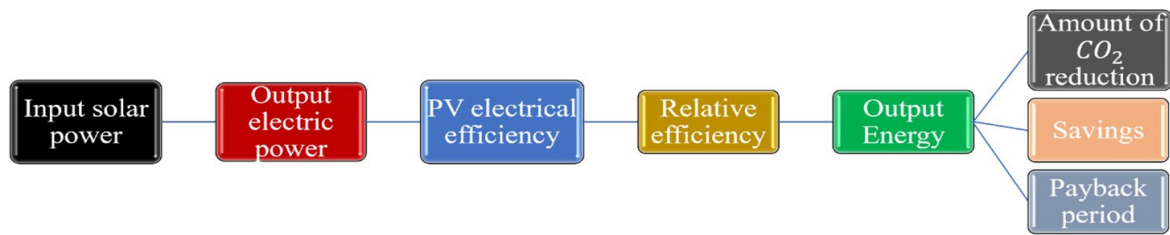


Fig. 2. Analysis schematic.

A proposed PV panel with a specified efficiency was used as the benchmark for traditional PV systems and other cooling methods analyzed in this study. Based on this reference, the relative efficiency improvement of each water-cooling technique was determined and evaluated in terms of energy performance, environmental impact, and economical savings, considering the climatic conditions of Lebanon's regions. Moreover, for each water-cooling method, the mean efficiency was calculated by averaging the values obtained from the literature review, which included three experimental studies for each cooling technique. The individual efficiency values were summed and then divided by three to derive the average. This mean efficiency, combined with the solar insolation data of Beirut, serves as a key parameter for calculating energy enhancement, cost savings, and CO₂ reduction, all evaluated for the same PV panel area.

The parametric analysis presented in this study is based on a set of defined assumptions to estimate the effectiveness of water-cooling methods. These assumptions include standardizing the analysis to a single photovoltaic (PV) panel across all reviewed studies and approximating the cost of each system component based on current market prices in Lebanon.

However, despite the considerable advantages of water-based cooling for photovoltaic (PV) panels, some limits must be acknowledged. A primary problem is the inconsistency of meteorological conditions. Variations in solar irradiation and ambient temperature directly affect heat buildup on photovoltaic surfaces and the efficiency of cooling systems. Under gloomy or wet circumstances, the demand for cooling is negligible. In contrast, elevated

ambient temperatures and strong solar irradiation augment the thermal load, thereby intensifying the necessity for efficient cooling to preserve panel efficacy.

Another critical limitation is water availability, especially in dry and semi-arid countries where ongoing water usage may prove unsustainable. This limitation diminishes the viability of traditional water-cooling systems and necessitates the incorporation of water-conserving methods, such as closed-loop recycling or hybrid cooling techniques that demand minimum water usage. The utilisation of low-quality or untreated water can result in scaling, corrosion, or fouling of cooling components, thus diminishing system performance and reducing equipment longevity unless appropriate filtration or water treatment protocols are employed.

4. Configurations and parametric analysis

To enhance comprehension of how water cooling affects PV efficiency, a detailed study was conducted using the eight water cooling techniques. The methods studied are: IPV, SPV, PVWT, FPV, MCPV, EWHE, JWPV, and finally EPV. The analysis was conducted using data from three selected studies for each cooling method, focusing on the average relative efficiency enhancement. The data collected from the literature for this parametric study is summarized in Table 2.

Starting with IPV, Mehrotra et al. [29] investigated the impact of immersing a PV panel inside a plastic enclosure with a depth of 10.8 cm. Their findings revealed that at a submersion depth of 1 cm, the electrical efficiency improved by 17.8%. Similarly, Lanzafame et al. [30] examined the effect of varying immersion depths on PV performance, reporting a 15% increase in electrical efficiency at a depth of 4 cm. Furthermore, Rosa-Clot et al. [31] conducted a study on PV panel submersion at different depths, identifying an optimal range between 3 and 5 cm, where electrical efficiency was enhanced by 15%.

Regarding the spray nozzles water cooling of PV panels, Laseinde et al. [32] revealed that when spraying water functions at 80 ml/s, the efficiency increased by 16.65%. However, according to Hadipour et al. [33], implementing the water spray cooling system on the PV panel boosted the electrical efficiency by 33.3%. In addition, Nizetic et al. [34] showed a 14.1% increase in the electrical efficiency of the PV panel when mounting a spray cooling system on the PV panel.

Regarding the evaporative water cooling of PV panels method, Chandan et al. [35] used a passive cooling method of Cotton Wicks and water. The results showed that the electrical efficiency of the panel increased by 11.3%. In addition, Zizak et al. [36] used Cotton-Cellulose Fiber with water as a passive cooling. The findings revealed that the PV electric efficiency increased by up to 9.6%. Finally, Jirapongphatai et al. [37] used a hydrophilic Pad Made of Mixture of Polypropylene and Synthetic Fiber using water as a coolant. The results showed a 10% increase in electrical generation.

At the level of Jet impingement water cooling systems, Javidan et al. [38] investigated the cooling of PV modules using a multi-nozzle jet impingement water cooling system. The findings revealed that the maximum output power enhancement in the optimum conditions was 47.67%. In addition, Bahaidarah et al. [39] conducted experimental and numerical evaluations on an uncooled PV system and an impingement-cooled PV system with water. The results showed a 51.6% increase in the power output in June. Furthermore, Hasan et al. [40] developed a photovoltaic-thermal (PVT) solar water collector incorporating a jet impingement water-cooling system. Their study investigated the improvements in both electrical and thermal efficiencies of the PV and PVT systems under varying mass flow rates and solar radiation intensities. The results demonstrated that, at a solar radiation level of 1000 W/m^2 , the system achieved a relative efficiency increase of 22.83%.

Regarding cooling PV panels with EWHE, Jakhar et al. [41] proposed and modeled a novel cooling system known as the Earth-Water Heat Exchanger. The system was analyzed using transient simulations in TRNSYS, specifically for the climatic conditions of Pilani, Rajasthan, India. The results showed that the relative electrical efficiency increase is 11%. Also, Ruoping et al. [42] introduced a solar photovoltaic system integrated with ground heat exchangers (PV-GHEs) to lower the operating temperature of PV panels and maintain high efficiency, particularly in the arid climate of northwestern China. The results showed that the electrical efficiency is increased by 10% compared to uncooled PV panels. In addition, Jakhar et al. [43] investigated an integrated photovoltaic-thermal solar system (IPVTS) coupled with an earth-water heat exchanger (EWHE). Their study demonstrated that the system achieved an average relative efficiency increase of 13.65% at an optimal water flow rate of 0.033 kg/s .

At the level of FPV, Azmi et al. [44] studied a conventional photovoltaic (PV) module and a floating photovoltaic (FPV) system in Malaysia. The results showed that electrical efficiency increased by 16.7% compared to conventional PV. In addition, Majid et al. [45] analyzed the performance of an 80-W floating PV panel within a controlled pond simulator environment. The findings showed that the floating panel demonstrated up to a 15.5% increase in energy gain

in a two-hour experiment compared to a conventional panel. Furthermore, Junianto et al. [46] conducted an experiment on FPV in Palembang, Indonesia. The results showed a 20.6% increase in electrical efficiency compared to ground PV.

At the level of micro cooling PV (MCPV), Muzaffar et al. [47] conducted both CFD simulations and real-time experimental investigations on a solar panel utilizing microchannel cooling. Their findings revealed that at a flow rate of 3 LPM, the relative efficiency increase is 24%. Additionally, Younas et al. [48] investigated the effect of integrating a simple steel water-cooling channel into a PV cell. The results showed that the average relative increase in the efficiency between the reference and the cooled panel is 19.3%. Furthermore, Baloch et al. [49] conducted an experimental and numerical analysis of a converging micro cooling channel to the PV in Saudi Arabia. The results showed that the relative average efficiency increase in June was 30%.

Finally, regarding photovoltaic thermal water cooling (PVT), Habchi et al. [50] studied the effect of water cooling through a hybrid PVT system experimentally using simple parallel water pipes on the back of the PV panel. The results demonstrated a relative electric efficiency increase of 15%. In addition, Chen et al. [51] conducted a numerical and experimental study to analyze the effect of active water cooling on a hybrid PVT system using different comprehensive models. Among the various results obtained, one notable outcome demonstrated a 17.6% increase in electrical efficiency due to the implementation of active water cooling. Furthermore, Fouas et al. [52] performed a comprehensive numerical and parametric analysis of a PVT system in Romania. The study revealed a significant improvement in electrical performance, with a relative increase in electrical efficiency of 22.24%.

Cooling Technique	Relative efficiency increase	Average efficiency
Immersed Photovoltaic (IPV)	17.8% [29]	15.93%
	15% [30]	
	15% [31]	
Spraying nozzles (SPV)	16.65% [32]	21.35%
	33.3% [33]	
	14.1% [34]	
Evaporative cooling (EPV)	11.3% [35]	10.3%
	9.6% [36]	
	10% [37]	
Jet water impingement (JWPV)	47.67% [38]	40.7%
	51.6% [39]	
	22.83% [40]	
Earth water Heat exchanger (EWHE)	11% [41]	11.55%
	10% [42]	
	13.65% [43]	
Floating Photovoltaic (FPV)	16.7% [44]	17.6%
	15.5% [45]	
	20.6% [46]	
Micro cooling photovoltaic (MCPV)	24% [47]	24.46%
	19.4% [48]	
	30% [49]	
Thermal photovoltaic (PVWT)	15% [50]	18.28%
	17.6% [51]	
	22.24% [52]	

Table 2: Relative efficiency increases for different water-cooling systems.

Numerous factors, including the tilt angle, the mass flow rate of the working fluid, Reynolds number, Nusselt number, PV design and implementation, cooling channel geometry, ambient humidity, and solar irradiance, influence the efficiency of PV panels. Optimizing these parameters is crucial for enhancing the overall performance and energy yield of PV systems.

In Lebanon, the electricity supply is highly unreliable, with Électricité du Liban providing only about 4 hours of electricity per day for \$ 0.27 per kWh. For the remaining 20 hours, citizens rely on diesel generators to meet their energy needs. This dependence on diesel generators raises environmental concerns due to increased emissions and places a significant financial burden on households. The estimated price of electricity from these generators is 0.46 USD per kWh. An average price of 0.43 USD per kWh, calculated from 0.27 USD per kWh from EDL for 4 hours

and 0.46 USD per kWh from private generators, is used in this study for calculations. Additionally, the calculation of CO₂ reduction assumes that 0.58 kg of CO₂ is emitted into the atmosphere for every kWh of electricity generated from fossil fuel sources [53].

This study utilizes several key inputs to assess energy improvement, including solar insolation, the PV panel area, the number of days in a month, and the relative efficiency enhancement. To compute CO₂ reduction and fossil fuel savings, additional inputs such as the cost per kWh of electricity generated from fossil fuels and the increased energy output are considered. Furthermore, the initial investment and total savings of each system are factored into the payback period analysis. The results derived from these calculations include the reduction in CO₂ emissions, the payback period, overall financial savings, and the net energy improvement. When analyzing the PV panel, its primary outputs consist of voltage, current, power, and efficiency, while the key inputs include the PV panel area and solar insolation. Additionally, the consumption ratio (R) is defined as an input that depends on the power consumption characteristics of the PV panel.

5. Results and analysis

For the study, we use a reference panel of 600W from Trina Solar’s Vertex Bifacial Dual Glass. The instructions and the properties of the panel are listed in Table 3.

Table 3: Specifications of the reference PV panel [54].

Model	Trina Solar’s Vertex Bifacial Dual Glass
Type	Monocrystalline
Dimensions	2172×1303×40 mm
Surface Area	2.172x1.303=2.83m ²
Maximum efficiency	21.2%
Maximum power output	600W
Open circuit current	18.42A
Open circuit voltage	41.7V
Maximum Power Voltage (V)	34.6V
Maximum Power Current(A)	17.34A
Number of cells	120
Weight	35.3kg
Frame	40mm Anodized Aluminium Alloy

The analysis conducted in this study focused on the average relative increase in electrical efficiency across nine photovoltaic (PV) panels: one reference panel and eight additional panels, each integrated with a distinct water-cooling technique. Lebanon is geographically

divided into three main regions: the coastal zone, which borders the Mediterranean Sea; the Lebanese mountain range; and the interior region, situated between the Lebanese mountain chain and the Syrian mountain range. This study focuses on solar insolation levels specific to Lebanon's coastal region, as referenced in [55].

Figure 3 shows the solar insolation in Beirut-Lebanon in $\text{kWh/m}^2 \cdot \text{day}$ for the months of the year. As depicted, solar insolation reached its lowest point in December, measuring 2 kWh/m^2 per day. In contrast, the peak solar insolation occurs in July, with a value of 6.67 kWh/m^2 per day. This significant variation highlights the seasonal fluctuations in solar energy availability, with summer months providing more than three times the solar energy compared to the winter months.

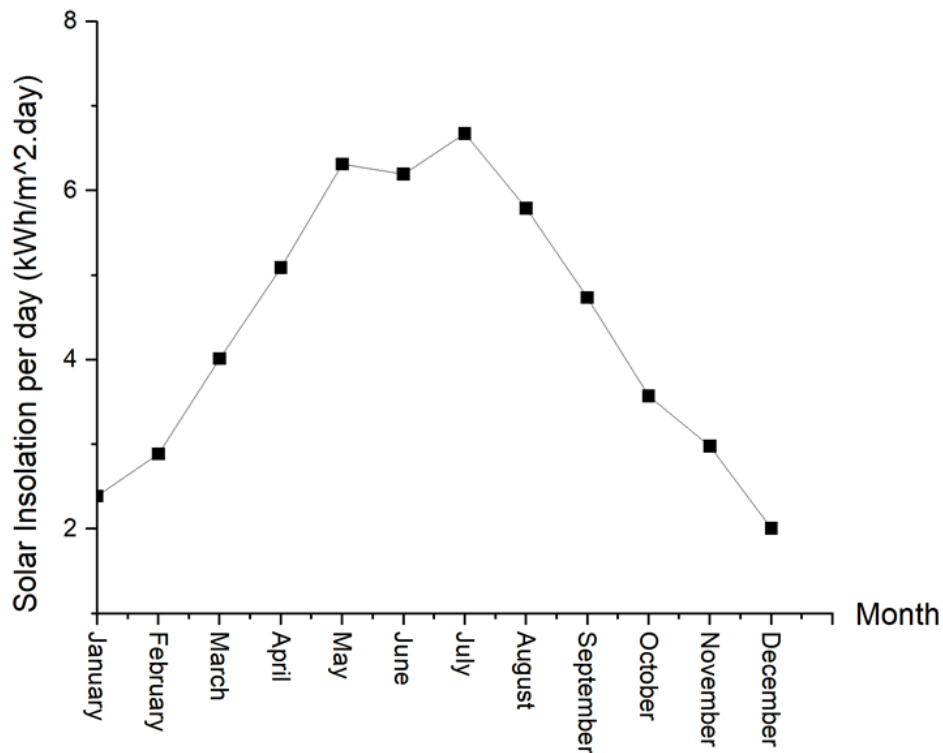


Figure 3: Solar Insolation in Beirut-Lebanon [53].

In this section, the average relative efficiency improvements achieved by each cooling method were analyzed in terms of energy enhancement, cost savings, and CO_2 emission reduction, with all values adjusted by the energy usage ratio (R).

Given Lebanon's fluctuating solar insolation, the performance of various cooling systems was evaluated under these dynamic climatic conditions. Water cooling demonstrated a significant improvement in energy efficiency, cost savings, and CO_2 reduction, particularly during the high solar insolation months of summer. In contrast, during the lower solar insolation of winter, the

energetic, economic, and environmental benefits of PV cooling were less pronounced. However, despite their reduced impact, these benefits remained advantageous compared to conventional PV systems. The analysis highlights the significant influence of solar insolation on cooling efficiency. This insight enables stakeholders to make more informed and strategic decisions when selecting the most effective cooling method tailored to specific climatic conditions.

In addition, the study of various water-cooling techniques, as documented in the literature, provided practical insights into enhancing the average relative efficiency of PV panels across a broad spectrum of solar insolation variations relevant to the case study. These findings offer useful recommendations for implementing PV cooling strategies in real-world applications. Moreover, it supports developing tailored solutions to maximize PV performance year-round. Ultimately, this theoretical foundation paves the way for further research and innovation in photovoltaic cooling technologies.

5.1. Energy enhancement

The energy generated by a PV panel is largely influenced by the amount of solar radiation it receives on its front surface, as well as the panel's surface area. Fig. 4 presents a comparison of the energy performance between water-cooled PV panels and conventional PV panels. The data clearly demonstrates that incorporating a water-cooling system enhances the panels' efficiency by lowering their operating temperature, leading to increased energy production.

The graph in Fig. 4 illustrates that all energy enhancement curves begin to rise in January, gradually increasing as solar radiation intensifies. They reach their peak in July, coinciding with the highest solar radiation levels due to Lebanon's summer weather conditions. After July, the curves exhibit a gradual decline, with energy enhancement reaching its lowest point by December.

The highest energy enhancement was achieved by the jet impingement water cooling system, which recorded an impressive average energy gain of 112.84R kWh and a total annual enhancement of 1354.10R kWh. This was followed by the micro-cooling water panel system, with an average energy gain of 99.82R kWh and an annual total of 1197.80R kWh. The spray nozzle cooling system ranked next, demonstrating an average enhancement of 97.32R kWh and a yearly total of 1167.87R kWh.

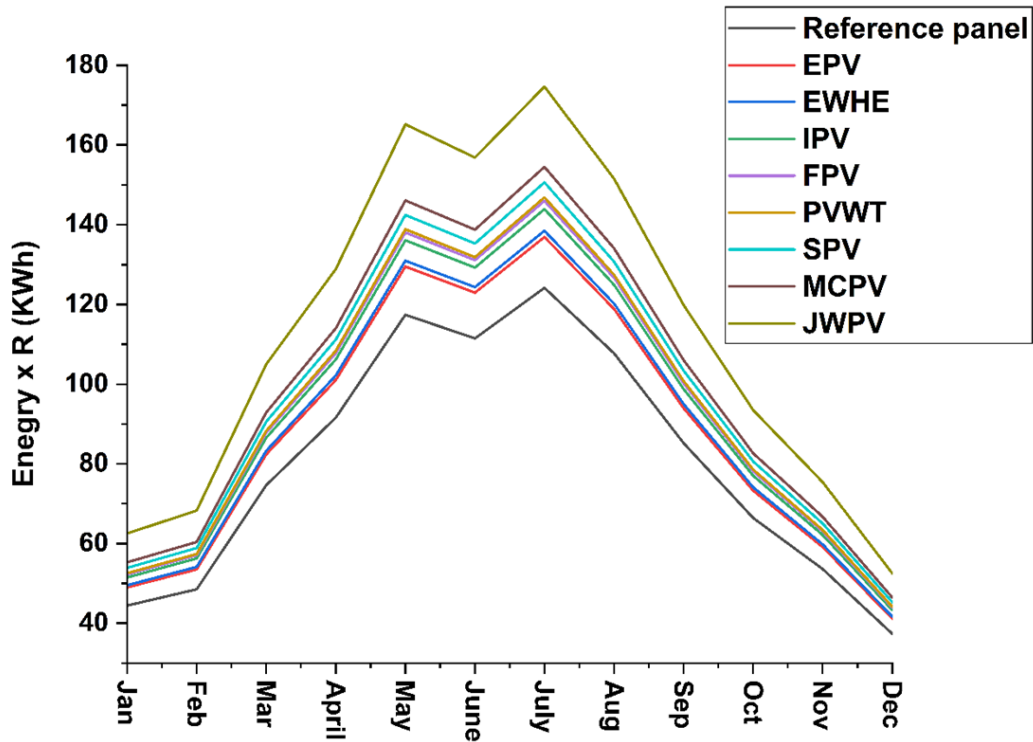


Fig. 4. Energy enhancement graph for different water-cooling systems per month.

Following these, the PVWT and FPV cooling systems delivered comparable results, with average energy enhancements of 94.86R kWh and 94.32R kWh and corresponding annual totals of 1138.33R kWh and 1131.78R kWh, respectively. On the lower end of performance, the IPV cooling system achieved an average energy enhancement of 92.98R kWh and a total annual gain of 1115.71R kWh, ranking just below the FPV system. The EWHE system followed, with an average enhancement of 89.46R kWh and a yearly total of 1073.56R kWh.

Among all the water-cooling methods analyzed, the evaporative cooling system (EPV) exhibited the lowest energy enhancement, registering an average of 88.46R kWh and a total annual gain of 1061.53R kWh. In comparison, the standard uncooled PV panel demonstrated the lowest overall energy output, with an average energy production of 80.20R kWh and a yearly total of 962.40R kWh.

The PVWT and FPV cooling systems exhibit very similar energy enhancements in both average and total values. This similarity is attributed to the close range of their average relative efficiency improvements, with the FPV system achieving a 17.6% increase in efficiency over the uncooled PV panel, while the PVWT system records an 18.28% increase. As a result of

these comparable efficiency gains, both systems are expected to demonstrate similar trends in cost savings and CO₂ emissions reduction.

This study highlights the critical role of relative efficiency increases in the decision-making process, demonstrating their significant impact on the overall performance of PV systems. By incorporating the average relative efficiency improvement for each cooling method, the analysis offers a comprehensive understanding of how different water-cooling techniques enhance the efficiency of uncooled PV panels under varying climatic conditions. The observed improvements in electrical efficiency are primarily attributed to the reduction in PV panel temperature, which directly boosts energy output. Consequently, as will be further discussed, these efficiency gains lead to greater financial savings and substantial reductions in CO₂ emissions, reinforcing the value of adopting advanced cooling strategies in PV system design.

5.2. Savings

The savings reflect the reduction in the investor's energy expenses achieved through the operation of each PV panel. The increase in a panel's savings is directly attributed to the improvement in its electrical efficiency. Based on an electricity rate of \$0.43 per kWh, **Fig. 5** presents the monthly savings produced by each PV water cooling system per month throughout the year.

As shown in **Figure 5**, July records the highest savings for all PV panels. This is primarily due to longer daylight hours and greater solar intensity during the summer. On the other hand, January and December show the lowest savings in both cases of relative efficiency improvements, largely influenced by shorter days and reduced solar radiation in winter months.

Like the trends observed in the energy enhancement graph, the JWPV system utilizing the water-cooling method achieved the highest savings, averaging \$48.52R per month and totaling 582.26R USD annually. Following closely, the micro-cooling water panel system recorded an average monthly saving of \$42.92R, leading to a total annual saving of \$515.06R. Ranking next, the spray nozzle cooling system demonstrated an average monthly saving of \$41.85R and an annual total of \$502.19R.

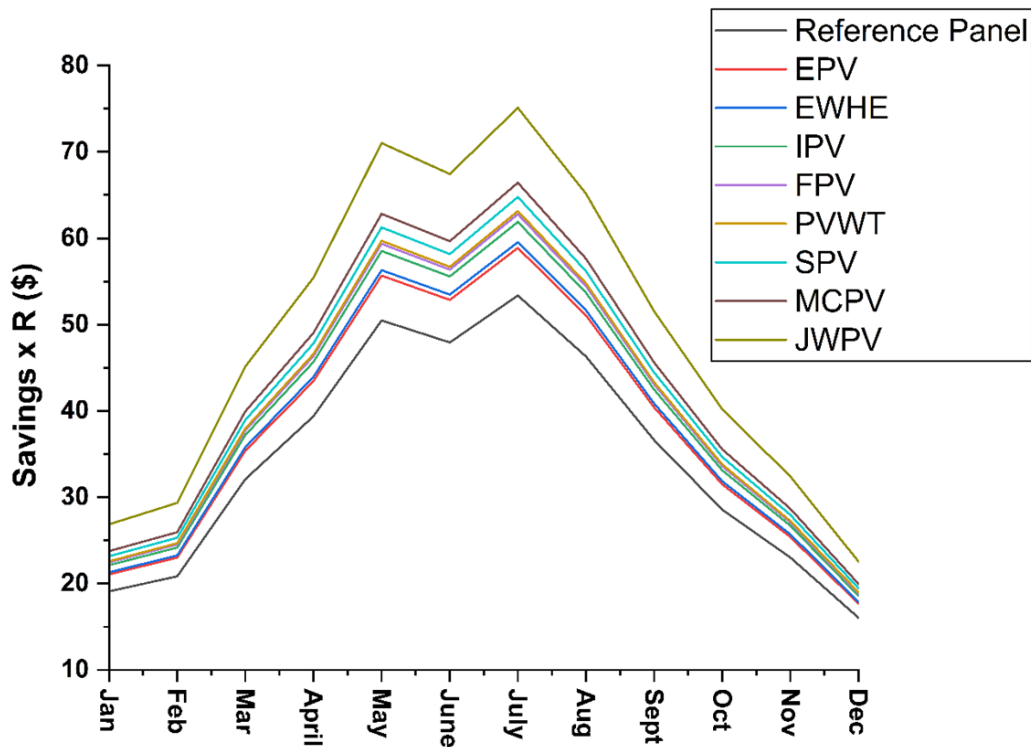


Fig. 5. Savings of each water-cooling system per month.

Consistent with the findings presented in the energy efficiency section, both the PVWT and FPV cooling systems delivered comparable results. The PVWT system averaged \$40.79R per month, with a yearly total of \$489.50R, while the FPV system followed closely with \$40.56R monthly and \$486.67R annually.

On the lower end of performance, the IPV cooling system achieved an average monthly saving of \$39.98R, amounting to 479.76R USD per year, and ranking just below the FPV system. The EWHE system followed, showing an average monthly saving of 38.47R USD and a total annual saving of 461.63R USD.

As observed in the energy enhancement results, the evaporative cooling system (EPV) exhibited the lowest savings among the cooling technologies, with an average monthly saving of 38.04R USD and a yearly total of 456.46R USD. In comparison, the standard uncooled PV panel yielded the lowest overall savings, averaging 34.49R USD per month and 413.83 USD annually.

In conclusion, PV cooling technologies demonstrate significant economic advantages over standard uncooled PV panels. Even the least efficient cooling system, the EPV, yields measurable savings, highlighting the overall financial benefits of incorporating cooling methods into photovoltaic installations. The current savings analysis findings emphasize these

solutions' cost-effectiveness and provide valuable insights for making informed decisions when selecting the most economically viable cooling system. However, integrating cooling technologies may lead to higher initial investment costs. Still, the long-term financial returns driven by enhanced energy efficiency and stable system performance far dominate these upfront expenses.

5.3. CO_2 reduction

Considering that every kilowatt-hour (kWh) of electricity generated from fossil fuels emits approximately 0.58kg of CO_2 , the transition to photovoltaic systems offers substantial environmental benefits. This reduction reflects the decrease in carbon emissions achieved by using each PV panel with a different water-cooling system as an alternative to fossil fuel-based electricity generation.

As illustrated in Figure 6, the monthly CO_2 reduction varies throughout the year for each system.

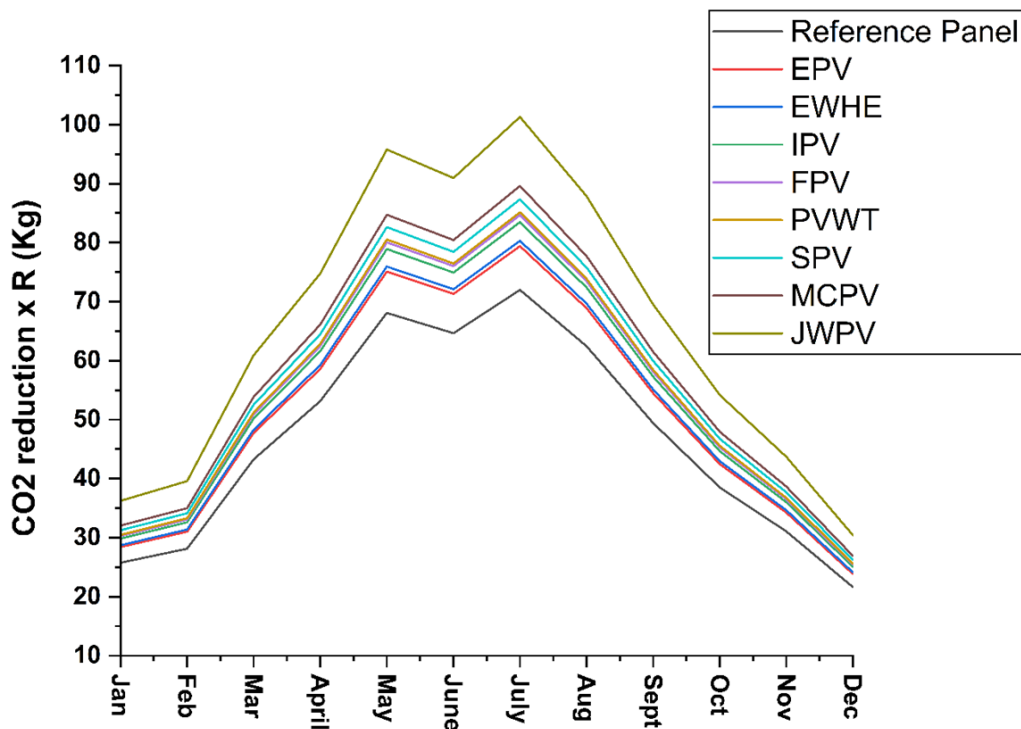


Fig. 6. CO_2 reduction graph for different water-cooling systems per month.

The highest levels of CO_2 reduction is observed in July when solar energy production is at its peak across all PV systems. Conversely, the lowest CO_2 reduction values are recorded in January and December due to reduced solar irradiance during the winter season. These results are consistent with the patterns observed in energy generation and savings.

In alignment with the trends observed in the energy enhancement graph and savings graph, the JWPV system utilizing the water-cooling method demonstrated the highest effectiveness in reducing CO₂ emissions, achieving an impressive average of 65.45R kg per month, culminating in an annual reduction of 785.38R kg. Close behind, the micro-cooling water panel system recorded a monthly average of 57.89R kg, resulting in a total yearly reduction of 694.73R kg.

Following these top performers, the spray nozzle cooling system achieved a monthly CO₂ reduction of 56.48R kg, amounting to 677.37R kg annually. Consistent with the energy efficiency findings, both the PVWT and FPV systems delivered nearly identical outcomes. The PVWT system registered an average monthly reduction of 55.02R kg and an annual total of 660.23R kg, while the FPV system closely followed with 54.7R kg monthly and 656.43R kg per year.

Toward the lower end of the performance spectrum, the IPV system recorded an average monthly CO₂ reduction of 53.93R kg, totaling 647.11R kg annually, placing it just below the FPV system. The EWHE system showed slightly lower performance, averaging 51.89R kg per month, with an annual reduction of 622.66R kg.

As seen in the energy enhancement analysis, the evaporative cooling system (EPV) yielded the lowest CO₂ reduction among all cooling technologies, averaging 51.31R kg monthly and 615.68R kg annually. In comparison, the standard uncooled PV panel exhibited the least reduction overall, with a monthly average of 46.52R kg and a total annual reduction of 558.19R kg.

The analysis clearly demonstrates that water-based cooling techniques significantly enhance the CO₂ reduction performance of photovoltaic systems. Among all methods evaluated, the JWPV system with direct water cooling achieved the highest CO₂ reduction, followed closely by the micro-cooling water panel and spray nozzle systems. These results underscore the effectiveness of water-cooling technologies in improving environmental sustainability by substantially lowering carbon emissions. Compared to uncooled PV panels, water-cooled systems offer a measurable advantage, making them a promising solution for greener energy production and climate change mitigation.

Finally, Table 4 presents a comparative analysis of energy enhancement, cost savings, and CO₂ reduction across the eight water-cooling systems, benchmarked against the standard uncooled PV panel. The evaluation is based on the consumption ratio (R) under the scenario where an average relative efficiency improvement is applied to a single photovoltaic panel.

Table 4: Energy enhancement, savings, and CO_2 reduction of water-cooling techniques compared to the standard PV as a function of R.

Water Cooling Technique	Energy enhancement $\times R$		Savings $\times R$		CO_2 reduction $\times R$	
	(kWh)		(\$)		(kg)	
	Average	Total	Average	Total	Average	Total
JWPV	112.84	1354.09	48.52	582.26	65.45	785.38
MCPV	99.82	1197.8	42.92	515.05	57.89	694.73
SPV	97.32	1167.87	41.85	502.18	56.48	677.37
PVWT	94.86	1138.32	40.79	489.48	55.02	660.23
FPV	94.32	1131.78	40.55	486.67	54.7	656.43
IPV	92.98	1115.71	39.98	479.75	53.93	647.11
EWHE	89.46	1073.56	38.47	461.63	51.89	622.66
ECPV	88.46	1061.53	38.04	456.46	51.31	615.68

5.4. Payback period

The time it takes for an investment's net cash inflows or savings to cover its initial cost is known as the payback period. The approximate cost of each system is shown in Table 5, along with the costs of the various parts, such as a 5800W inverter, a 200Ah battery, and a 600W PV panel. The chart also includes the total cost of each full configuration. In this study, prices in the Lebanese market are used to determine the installation costs of the systems.

As indicated in Table 5, the lowest initial cost is for the standard PV panel for 1025 USD, while the highest initial cost was EWHE PV panel with 1605 USD. The payback period for each system was established based on its original total cost and the annual savings it generates. It shows how long it will take for the investment to be recouped using the system's revenue or savings. This computation was done for every cooling technique that was used.

Table 5: PV individual and total system cost.

System	Components		Total system cost (USD)
	Unit	Individual cost (USD)	
Standard PV	PV panel	270	1025
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	50	
JWPV	PV panel	270	1365
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Jet Nozzles	40	
	Water Pump	60	
	Water reservoir	20	
	Drainage system	50	
	System Controller	70	
	Sealing	50	
MCPV	PV panel	270	1355
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Hit sink	100	
	Water pump	60	
	Water reservoir	20	
	Drainage system	50	
	Sealing	50	
	SPV	PV panel	
Acid Battery (200 Ah)		180	
Invertor (5.8 kW)		425	
Stand		100	
Some connections		100	
Water pump		60	
Water reservoir		20	
Drainage system		50	
Filtration system		50	
System Controller		70	
PVWT		PV panel	270
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Thermal collector	50	
	Water pipes	50	

	Insulation layer	50	
	Water pump	60	
	Water reservoir	20	
	System controller	70	
FPV	PV panel	270	1305
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Anchoring system	100	
	Monitoring system	80	
	Waterproof electrical components	50	
IPV	PV panel	270	1185
	Acid Battery (200Ah)	180	
	Invertor (5.8kw)	425	
	Stand	100	
	Some connections	100	
	Encapsulation Material	30	
	Antireflective Coating	30	
	Mounting Structure	50	
EWHE	PV panel	270	1605
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Water Pump	60	
	Earth Heat Exchanger	300	
	Insulation	100	
	System controller	70	
ECPV	PV panel	270	1235
	Acid Battery (200 Ah)	180	
	Invertor (5.8 kW)	425	
	Stand	100	
	Some connections	100	
	Water pump	60	
	Water reservoir	20	
	Dippers	30	
	Filtration system	50	

The Jet Impingement Water-Cooled PV (JWPV) panel had the quickest payback period, at 2.3 years, as shown in Fig. 7.

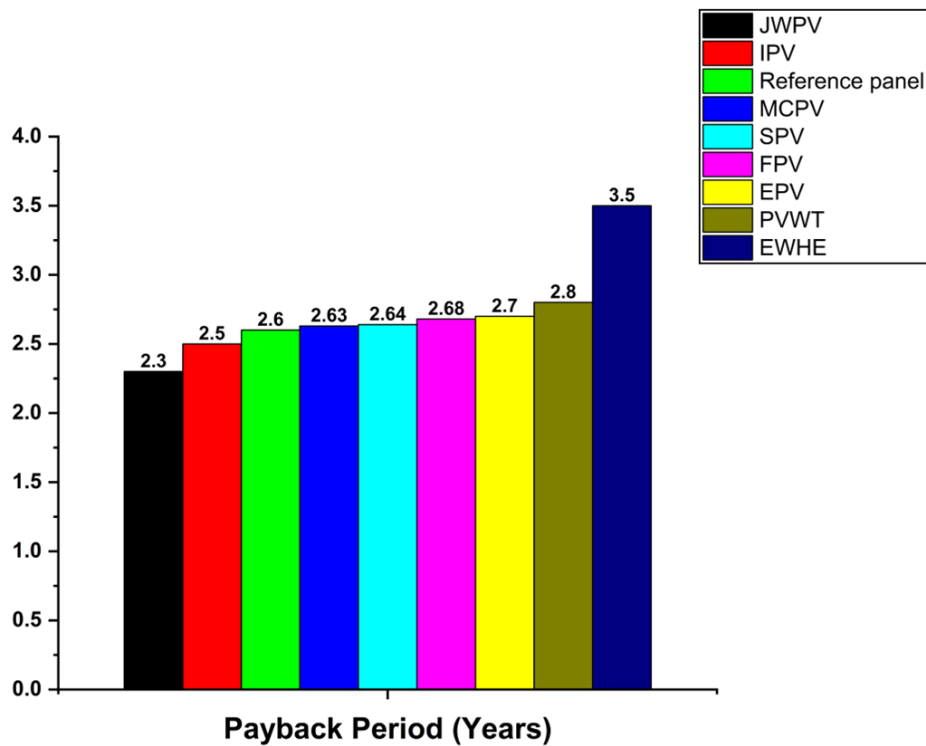


Fig. 7. Payback period of all water-cooling methods in years.

This is mostly because jet impingement cooling has a small installation cost and produces significant annual energy savings. On the other hand, because of its relatively low yearly energy savings and high initial installation cost, the EWHE PV panel had the longest payback period at 3.5 years. The IPV, reference panel, MCPV, SPV, FPV, EPV, and PVWT follows the JWPV with respective payback periods of 2.5, 2.6, 2.63, 2.64, 2.68, 2.7, and 2.8 years.

The systems showed competitive but slightly longer payback durations. These findings emphasize the importance of considering both installation cost and energy-saving potential when selecting an optimal cooling method for photovoltaic systems.

6. Interval and Scaled Study

6.1. Interval study

Using the maximum and minimum values recorded for each cooling system, this section analyses the range of relative electrical efficiency for eight distinct cooling systems. The energy

enhancement, energy savings, and CO₂ emission reduction per unit area of a PV panel are used to analyze these efficiency intervals. This method gives researchers a practical estimate that they can utilize in their research on any section of PV panels.

The eight water-based cooling methods in this study have the following relative electrical efficiency increases: IPV [15–17.8%], SPV [14.1–33.3%], EPV [9.6–11.3%], JWPV [22.83–51.6%], EWHE [10–13.65%], FPV [15.5–20.6%], MCPV [19.4–30%], and PVWT [15–22.24%]. These efficiency ranges offer a more precise framework for estimating the potential for the development of each cooling technique and can be applied successfully to comparative evaluation and performance analysis in PV systems.

6.1.1. Energy Enhancement Interval Study

The monthly maximum and minimum energy enhancement per unit area for each water-based cooling technology is shown in Figures 8 and 9. The bar charts show that July has the highest energy augmentation values, mostly because of Lebanon's current weather. The same pattern is seen in all eight cooling systems: energy enhancement rises progressively from January to May, then slightly declines in June before peaking in July. The readings gradually decrease for the rest of the year after this high, reaching their lowest point in December.

Figure 8 illustrates the energy enhancement per unit area for four water-based cooling systems: IPV, SPV, EPV, and JWPV. For the IPV system, the maximum energy enhancement, corresponding to the highest relative efficiency increase, reached 36.83 kWh/m² in July. At the lowest level of relative efficiency improvement, the energy enhancement was 31.04 kWh/m², also recorded in July. Additionally, the SPV system achieved a maximum energy enhancement of 68.1 kWh/m² in July, corresponding to its highest relative efficiency increase. At the lower bound of its efficiency improvement range, the system still delivered an energy enhancement of 29.18 kWh/m², also in July.

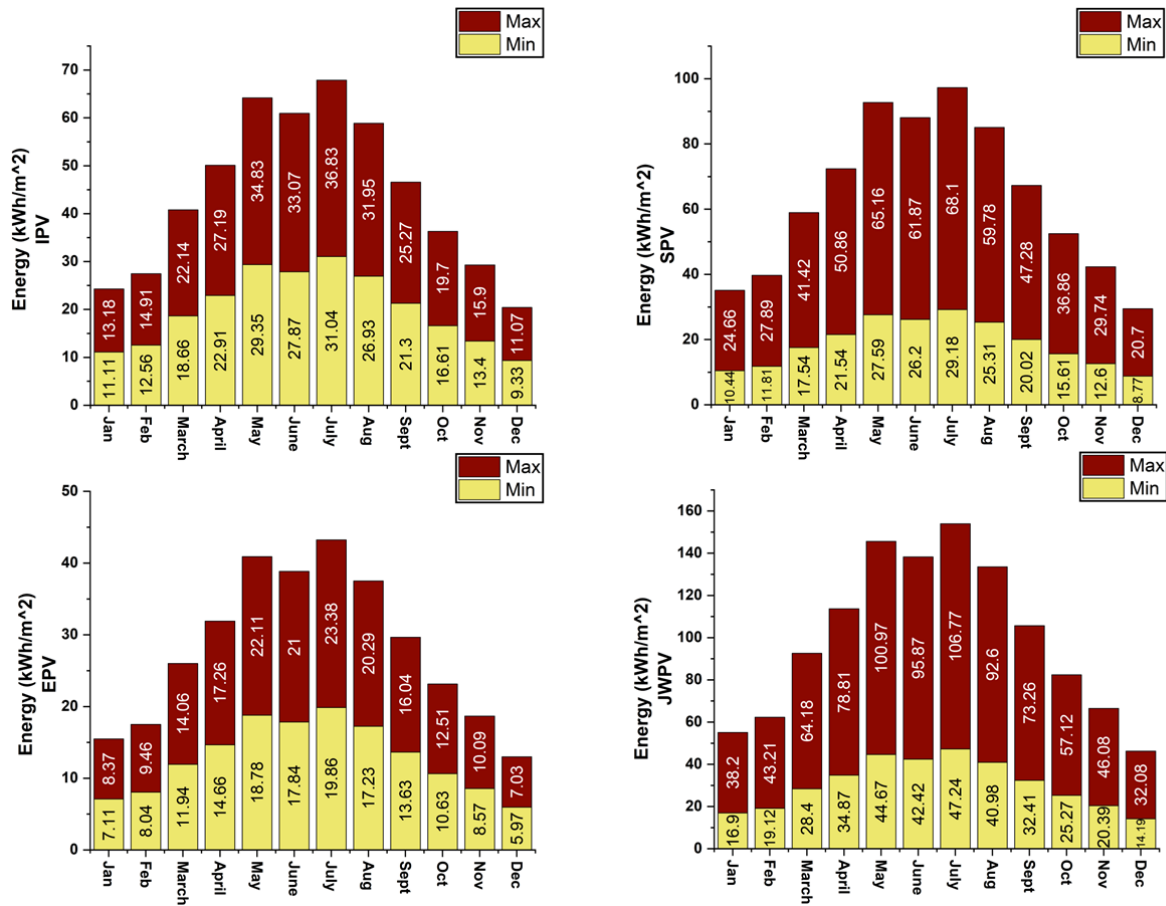


Fig. 8. Energy enhancement interval for the first four water-based cooling methods.

Moreover, the EPV system achieved a maximum energy enhancement of 23.38 kWh/m² in July, corresponding to its highest relative efficiency increase. At the lower bound of its efficiency improvement range, the system still delivered an energy enhancement of 19.86 kWh/m², also occurring in July. Finally, July exhibited the highest energy enhancement recorded by the JWPV system, with maximum and minimum relative efficiency increases of 106.77 kWh/m² and 47.24 kWh/m², respectively.

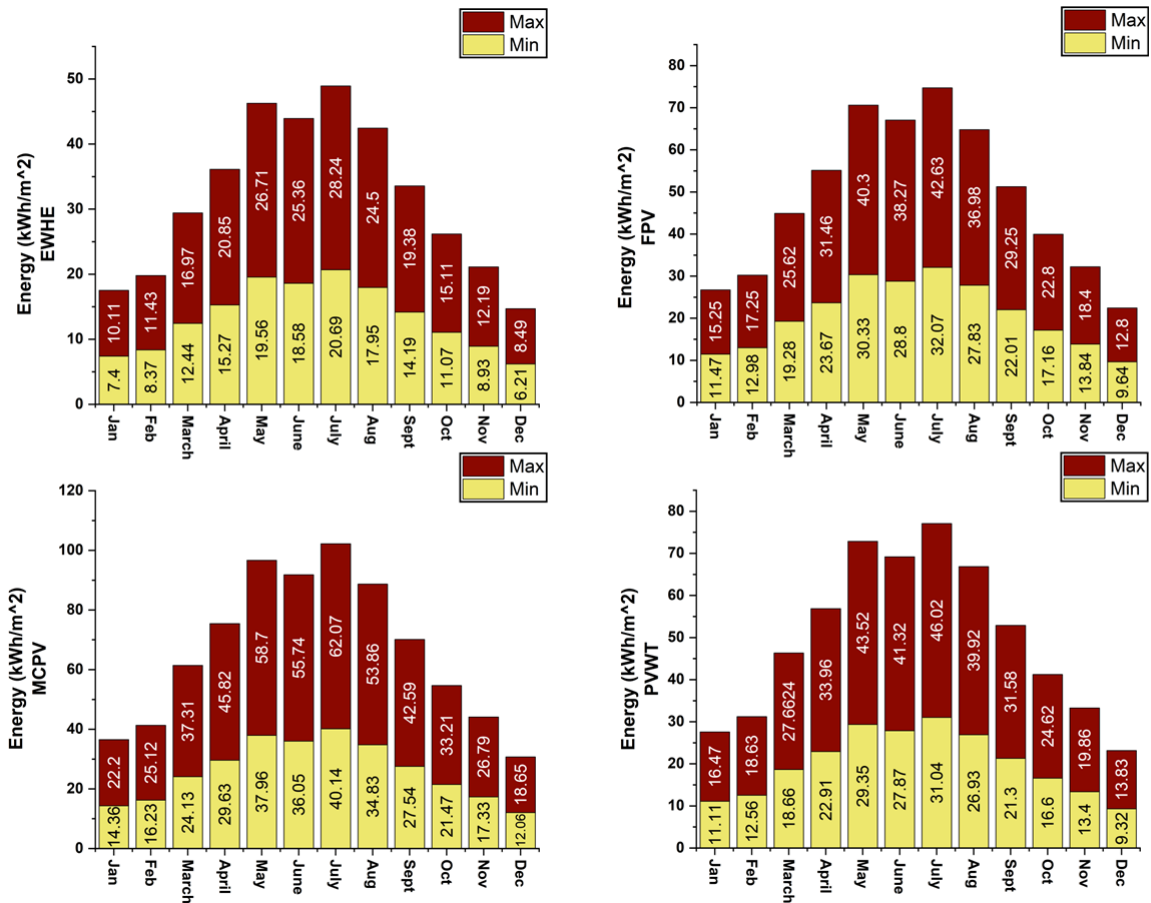


Fig. 9. Energy enhancement interval for the remaining four water-based cooling methods.

Figure 9 illustrates the energy enhancement per unit area for the remaining four water-based cooling systems: EWHE, FPV, MCPV, and PVWT. For the EWHE system, the maximum energy enhancement, corresponding to the highest relative efficiency increase, reached 28.24 kWh/m² in July. At the lowest level of relative efficiency improvement, the energy enhancement was 20.69 kWh/m², also recorded in July. Additionally, the FPV system achieved a maximum energy enhancement of 42.63 kWh/m² in July, corresponding to its highest relative efficiency increase. At the lower bound of its efficiency improvement range, the system still delivered an energy enhancement of 32.07 kWh/m² in July. Moreover, the MCPV system achieved a maximum energy enhancement of 62.07 kWh/m² in July, corresponding to its highest relative efficiency increase. At the lower bound of its efficiency improvement range, the system still delivered an energy enhancement of 40.14 kWh/m², also occurring in July. Finally, July exhibited the highest energy enhancement recorded by the JWPV system, with maximum and minimum relative efficiency increases of 46.02 kWh/m² and 31.04 kWh/m², respectively.

6.1.2. Savings Interval study

The monthly maximum and minimum savings per unit area for each water-based cooling technology are presented in Figures 10 and 11. Like the energy enhancement trends shown previously, the bar charts in Figures 10 and 11 demonstrate that July consistently records the highest savings across all systems, largely due to favorable weather conditions. In all eight cooling technologies, savings increase steadily from January through May, experience a slight decline in June, and then peak in July. Following this peak, the values gradually decrease over the remaining months, reaching their lowest point in December.

Figure 10 displays the savings per unit area for four water-based cooling systems: IPV, SPV, EPV, and JWPV. For the IPV system, the maximum savings corresponding to the highest relative efficiency increase reached 15.83 USD/m² in July, while the minimum savings, associated with the lowest efficiency gain, was 13.35 USD/m², also in July. The SPV system showed a similar pattern, with maximum savings of 29.63 USD/m² and minimum savings of 12.54 USD/m², both recorded in July. For the EPV system, July again marked the peak month, with savings ranging from 10.05 USD/m² with a maximum efficiency increase to 8.54 USD/m² with a minimum efficiency increase. The JWPV system exhibited the highest savings among this group, with July values reaching 45.91 USD/m² at peak efficiency and 20.31 USD/m² at the lower end.

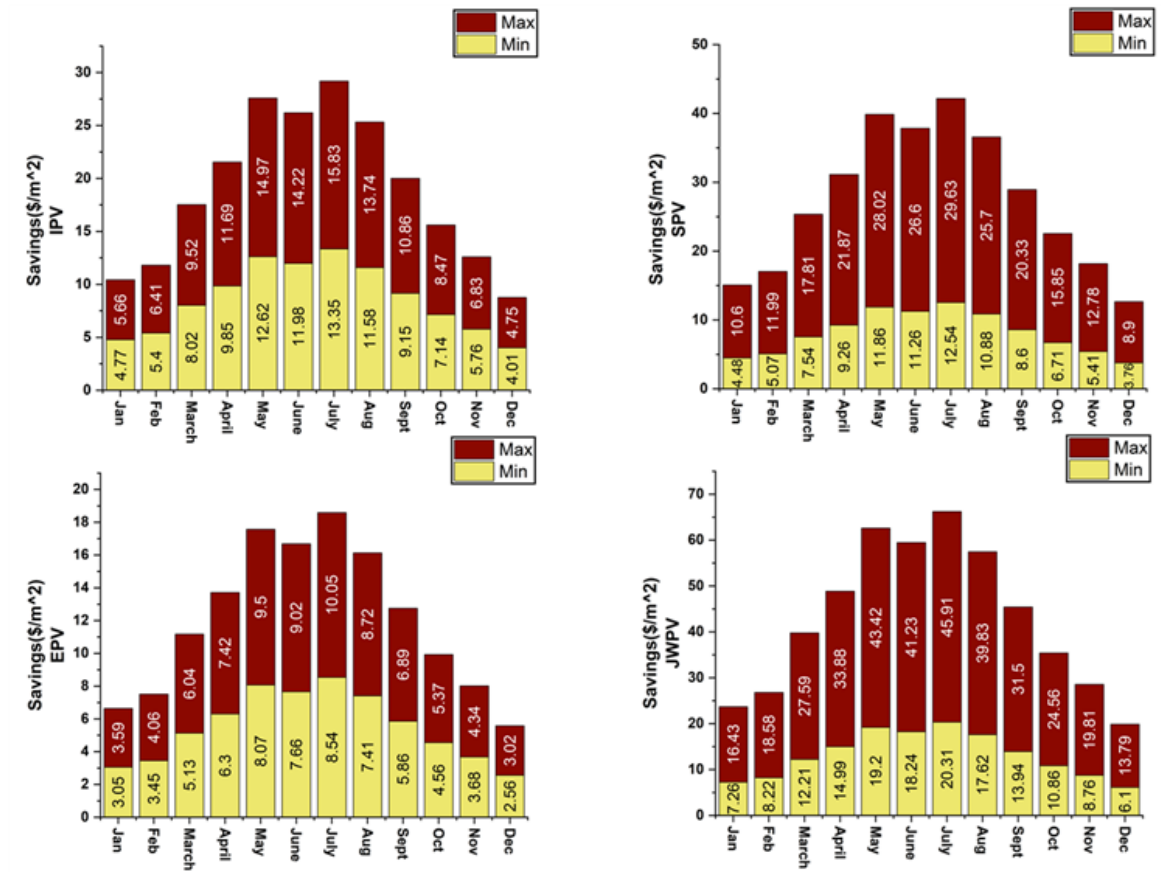


Fig. 10. Savings interval for the first four water-based cooling methods.

Figure 11 presents the savings data for the remaining four systems: EWHE, FPV, MCPV, and PVWT. The EWHE system achieved maximum savings of 12.14 $\$/m^2$ and minimum savings of 8.89 $\$/m^2$, both in July. For the FPV system, savings in July ranged from 18.33 $\$/m^2$ at maximum efficiency to 13.79 $\$/m^2$ at minimum. The MCPV system followed the same trend, with July savings spanning 26.69 $\$/m^2$ with maximum efficiency to 17.26 $\$/m^2$ with minimum efficiency. Finally, the PVWT system recorded savings of 19.78 $\$/m^2$ and 13.34 $\$/m^2$ for its maximum and minimum efficiency levels, respectively, once again peaking in July.

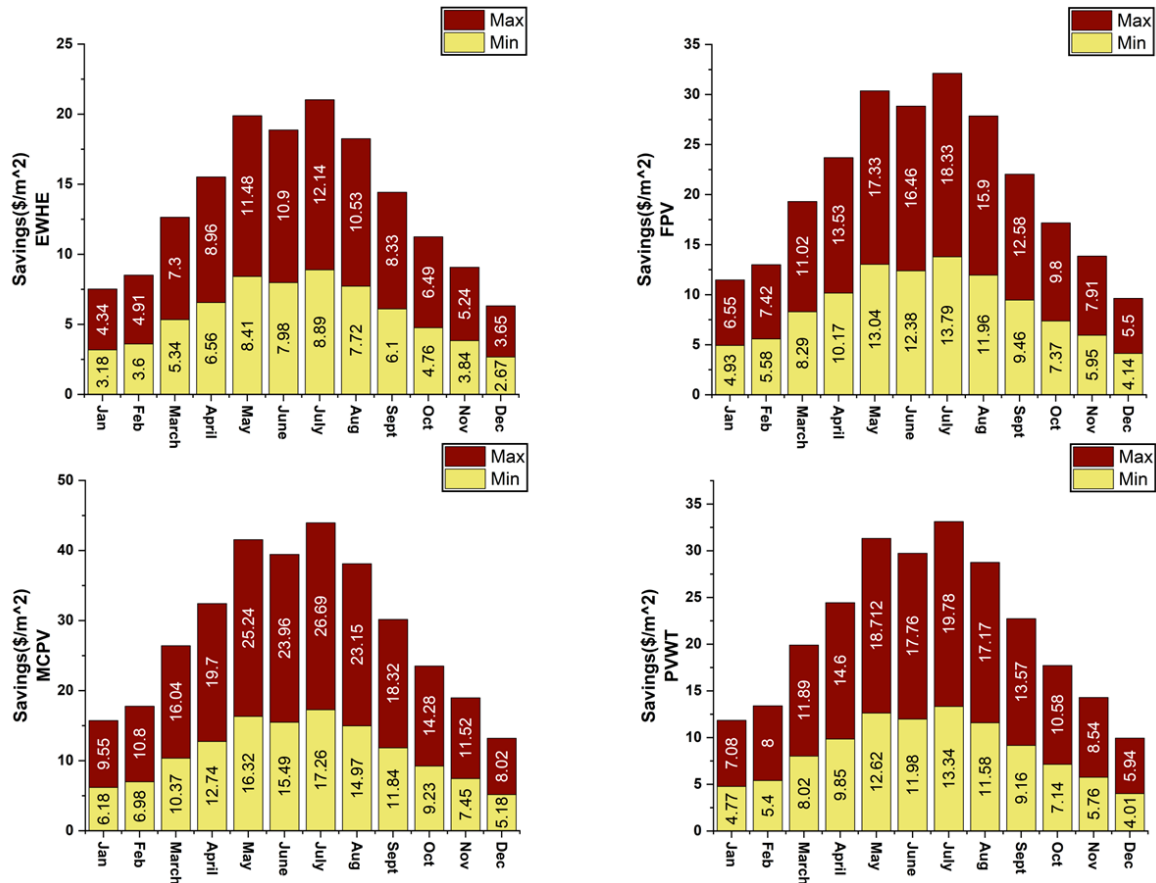


Fig. 11. Savings interval for the remaining four water-based cooling methods.

6.1.3. CO₂ reduction Interval study

The monthly maximum and minimum CO₂ reductions per unit area for each water-based cooling technology are presented in Figures 12 and 13. As observed with energy enhancement and savings, the bar charts in Figures 12 and 13 indicate that July consistently exhibits the highest CO₂ reduction values across all systems. For each of the eight cooling technologies, CO₂ reduction increases progressively from January to May, dips slightly in June, and peaks in July. After July, the values gradually decline, reaching their lowest levels in December.

Figure 12 illustrates the CO₂ reduction per unit area for the first four water-based cooling systems: IPV, SPV, EPV, and JWPV.

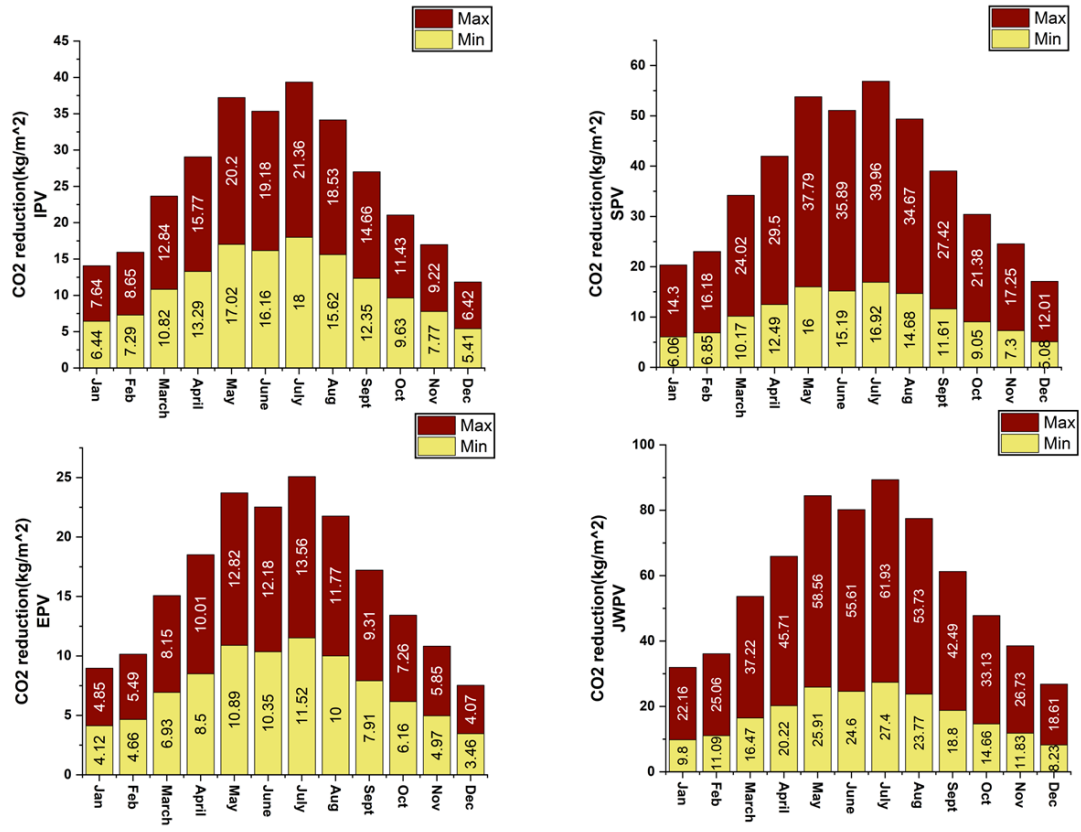


Fig. 12. CO₂ reduction interval for the first four water-based cooling methods.

For the IPV system, the maximum CO₂ reduction in July, corresponding to the highest relative efficiency increase, was 21.36 kg/m², while the minimum efficiency gain resulted in 18 kg/m², also in July. The SPV system followed a similar pattern, achieving 39.96 kg/m² at peak efficiency and 16.92 kg/m² at minimum efficiency, both in July. The EPV system recorded its highest CO₂ reduction in July as well, with values ranging from 13.56 kg/m² with maximum efficiency to 11.52 kg/m² with minimum efficiency. Among these four, the JWPV system delivered the highest CO₂ reduction, with July values of 61.93 kg/m² at peak efficiency and 27.4 kg/m² at the lower bound.

Figure 13 presents the CO₂ reduction per unit area for the remaining four cooling systems: EWHE, FPV, MCPV, and PVWT.

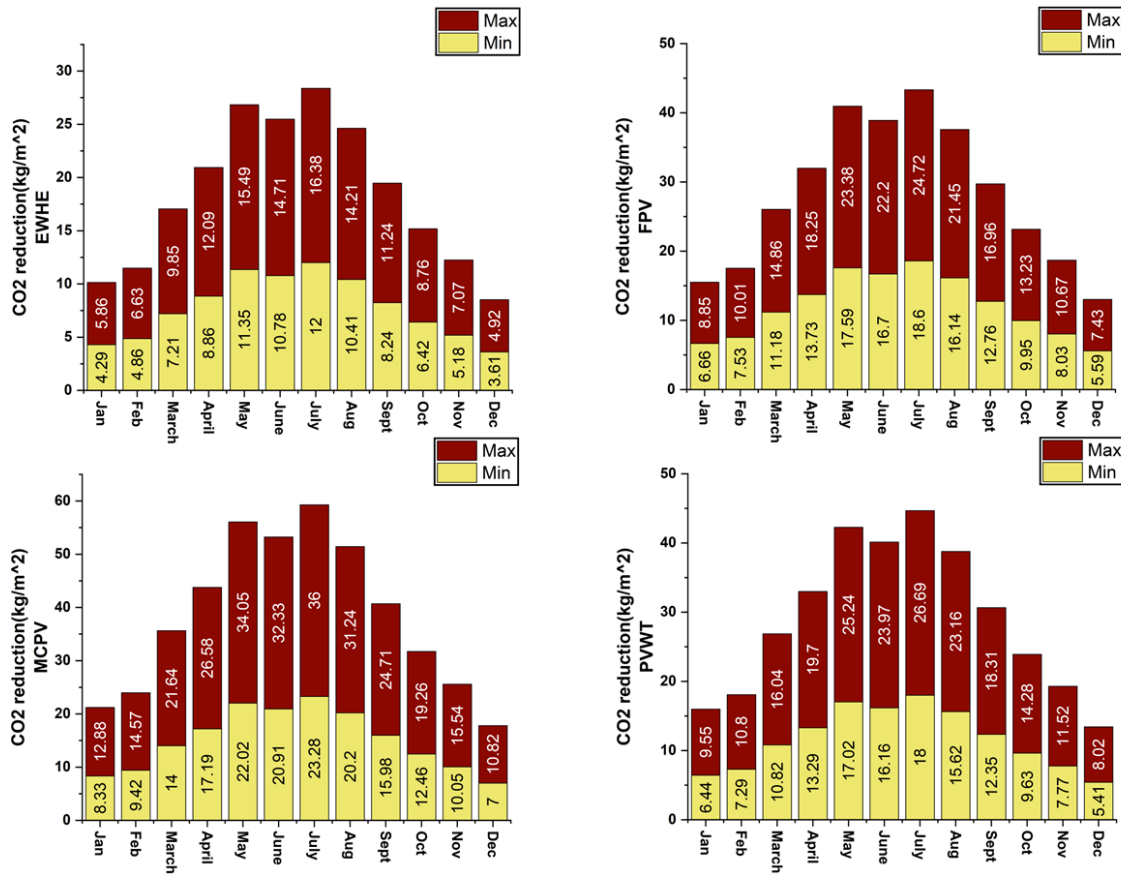


Fig. 13. CO₂ reduction interval for the remaining four water-based cooling methods.

The EWHE system achieved a CO₂ reduction of 16.38 kg/m² at maximum efficiency and 12 kg/m² at minimum, both in July. The FPV system followed suit, with CO₂ reductions ranging from 24.72 kg/m² with maximum efficiency to 18.6 kg/m² in July with minimum efficiency. For the MCPV system, the reduction peaked at 36 kg/m² 23.28 kg/m² at maximum and minimum efficiency, respectively, again both in July. Finally, the PVWT system recorded CO₂ reductions of 26.69 kg/m² at maximum efficiency and 18.6 kg/m² at minimum efficiency, continuing the consistent July peak trend.

6.2. Scaled Analysis

This section analysis is presented in terms of PV surface area, allowing readers to estimate the energy enhancement, savings, and CO₂ reduction based on their PV surface area, as the relative efficiency increase ranges from 3% to 54%.

Figure 14 displays the annual energy enhancement values as a function of the relative efficiency increase, which ranges from 3% to 54%. As seen in Fig. 11, July has the highest energy

enhancement values, whereas December has the lowest energy enhancement values, which is attributable to the weather conditions in Lebanon. The energy enhancement in July is 6.2 kWh/m² when the relative efficiency gain is 3%, and it increases linearly to the highest level of energy enhancement at 54% efficiency, where it registers 111.74 kWh/m², while in December, the energy enhancement values increase from 1.86 kWh/m² to 33.57 kWh/m² as the relative efficiency increases from 3% to 54%.

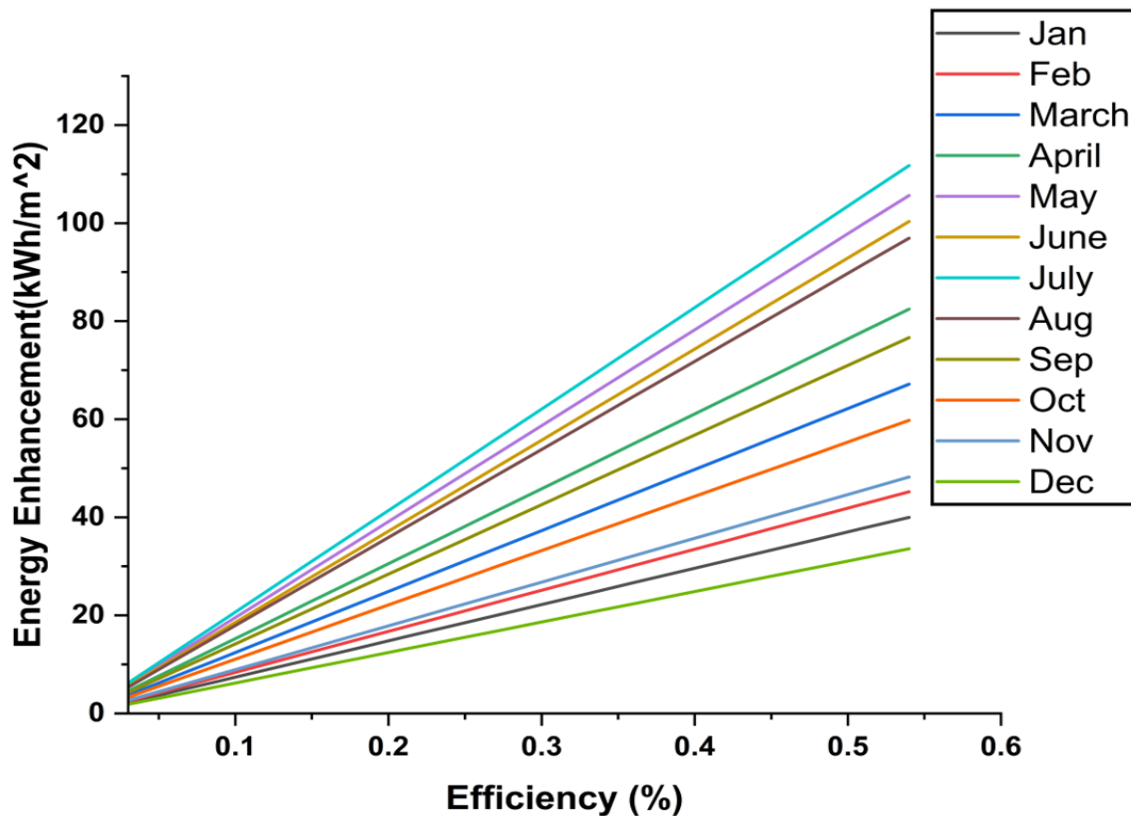


Fig. 14. Energy enhancements scaled analysis per unit area of a PV panel.

Fig. 15 and Fig. 16 show the annual savings values and CO₂ reduction values both as a function of the relative efficiency increase. Similarly, as the behavior of the annual energy enhancement, both graphs show a linear correlation, which leads to an increasing straight line. In addition, July was the month with the highest savings and reduction of CO₂, while December showed the minimum savings and CO₂ reduction. In July, the savings and the CO₂ reduction were 2.67 USD/m² and 3.6 kg/m², respectively. At a 3% relative efficiency increase, these values continue to rise where savings reached 48.05 USD/m² and CO₂ reduction of 64.8 kg/m². However, in December, the savings and the CO₂ reduction were 0.8 USD/m² and 1.08 kg/m², respectively, at a 3% relative efficiency increase. These values rise, where savings reach 14.44 USD/m² and CO₂ reduction is 19.5/m², a 54% relative efficiency increase.

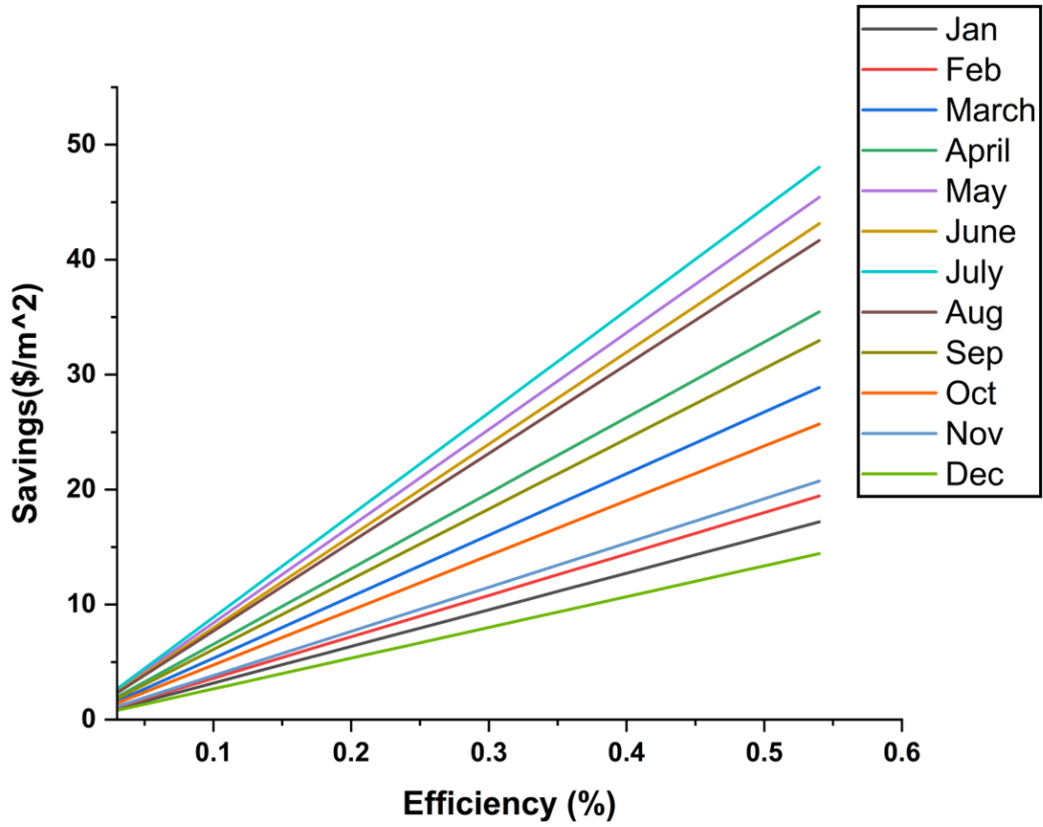


Fig. 15. Savings scaled analysis per unit area of a PV panel.

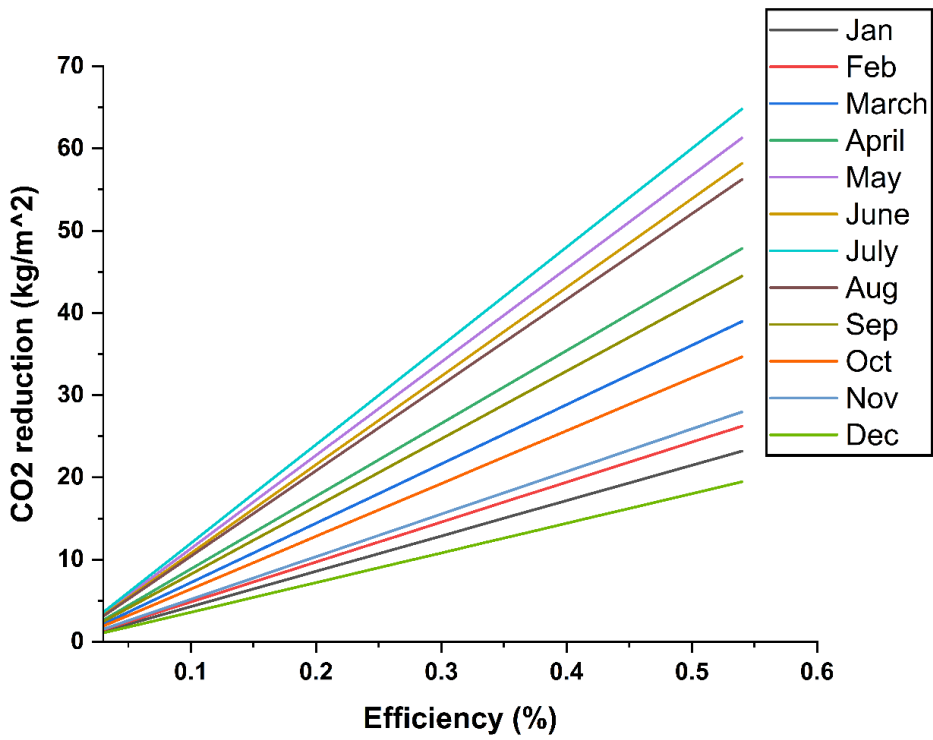


Fig. 16. CO₂ reduction scaled analysis per unit area of a PV panel.

This section discusses a linear correlation approximation method that researchers can use to predict the energy enhancement, savings, and CO₂ reduction at a given PV panel area as the relative electrical efficiency increases. This demonstrates the significance of cooling strategies on PV performance.

7. Conclusions

The present study offers a thorough parametric analysis of eight water-based cooling methods for photovoltaic (PV) panels, demonstrating considerable potential to improve energy output, decrease carbon emissions, and yield economic benefits. Among the evaluated systems, jet impingement cooling consistently surpassed competitors in all measures, providing the greatest energy gains, environmental advantages, and the briefest payback period.

The eight cooling methods analyzed included JWPV, IPV, MCPV, SPV, FPV, EPV, PVWT, and EWHE. Each technique was examined using a dataset that included three distinct experiments.

The findings emphasise that the selection of a cooling technique must be context-dependent, considering installation costs, climatic conditions, and water availability. For example, while systems such as EWHE present environmental benefits, their elevated initial costs and minimal efficiency enhancements may restrict their applicability in resource-limited environments. In contrast, methods like spray or micro-cooling offer a judicious balance between performance and financial investment.

The JWPV, showed the most promising results above all water technologies in which its annual energy enhancement, savings, and quantity of CO₂ reduction were registered as follows 1354.097R kWh, 582.26R USD, and 785.38R kg, respectively. However, the least results were shown for the EPV in which its annual energy enhancement, savings, and quantity of CO₂ reduction were registered as follows 1061.53R kWh, 456.46R USD, and 615.69R kg, respectively. Among all the water-based cooling techniques, July consistently emerged as the most effective month for achieving maximum energy enhancement, cost savings, and CO₂ reduction. This peak performance was primarily attributed to Lebanon's climatic conditions during this period, characterized by clear skies and minimal cloud cover, allowing for optimal solar insolation and, consequently, the highest photovoltaic output.

The payback periods for the eight water-based cooling techniques were found to be relatively close in value, ranging from 2.3 to 3.5 years. The JWPV system demonstrated the most favorable payback period of approximately 2.3 years, attributed to its low installation cost paired with significant energy enhancement and a notable increase in relative efficiency. On the other end of the spectrum, the EWHE exhibited the longest payback period at 3.5 years, primarily due to its higher installation cost and comparatively lower performance in both energy enhancement and efficiency gains.

In addition to economic viability, the study also highlighted the strong environmental benefits of these cooling techniques. When compared to conventional PV systems, each method contributed to a measurable reduction in CO₂ emissions, reinforcing their potential to mitigate atmospheric pollution and promote more sustainable solar energy solutions.

During the interval-based analysis, the JWPV technique demonstrated the highest performance across all key metrics in the month of July. It achieved the maximum energy enhancement, cost savings, and CO₂ reduction, with respective values of 106.77 kWh/m², 45.91 USD/m², and 61.93 kg/m² corresponding to the maximum relative efficiency increase observed in the study. In contrast, at the level of the minimum relative efficiency increase the EPV cooling technique recorded the lowest performance in the same month, with energy enhancement, savings, and CO₂ reduction values of 19.86 kWh/m², 8.54 USD/m², and 11.52 kg/m², respectively.

The scaled parametric analysis revealed that July provides the optimal conditions for maximizing the performance benefits of water-based PV cooling techniques. In July, these techniques consistently delivered the highest values of energy enhancement, cost savings, and CO₂ reduction across the full range of efficiency improvement levels, spanning from 3% to 54%.

The study provides pragmatic suggestions for stakeholders especially engineers, legislators, and investors aiming to improve solar system efficiency in arid regions like Lebanon. The designed scalable framework allows users to assess system performance based on photovoltaic area and relative efficiency, rendering it an effective decision support tool.

Considering its thorough methodology, this work possesses many limitations. The analysis relies on theoretical assumptions and aggregated literature data instead of empirical, site-specific experimental measures. Moreover, the quantification of water consumption and long-term maintenance implications was insufficiently detailed. Subsequent research must rectify these deficiencies by including experimental validation, lifespan evaluation, and hybrid cooling

methodologies to enhance the models and bolster the implementation of sustainable photovoltaic technology.

8. Future recommendations

While ongoing research continues to seek innovative solutions for enhancing the thermal and electrical efficiency of PV panels, the findings of this study offer valuable insights. The following future recommendations can serve as a foundation for future research and technological advancements in the field:

- Future studies should include real-life experimental setups in various climates to validate theoretical results and improve practical practicality, maintenance requirements, and real-world performance.
- Explore combining water-based approaches with other passive or active cooling techniques to see if hybrid solutions can enhance efficiency and lower costs even further.
- Include a deeper analysis of water consumption for each cooling method.
- Create performance maps or regional suitability indexes to help stakeholders evaluate which technique fits best based on climate zones, urban density, or rooftop space availability.
- Examine how each water-based approach affects PV panel performance and material durability over the long run.

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