

# Assessing the feasibility of nighttime water harvesting from solar photovoltaic panels in a desert region

Jim Joseph John<sup>1\*</sup>, Nithin Sha Najeeb<sup>1</sup>, Harry Apostoleris<sup>1</sup>, Kaushal Chapaneri<sup>1</sup>, Gerhard Mathiak<sup>1</sup>,  
and Muhammad Alam<sup>2</sup>

<sup>1</sup> Research and Development Center, Dubai Electricity and Water Authority, Dubai, UAE

<sup>2</sup> Purdue University, West Lafayette, IN, USA

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**Abstract.** Photovoltaics has emerged as a crucial and progressively significant contributor to renewable energy generation. Nevertheless, its effectiveness is limited to daylight hours when sunlight is available. This research paper presents an approach to promote dual usage of solar panels beyond daytime operations to facilitate water production. An AWGPV (Atmospheric water generation on PV modules) system is built and operated for nearly a year. During this period, several prototypes were built to produce up to 2.5 L/panel per day without optimizing the energy consumed during direct cooling. A techno-economic assessment was done for the prototype AWGPV system. The prototype system consisting of 3 AWGPV panels connected to the grid was able to produce water at 33 USD cents per liter in Dubai, UAE. If the electricity for direct cooling is reduced, the cost of water can be reduced further. The results point to new avenues to explore methods for reducing the electricity consumption for cooling for achieving further cost reduction. A parameter n-MHI (night Moisture harvesting index) is introduced to evaluate the feasibility and energy demands of harvesting atmospheric moisture through direct cooling. Through a climate-based analysis of various locations, the global potential of this process is explored. The collected water can be used for dust cleaning of solar panels, agrophotovoltaic systems, and other applications where water and electricity generation needs to be decentralized.

**Keywords:** Photovoltaic / atmospheric water generation / solar cooling / integrated energy-water system

## 1 Introduction

In 2022, the global installation of photovoltaic (PV) systems experienced significant growth, reaching a cumulative capacity of 1.2 TW [1]. The Middle East region, particularly the Gulf countries, has emerged as a hub for exceptionally low solar tariffs in recent years. Most projects have been awarded prices that steadily approach an impressive rate of 1 USD cent per kilowatt-hour (ct/kWh). These accomplishments are attributable to favorable solar conditions, the availability of cost-effective desert land, low labor costs, affordable project financing, supportive tax systems, economies of scale benefitting large-scale projects, and decreasing prices of PV system components.

Projections suggest that the countries in the Middle East region will deploy approximately 50 GW of solar PV by 2030 [2]. For instance, the second phase of the MBR solar park in the UAE [3], with a capacity of 200 MWdc,

covers an area of 4.5 square kilometers and encompasses roughly 2.3 million solar panels. Based on this, a solar PV plant with a capacity of 1 MWdc occupies approximately 22,500 square meters. Consequently, by 2030, the collective utilization of the sunny desert lands by Middle East countries will occupy a substantial area of 1,125 square kilometers for solar PV plants.

The sub-tropical regions of the Middle East and Africa regions experience the highest average number of sunshine hours throughout the year. In the UAE, for example, the sunshine hours during winter and summer solstices amount to 12 and 14 h, respectively. Consequently, a significant portion of land remains unused during nighttime due to the presence of solar panels. This paper explores a potential solution that harnesses the utilization of the vast surface area occupied by solar panels during non-sunshine hours.

Numerous advancements [4–7] have been made in the field of water production, focusing on cost-effectiveness, accessibility, and environmental sustainability. The primary objective of these studies is to generate potable water. Globally, various approaches are employed to meet water

\* e-mail: [jim.joseph@dewa.gov.ae](mailto:jim.joseph@dewa.gov.ae)

supply demands, including seawater desalination, surface water extraction from lakes, rivers, and reservoirs, groundwater extraction from aquifers, sewage recycling, rainwater harvesting, and water production from air and fog. It is widely recognized that the Middle East and North African regions face severe water scarcity issues. These regions contribute approximately 48 percent of the daily global output of desalinated water, which amounts to 95 million cubic meters [8]. To mitigate the adverse environmental impacts, there is a pressing need for improved brine management strategies. Emphasizing the significance of unconventional water resources, their utilization is crucial in achieving Sustainable Development Goal 6 (SDG 6), which aims to ensure the availability and sustainable management of water resources for all.

An atmospheric water generator (AWG) refers to a technology designed to extract water from the surrounding humid air. This process involves condensing water vapor present in the air through methods such as cooling the air below the dew point temperature, utilizing desiccants, or pressurizing the air. The main challenge faced by AWG systems lies in their high initial costs and relatively higher energy consumption during operation. However, according to a forecast by the Grand View Research firm [9], these technologies are projected to experience a surge in demand and are expected to reach a market value of USD 8.9 billion by 2027. The driving factors behind this growing demand include the depletion of freshwater reserves, the ability to produce high-purity water, and the ease of transporting water generated by such systems.

There is a broad movement in the solar industry to share resources and promote dual usage of PV modules such as agro-photovoltaics, vehicle-integrated PV, and building-integrated PV. The integration of atmospheric water generators (AWG) with solar photovoltaic (PV) modules has emerged as a compelling area of research. An approach involving a sorbent material that captures water vapor from the air during nighttime was studied [10]. The system utilizes the heat generated by a PV panel during the day to facilitate the evaporation of the captured atmospheric water from the sorbent, resulting in the cooling of the panel. The condensed water vapor is collected to generate fresh water, which can be utilized for crop irrigation. Notably, a commercially available product called Hydropanels by Source Global [11] has successfully integrated solar PV and AWG systems.

In a previous study [12], we demonstrated through modeling that the average weekly water generation from solar panels, achieved by employing photonic thermal emissivity engineering, can be increased from 261 ml/m<sup>2</sup> to 681 ml/m<sup>2</sup>. These findings unveiled the potential for nighttime utilization of various existing sky-facing solar energy harvesting systems, traditionally assumed to operate exclusively during the daytime. However, it is essential to consider that the effectiveness of using radiative cooling to achieve water harvesting below the dew point temperature is reliant on clear nighttime skies. Consequently, ensuring consistent water production throughout the year may pose challenges in regions with varying weather conditions.

This research paper presents an approach wherein we showcase a system that actively cools solar panels during nighttime and can collect up to 2.5 L on a 1.6 m × 0.9 m PV module. The system incorporates a commercial chiller that facilitates condensation on its surface. The main focus of this paper is to establish a foundational understanding of the water harvesting potential during nighttime in desert regions. With further optimization in the cooling system, the proposed system can reach above 1.7 L/m<sup>2</sup> per day in contrast to the above-reported value of 681 ml/m<sup>2</sup>. Additionally, we conduct a comprehensive techno-economic analysis of the prototype and explore its scalability potential, particularly in the Middle East. Through this study, we aim to provide valuable insights into the feasibility and practicality of implementing such a system in arid environments such as in the middle-east regions and sites where large solar plants are proposed.

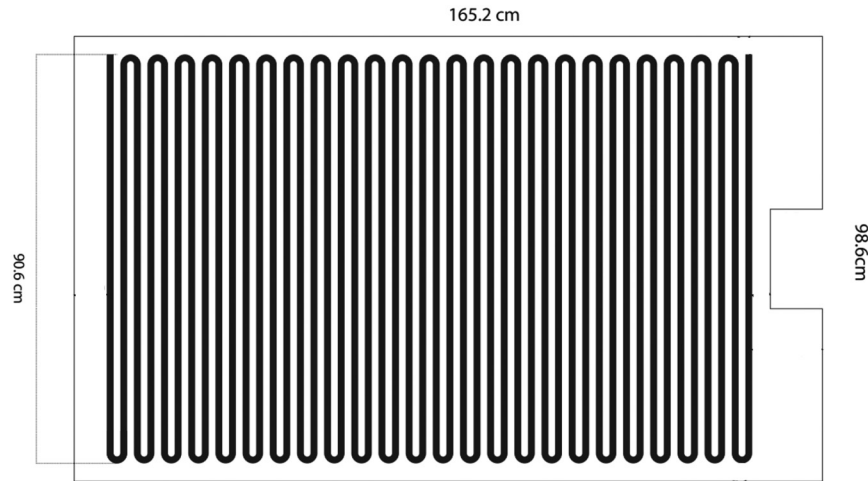
## 2 Prototype description

For the construction of the prototype, a PV module with a back glass measuring 1600 × 980 mm was selected. To facilitate water flow, a specially designed cooling panel was created by retrofitting the PV panel with a thick acrylic sheet. This cooling panel featured engraved channels to guide the water, and it was securely attached to the PV panel's back glass using a specialized watertight adhesive.

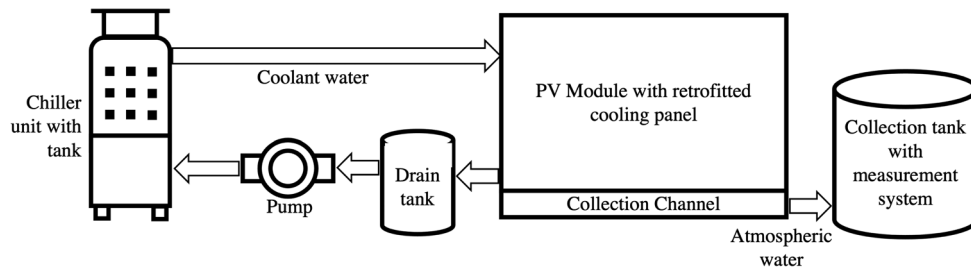
Most PV modules utilize a polymer backsheet, unless they have a metal layer, which allows for limited water or moisture penetration. To address this concern, the prototype employed a back glass instead of a polymer backsheet. The engraved water channels on the acrylic sheet followed the pattern illustrated in Figure 1, with a depth of 7 mm and a width of 15 mm. The cooling panel itself consisted of a 20 mm thick acrylic sheet, ensuring durability and efficient water flow.

The AWGPV panel, short for Atmospheric Water Generation on PV panel, is specifically designed to facilitate water condensation and is intended for nighttime operation. The process of condensation occurs when the surface temperature of an object (i.e PV module surface) is equal to or lower than the dew point temperature of the surrounding air, causing water vapor to transition into a liquid state. The dew point temperature, in turn, is primarily influenced by ambient temperature and humidity, which are key weather factors.

In this study, the AWGPV panel's surface is effectively cooled below the dew point temperature by utilizing a conventional chiller unit, as depicted in Figure 2. Coolant water is directed through the cooling panel via a bypass and subsequently collected in a drain tank. This collected water is then circulated through the chiller using a pump for cooling purposes. Given that these panels are typically installed at a tilt, any condensed water will naturally flow towards the panel's lower edge. To capture the water droplets, a collection channel is incorporated, and the collected water is measured using a custom-made water level sensor and then stored in a dedicated water tank for future use. For the experimental



**Fig. 1.** CAD design showing the cooling panel with water channels embedded in the acrylic sheet for landscape orientation in PV modules of size  $165.2 \times 98.6$  cm.

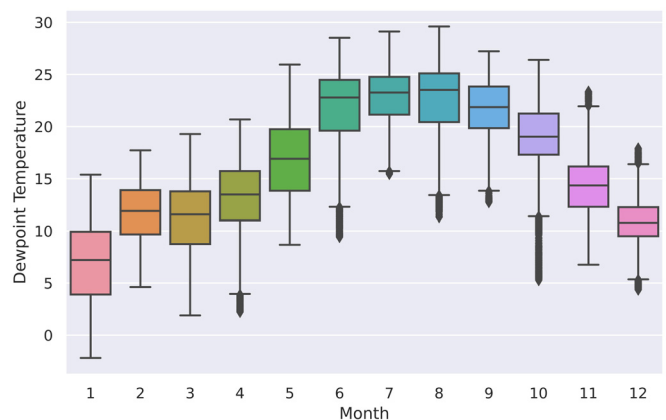


**Fig. 2.** Schematic of the AWGPV system – Chilled water is supplied by the chiller unit which is made to circulate within the cooling panel and then flows back to the chiller using a drain tank and pump. The condensed water formed on the PV module surface is collected in the collection channel and then stored in the collection tank.

setup in this research, a tilt angle of 24 degrees was employed, aligning with the energy yield optimized tilt angle of Dubai, UAE.

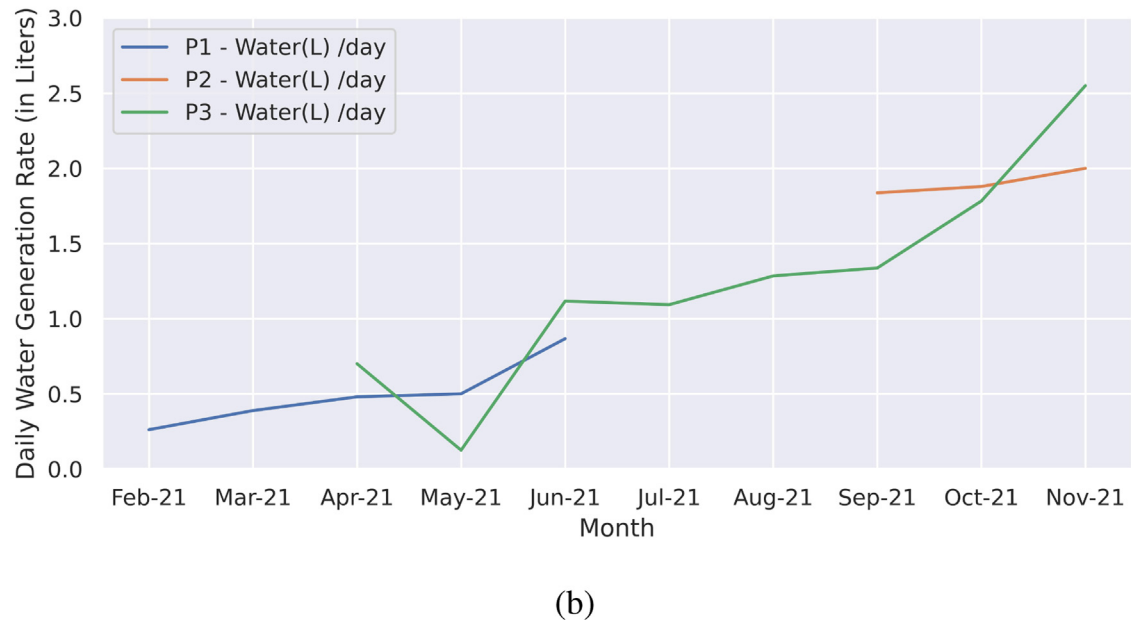
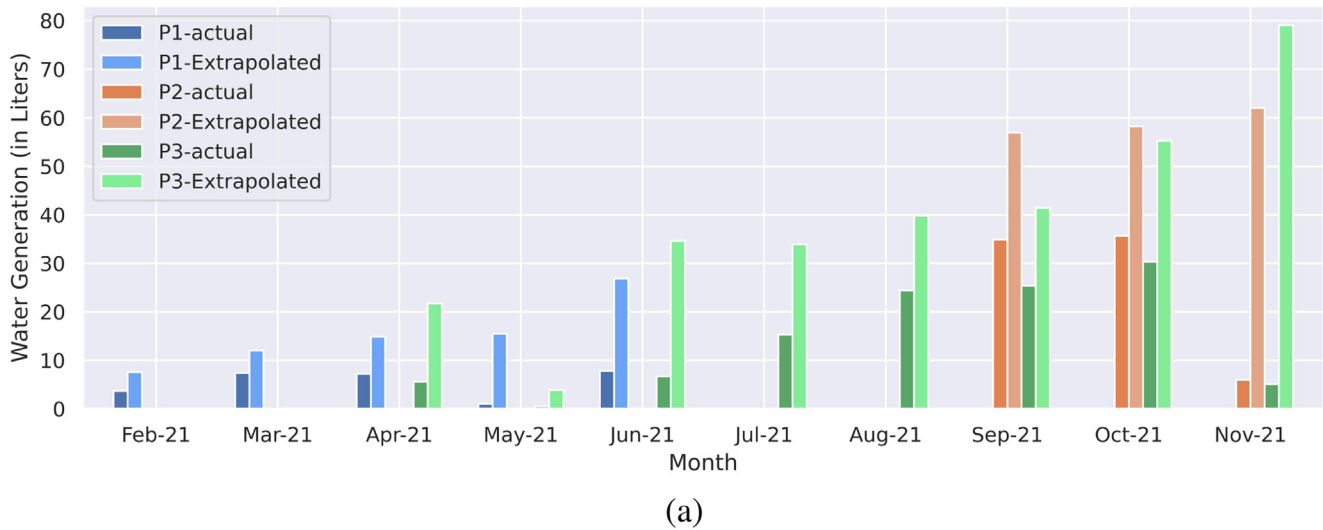
### 3 Experimental results

The occurrence of condensation on a surface is determined by the dew point temperature, which relies on factors such as humidity and ambient temperature. To assess this temperature, the measurements collected at the experiment location were utilized, and the boxplots presented in Figure 3 depict the distribution of dew point values for the entire year of 2020. In the United Arab Emirates (UAE), the dew point temperature tends to be higher during the summer months compared to the winter months. Specifically, during the summer months, the average dew point temperature exceeds 10 degrees (excluding May), whereas, during the winter months, it remains above 5 degrees. Consequently, a cooling technology capable of providing a consistent temperature of 5 degrees throughout the year, with water as the circulating fluid, can be effectively employed.



**Fig. 3.** Dew point temperature ( $^{\circ}\text{C}$ ) during nights for a full year in Dubai UAE. These values are used to set the chiller temperature.

The initial installation of the first prototype, P1, took place in the final week of January 2021. Subsequently, water collection was monitored and recorded from February to June. During the testing phase of P1, an



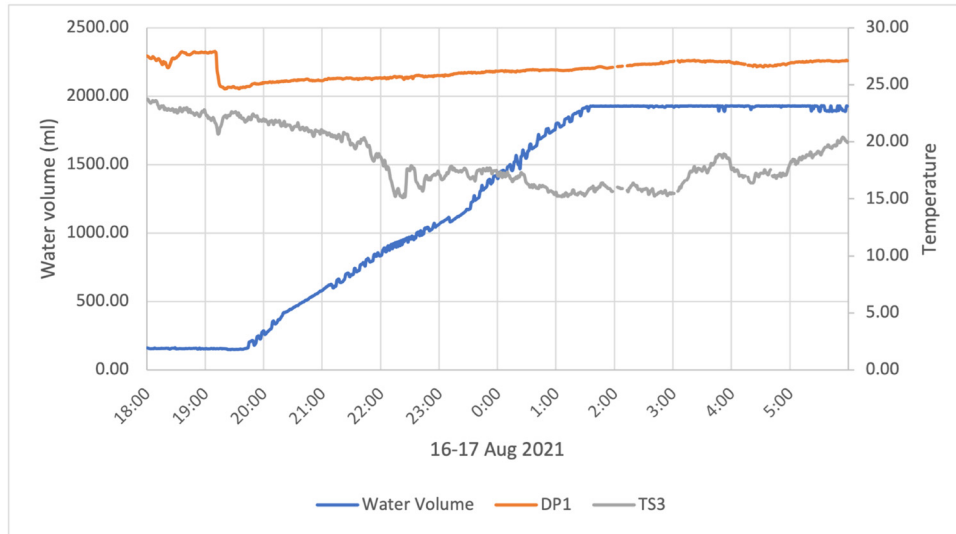
**Fig. 4.** Total Water generated that includes the actual and extrapolated amount in liters/panel (a) and Daily average water generation rate/panel (b) from 3 different prototypes – P1 (blue), P2 (Orange), P3 (Green), demonstrating the possibility of water collection during nighttime on solar panels.

updated prototype, P3, was developed and installed in March. In addition, an identical third prototype, P2, was constructed and put into operation in August. Figure 4a presents the monthly water production data for all three prototypes. Throughout the testing period, various technical challenges were encountered, leading to intermittent water monitoring. These challenges included problems with the chiller, such as failure to reach the desired temperature and leaks in the tank, as well as data collection interruptions during holidays and weekends. Furthermore, issues such as leaks in the collection channel, collection tank, and prototype itself, arising from fabrication complications, were also experienced. Consequently, the average daily water collection for each month was

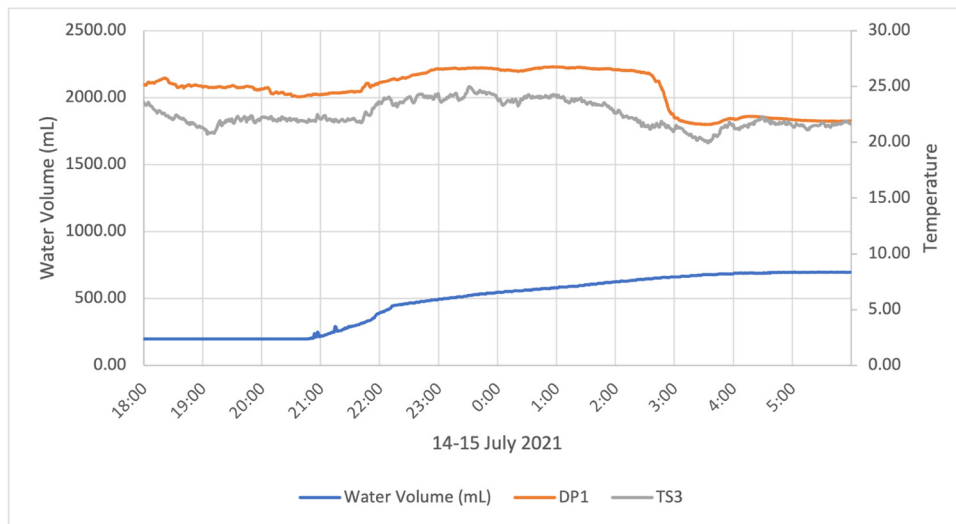
calculated, as shown in Figure 4b, and based on this data, an estimated monthly water generation was extrapolated. As the testing did not fully capture the impact of weather conditions due to manufacturing difficulties, the chiller set temperature was not achieved until September.

The most promising results in terms of water generation were observed from P2, as shown in Figures 4a and 4b, where over 30 L/panel of water was collected in a month despite a few days with technical issues. Extrapolating the daily average water collection, it is estimated that close to 60 L/panel of water can be collected during these months.

The rate of water collection was measured using the ultrasonic sensor (a custom solution used to measure water level) for some days during the project period. The water



(a)



(b)

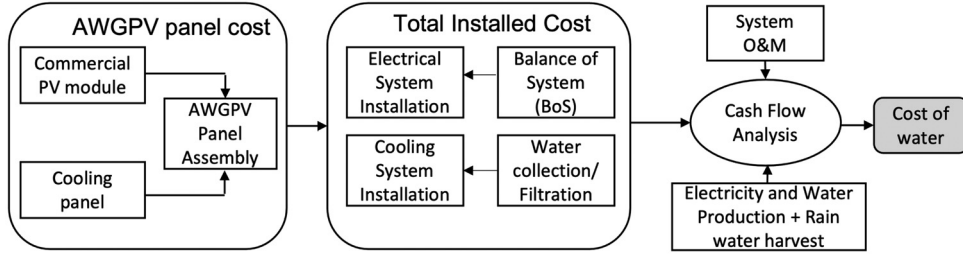
**Fig. 5.** Water collection profile of 2 days from prototype P3 showing (a) 1900 mL/panel (After 1:30 the measurement system could not measure since the water collector was full) and (b) 700 mL/panel water generation with their respective recorded surface temperature, TS, and dew point temperature, DP. It is observed that the temperature difference between the PV module surface (TS) and the dew point temperature (DP) should be above 5 °C to achieve higher water collection.

collection rate profile for 2 days with the PV module surface temperature and dew point temperature are shown in Figure 5a. The figure shows the rate of water generated for a day with high water collection (1.9 L/panel), and Figure 5b shows the water generation for a day with low water collection. It is observed that the temperature difference between the PV module surface (TS) and the dew point temperature (DP) should be above 5 °C to achieve higher water collection.

During the testing period in September and October 2021, the chiller's energy consumption was measured at 134 kWh and 132 kWh respectively. By considering the average monthly chiller energy consumption of 133 kWh

and 60 L per month of water generation, we can estimate that it consumes approximately 2.22 kWh per liter of water produced in a year. There are several potential strategies for further reducing this energy expenditure. These include operating the chiller at night to minimize thermal losses, utilizing insulation to prevent heat loss from the rear side of the PV module, enhancing heat insulation of the pipes, improving the module's surface coating (e.g., super-hydrophobic) to facilitate faster water collection, and reducing leakages in the water collection process. It was also observed that there is an increase operating temperature of the AWGPV panel during the day when there is no water flow in the cooling panel. It was measured to be a





**Fig. 6.** AWGPV panel cost modeling framework and components. The electricity and water output is considered in the cash flow, even though rainwater harvesting is an additional value gain without the need for any extra CAPEX.

maximum of 9°C higher than a commercial Glass-Glass PV module. In a future prototype, a PVT panel will replace the Glass/Glass PV module with an acrylic cooling panel that can mitigate the increase in module temperature by performing dual use of a supply of heat during the day and promoting condensation during the night.

## 4 Economic value model

To quantify the economic value of this system under different future cost assumptions, we construct a model based on the net present value (NPV). This is a generally applicable metric in project development and can provide additional insights beyond levelized cost, especially when considering an energy system with multiple output streams [13]. A detailed cost modeling framework and its respective components are shown in Figure 6.

The AWGPV system has mainly two output streams: electricity generated during the day from the PV ( $E_G$ ) and water produced at night ( $W_G$ ). Each of these has a value or price given by  $P_{EG}$  and  $P_W$ . To construct the model we first build up the system CapEx as the sum of the components, including the standard rooftop PV system, serpentine heat pipe and heat pump or chiller. The estimated cost for building the prototype system that consists of 3 AWGPV panels, a chiller unit, pumps, tank and other miscellaneous items is USD 7,845. This translates to a CAPEX cost of USD 2615 per panel. Note that this cost is not an optimized system cost and has room for improvement. However, the objective is to provide an indication of the cost involved and to arrive at the cost of water production. Actual cost based on the development of the prototype, was used for the techno-economic study. The assumed values in the paper are limited to electricity generation, operating cost, and discount rate. The electricity generated in 1 yr is assumed to be 2115 kWh/kWp based on a PV system that is cleaned regularly. The operating cost was estimated based on the experience of operating the prototype for 1 yr. The discount rate was selected as 4% based on the typical solar projects in Dubai UAE. The total Capex is input into the full NPV expression for the system, given by [14]:

$$NPV = \sum_{i=1}^{L=25} \frac{(CF)}{(1+r)^i} - C_0. \quad (1)$$

Initial value investment is represented by  $C_0$ , discount rate  $r$ , cash flow period  $i$  and  $L$  is the life of the project in years. The annual cash flow, CF of the AWGPV system can be defined in the below format, without considering the initial investment:

$$CF = P_W W_G + P_{EG} E_G - O - P_{EC} E_{chill_{1L}} W_G, \quad (2)$$

where  $P_W$  represents the price of water generated in USD/L,  $W_G$  water generated in 1 year by a single AWGPV panel,  $P_{EG}$  price of electricity generated by AWGPV panel,  $E_G$  annual electricity generated,  $O$  opex,  $P_{EC}$  price of electricity consumed by the chiller and pumping system, and  $E_{chill_{1L}}$  Energy consumed by chiller to produce 1 L of water.

$$NPV_{AWG-PV} = \sum_{i=1}^L \frac{P_W (W_G)_i}{(1+r)^i} + \sum_{i=1}^L \frac{P_{EG} (E_G)_i}{(1+r)^i} - \sum_{i=1}^L \frac{O_i}{(1+r)^i} - \sum_{i=1}^L \frac{P_{EC} (E_{chill_{1L}})_i}{(1+r)^i} - C_0. \quad (3)$$

In the first case, we assume local utility rates for both daytime and nighttime electricity as well as public water, as per DEWA tariff schedule[15]. This corresponds to an NPV of −229 USD per module at a discount rate of 4%/yr. As 4%/yr represents a low-end financing cost estimate for a new energy project, a project must have a positive NPV at this discount rate in order to be viable in the real world. This point is achieved in the present model for a water price of 0.33 USD/L. This suggests that the system could possibly be viable in remote areas where transporting water is costly. Table 1 summarizes the data used for this calculation.

The energy requirement per module is many times higher than the electricity production and therefore a large input of electricity would be required to operate this system with all modules used for AWG. This means that the cost of consumed energy dominates the value of generated energy in the NPV calculation. Therefore, if the electricity price is dropped to 0.022 USD/kWh, consistent with recent power purchase agreements for utility-scale PV projects in UAE, the minimum viable price of water reduces to 0.28 USD/L.

**Table 1.** The input values considered for NPV calculation for a grid-connected AWGPV system installed in Dubai UAE normalized for 1 PV module with 333 Wp (165 cm × 90 cm).

| Parameter        | Description                                        | Unit    | Values |
|------------------|----------------------------------------------------|---------|--------|
| $W_G$            | Water generated in 1 yr                            | L       | 720    |
| $E_G$            | Electricity generated in 1 yr by 333 Wp PV module  | kWh     | 705    |
| $E_{chill_{IL}}$ | Energy consumed by chiller to produce 1 L of water | kWh/L   | 2.22   |
| $C_0$            | Initial investment cost normalised to 1 panel      | USD     | 2615   |
| $O$              | Operating cost for 1 yr per panel                  | USD     | 13.62  |
| $P_{EG}$         | Price of electricity generated for 1 yr*           | USD/kWh | 0.063  |
| $P_{EC}$         | Price of electricity consumed by cooling unit*     | USD/kWh | 0.063  |
| $L$              | Lifetime of project                                | yr      | 25     |
| $r$              | Discount rate                                      | %/yr    | 4      |
| $P_W$            | Price of water generated for NPV = 0               | USD/L   | 0.33   |

\* As per utility price of Dubai. The above electricity generation assumes that 1kW PV system generates 5.8kWh per day in Dubai UAE.

However, it may be more useful for practical purposes to consider a system where no net import of electricity is required. We next consider a balanced system that is still grid-connected but that has zero net energy input for the AWG functionality. A certain fraction of the total energy production is allocated to AWG; in this case, this power is exported to the grid during the day in exchange for an equal input of power during the night. Based on the efficiency displayed by the present system, PV generation would be divided evenly between electrical output and water generation if 22% of the modules are modified for AWG. In this case, the capex of the system would be 78% PV and 22% AWG components. The net electricity output would be 50% of the total generation, and the water output would be 22% of the total production in the first case. As the water production is reduced by a factor of 4.5, the minimum viable water price is increased to 0.42 USD/L at 0.06 USD/kWh, and 0.42 USD/L at 0.022 USD/kWh. We note that in this case, the relationship between the water and electricity price is independent, as the electricity revenue is equal to the cost of the electricity consumed by the chiller.

In practice, the value of exported energy and consumed energy may be different. Specifically, as solar energy penetration increases, energy during peak solar hours will be abundant and extremely cheap, while overnight electricity relying on a combination of storage and thermal generators will be more expensive. If we consider the value of generated electricity to be 0.022 USD/kWh but the cost of consumed electricity to be 0.06 USD/kWh, the minimum viable water price rises to 0.51 USD/L.

Another configuration that is worth considering is a standalone system in which a portion of the generated energy is stored in batteries and used to produce water overnight. We model a reasonable implementation of this system using a battery storage capacity of 2 kWh-battery/kW-module, or 2 times the daily average energy requirement for atmospheric water generation. Again using 0.022 USD/kWh as the value of generated electricity, the minimum viable price of water is 0.57 USD/L, indicating that the cost of supplying electricity from storage is slightly more expensive than purchasing from the grid at a different day and night tariff.

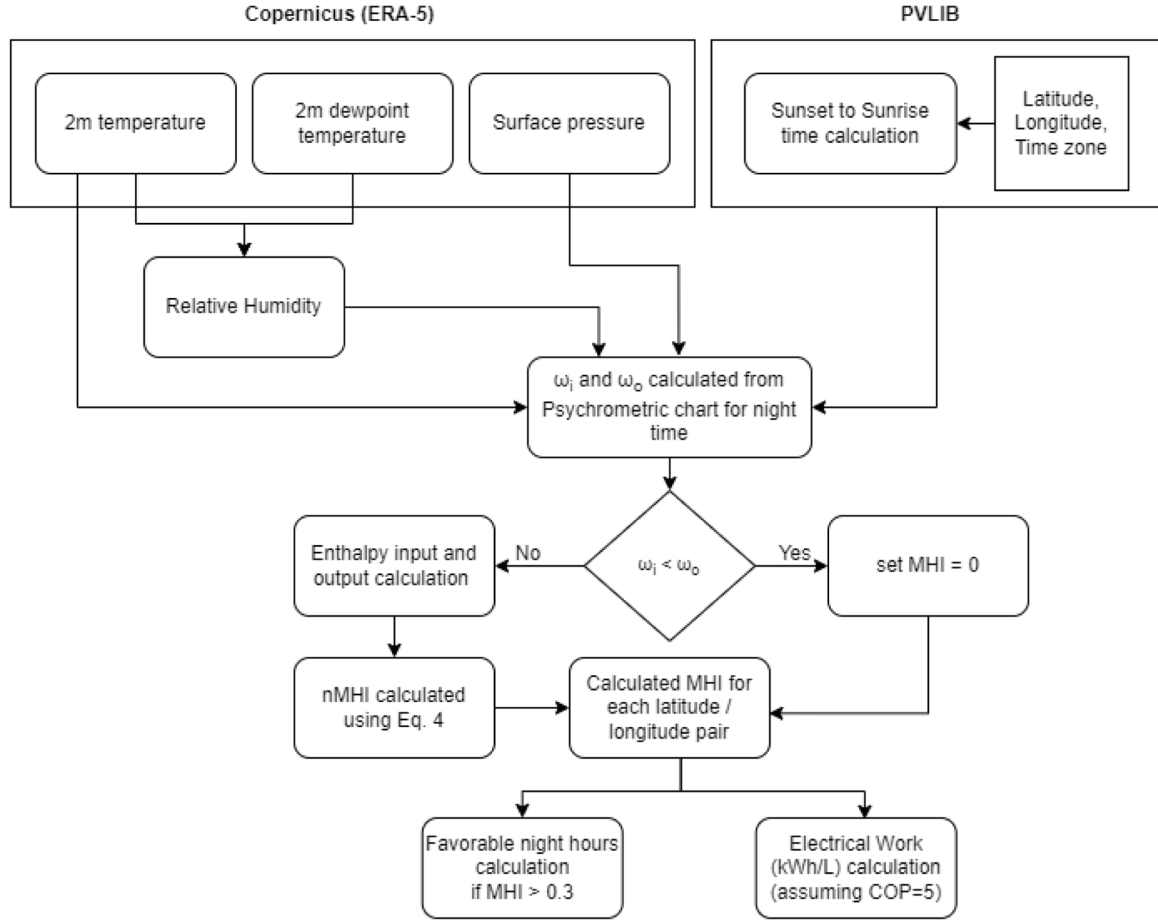
## 5 Night moisture harvesting index

In this section, we explore the potential usage of AWGPV systems in different parts of the world and study the minimum energy requirement for generating 1 L and the number of favorable days for generation. Gido et al [16] introduced the Moisture Harvesting Index (MHI) as an index for evaluating the feasibility and energy demands of direct cooling-based atmospheric water generation (AWG) systems. The MHI serves as a valuable metric for selecting suitable locations and determining optimal operational time periods throughout the day and year, thereby significantly reducing the specific energy requirements of the process.

In an AWG system, the condensed water is the desired output. Consequently, the latent heat of condensation, which facilitates the phase change of water vapor, is an unavoidable factor. However, the sensible cooling of air imposes an additional energy burden. Minimizing the sensible heat interaction becomes crucial for enhancing the overall process efficiency. The MHI represents the ratio of latent heat to total heat interactions and serves as a reliable parameter for assessing the energy requirements of atmospheric water generation through direct cooling. It can be mathematically expressed as follows [16,17]:

$$MHI = \frac{h_{fg}}{q_{tot}^*} = \frac{\omega_i - \omega_o}{h_i - h_o} h_{fg}, \quad (4)$$

where  $h_{fg}$  [kJ/kg<sub>w</sub>] is the enthalpy of condensation for the production of 1 kg<sub>w</sub> of water and  $q_{tot}^*$  [kJ/kg<sub>w</sub>] is the total heat required to be removed from the air during the production of 1 kg of water. Total heat interaction is the enthalpy difference,  $h$  between its inlet,  $i$ , and outlet,  $o$  of the moist air. However, it can be divided by the difference of the specific humidity  $w$  [kg<sub>w</sub>/kg<sub>a</sub>] at its inlet and outlet, to provide the total heat required to be removed from the air during the production of 1 kg of water. Enthalpy of condensation,  $h_{fg}$  depends on the condensation temperature and is set to 4 °C and with specific humidity of 5 g/kg for the MHI calculation.



**Fig. 7.** Flowchart showing the method used for calculating n-MHI for different geographical coordinates. The meteorological data used is from ERA5 for the year 2022 [18] and the nighttime is identified for every geographical location using the PVLIB library [19].

The relationship between temperature and humidity is widely recognized, where an increase in temperature during daytime hours leads to a decrease in relative humidity, resulting in lower absolute humidity and drier air. Conversely, during nighttime, as temperatures decrease, relative humidity increases, leading to moister air. Given this phenomenon, the MHI in this study is specifically calculated for nighttime conditions. Furthermore, the non-operational state of solar PV modules during this time allows for utilizing their surfaces for water harvesting. The nighttime MHI, referred to as n-MHI is estimated using the above equation and filtered for the time period between sunset and sunrise for all locations. This is done using the meteorological data from ERA5 for the year 2022 [18] and identifying the night time for every geographical location using the PVLIB library [19]. The schematic of the methodology used is shown in Figure 7.

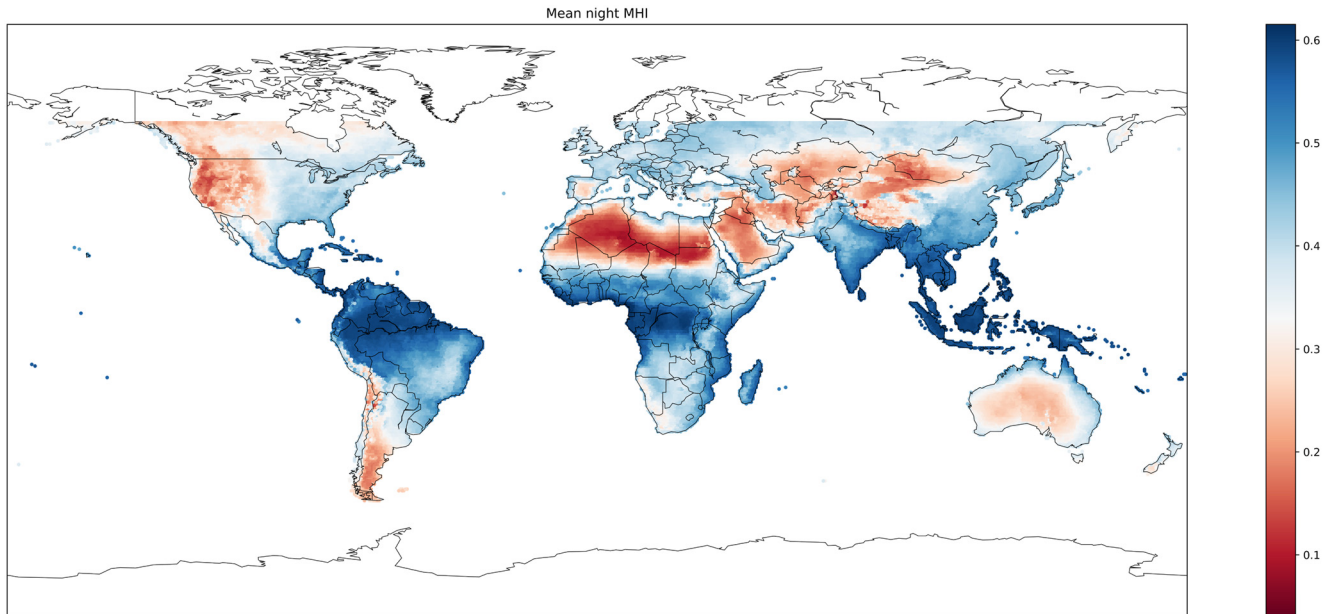
The global map of the average n-MHI for the year 2022 is shown in Figure 8. The achievement of n-MHI = 1 can solely be attained through the condensation process of pure water vapor. When moisture extraction occurs by directly cooling ambient air, the resulting n-MHI will always be less than 1. For instance, an n-MHI value of 0.5 indicates an equal contribution from sensible and latent heat interactions. Warm and highly humid ambient conditions are characterized by high n-MHI values, wherein the

requirement for sensible heat removal is minimal, leading to relatively high overall efficiency in the process. Conversely, low n-MHI values are indicative of ambient conditions that necessitate significant sensible heat removal and yield low moisture condensation. Southeast Asian countries, Central Africa, and the Northern part of South America are most suitable for night-time atmospheric water generation using the AWGPV system, which is characterized by an average n-MHI of 0.6.

The estimation of the annual average energy demand for the AWG process can be conducted by utilizing either site-specific climate data or a time series of meteorological observations that pertain to the specific location. The electricity consumption of the process is contingent upon the coefficient of performance (COP, dimensionless), a fundamental characteristic of the cooling apparatus. The COP signifies the ratio between the heat extracted from the cold AWGPV panel and the work necessary to sustain the process. Common commercial cooling systems have COP below 5. A COP = 5 is used to calculate the electrical work required for generating 1 kg of water using the below equation.

$$W = \frac{q_{tot}^*}{COP} = \frac{h_{fg}}{nMHI \times COP}, \quad (5)$$





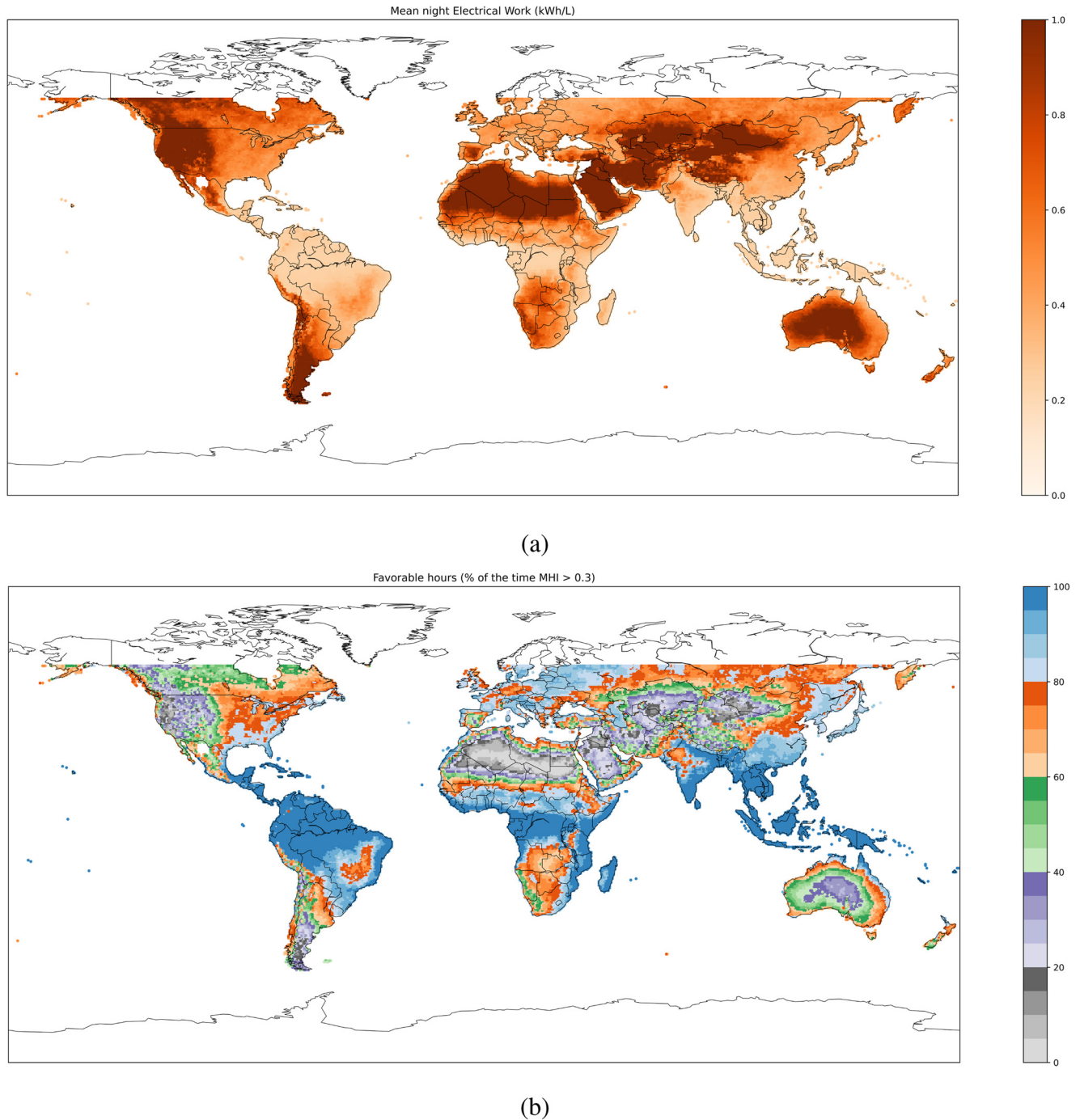
**Fig. 8.** Global map of night time MHI (n-MHI) values estimated for the year 2022, calculated from the Copernicus ERA5 hourly data [18].

A world map is generated using the above equation for every geographical coordinate that shows the energy required for generating 1 L of water. From Figure 9, it can be observed that most coastal countries have lower energy requirements of less than 0.5 kWh/L. The favorable night hours were estimated by calculating the number of hours where n-MHI values were above 0.3. Also, the coastal regions can generate water for more than 80% night hours in a year. Table 2 shows a small subset of locations in the World where large solar parks are being developed or planned. The large solar sites located in Morocco and UAE show the highest n-MHI values of 0.49 and 0.43 respectively. The solar site in Morocco has the potential to collect water 351 days a year (96.31%). MBR Solar Park located in Dubai UAE can generate 310 days a year (84.95%). The energy required to collect 1 L of water is also lowest in these 2 sites. The current AWGPV system that is installed at the MBR solar utilizes approx 2.22 kWh/L which is 5 times the estimated amount from the n-MHI (0.45 kWh/L). The notable five-fold increase in value can be attributed to several key factors. Firstly, the initial approach involved continuous cooling throughout the day and night to prevent water leaks. However, a more efficient strategy would be to restrict the cooling process to nighttime hours exclusively. Additionally, substantial thermal loss was observed from the rear side of the cooling panel. This issue can be effectively mitigated by adopting commercial PVT modules with improved heat insulation at the back. Furthermore, it was evident that there was room for improvement in the heat insulation of the water pipes, a factor that contributed to the elevated value. The Llano De Llampos solar park in Atacama Chile has the lowest n-MHI due to low specific humidity and low ambient temperature during most days of the year.

## 6 Discussion

This work addresses the suboptimal utilization of solar PV power plants, primarily caused by their reliance on solar irradiation available only during the daytime. Recognizing the significant land footprint occupied by solar power plants, this study proposes an alternative approach to maximize the usage of solar panels by utilizing their surface for water generation. Additionally, this system can be used for rainwater harvesting without adding any more components. Experimental results reveal that the AWGPV system consumes more energy than it produces. However, the analysis of the night Moisture Harvesting Index (n-MHI) demonstrates substantial potential for optimizing energy consumption in the cooling unit. This paper highlights the effectiveness of the n-MHI as a parameter for assessing the feasibility and cost-effectiveness of atmospheric water generation through direct cooling. Moreover, coastal regions, known for their proximity to expansive water bodies and elevated ambient humidity, emerge as favorable locations for implementing AWGPV systems compared to inland or continental areas such as the Sahara region.

For example, large-scale solar sites in Morocco and the UAE are situated near coastal areas, which are typically characterized as desert regions with limited human activities due to water scarcity. The cost of extending water pipelines to these regions is prohibitively high, further exacerbating the water access challenge. Furthermore, these coastal cities experience minimal rainfall and possess very little access to groundwater. However, these locations experience high night Moisture Harvesting Index (n-MHI) values and a significant proportion of favorable nighttime conditions (96% and 85% respectively) for atmospheric water generation.



**Fig. 9.** A world map is generated using the Copernicus ERA5 hourly data [18] that shows (a) the energy required for generating 1 L of water and (b) annual favorable night hours in % where  $n\text{-MHI} > 0.3$ .

Moreover, the consistently low temperatures of the water bodies in these regions present an intriguing opportunity to utilize them as heat sinks. This alternative approach could potentially replace traditional electrical cooling processes with more cost-effective heat exchangers. At present, seawater desalination stands as the favored and economically feasible approach for generating freshwater in coastal regions. This is due to its considerably lower energy requirement per liter (0.004 kWh/L) in reverse osmosis (RO) desalination plants. To make Atmospheric Water

Generation with Photovoltaic competitive with RO freshwater production, innovative energy-efficient direct cooling techniques could be developed. For instance, incorporating radiative cooling coatings or hydrogel-based desiccants on PV modules coupled with direct cooling could offset energy costs and ensure year-round water generation. The  $n\text{-MHI}$  analysis highlighted earlier section could aid in a climate-based feasibility process for identifying regions that are best suited for AWGPV system implementation.

**Table 2.** Estimated nighttime performance of AWG systems by direct cooling at different desert locations of the World where large-scale solar PV power plants are located. Meteorological data were obtained from ERA5 for the year 2022 [18].

| Country – nearest solar park (SP) [20]  | Avg temp<br>(°C) | Avg specific<br>humidity<br>(g <sub>w</sub> /kg <sub>a</sub> ) | Avg<br>n-MHI<br>(–) | Annual operating<br>night hrs<br>(%) | Energy<br>req.<br>(kWh/L) |
|-----------------------------------------|------------------|----------------------------------------------------------------|---------------------|--------------------------------------|---------------------------|
| Morocco – Noor Boujdour SP              | 18.32            | 11.12                                                          | 0.49                | 96.31                                | 0.31                      |
| UAE – MBR SP, Dubai                     | 26.08            | 12.76                                                          | 0.43                | 84.95                                | 0.45                      |
| India- Bhadla SP, Rajasthan             | 26.2             | 12.57                                                          | 0.40                | 69.67                                | 0.58                      |
| China – Tengger SP, Ningxia             | 18.02            | 8.29                                                           | 0.36                | 65.99                                | 0.68                      |
| USA – Moss SP, Arizona                  | 20.76            | 8.59                                                           | 0.34                | 61.52                                | 0.67                      |
| Namibia – Omaruru SP, Omaruru           | 19.26            | 8.65                                                           | 0.34                | 56.07                                | 0.94                      |
| Australia –Powell Creek SP, N.Territory | 29.03            | 10.03                                                          | 0.27                | 43.96                                | 1.07                      |
| Chile – Llano De Llampos SP, Atacama    | 17.88            | 6.31                                                           | 0.22                | 15.77                                | 1.29                      |

n-MHI were calculated under the assumption that the AWGPV panel is set at 4°C for the whole night. Favorable night hours were calculated by considering the number of night hours >0.3. Energy Requirements were calculated assuming COP = 5 during the night operation for 1 yr.

In locations where substantial investments in infrastructure, such as extensive water transportation piping are required, AWGPV systems can compete with seawater desalination using reverse osmosis (RO). However, for small and dispersed communities with relatively low freshwater demands, a decentralized solution like the AWGPV system may prove more practical compared to alternative options, especially when limited initial capital is available for infrastructure development. Additionally, if the chilled water produced as a by-product of the AWGPV system holds market value, AWGPV through direct cooling may be the preferred choice. This allows for the provision of a truly decentralized electricity and water generation system, offering increased sustainability and independence at the local level.

## 7 Conclusion

The global installation of photovoltaic (PV) systems has experienced significant growth, with the Middle East emerging as a hub for low solar tariffs. However, a substantial portion of land remains unused during nighttime due to the presence of solar panels. This research paper explores the potential of utilizing this surface area for water generation through the integration of atmospheric water generators (AWGs) with solar PV modules. The study highlights the feasibility and scalability of such systems, offering valuable insights into addressing water scarcity challenges and promoting sustainable solutions in arid environments like the Middle East.

The prototype of the AWGPV panel was successfully constructed by retrofitting a PV module with a specially designed cooling panel featuring engraved water channels. The use of a back glass instead of a polymer backsheet and the incorporation of a collection channel ensured efficient water flow and condensation. The cooling panel effectively cooled the surface of the PV module below the dew point temperature using a conventional chiller unit, allowing for the collection and storage of condensed water. The

potential for water generation during nighttime on solar panels was investigated by analyzing the dew point temperature in the United Arab Emirates (UAE). The distribution of dew point values throughout the year revealed higher cooling temperatures during the summer months, exceeding 10 degrees, and temperatures above 5 degrees during the winter months. This indicates the possibility of utilizing a cooling technology to maintain a consistent temperature of 5 degrees throughout the year, making water generation possible in Dubai Deserts. The testing of three prototypes demonstrated promising results, with Prototype P2 collecting over 30 L of water per panel in a month. The extrapolation of daily average water collection estimated that close to 60 L of water per panel could be collected during these months. The rate of water collection was found to be influenced by the temperature difference between the PV module surface and the dew point temperature, emphasizing the importance of maintaining a temperature difference above 5 degrees Celsius for higher water collection to account for thermal losses in the prototype system.

The Moisture Harvesting Index (MHI) introduced by Gido et al [16] provides a valuable metric for evaluating the feasibility and energy demands of atmospheric water generation (AWG) systems. The MHI, which represents the ratio of latent heat to total heat interactions, is used to assess the energy requirements of direct cooling-based AWG systems. By analyzing the MHI for nighttime conditions, referred to as n-MHI, it is possible to select suitable locations and determine optimal operational time periods, thus reducing the specific energy requirements of the process. The global map of average n-MHI values indicates that Southeast Asian countries, Central Africa, and the Northern part of South America are particularly suitable for nighttime AWG using the AWGPV system. Additionally, the estimation of energy demand for AWG is conducted based on the coefficient of performance (COP) and reveals that coastal regions generally have lower energy requirements for water generation. Overall, the MHI and energy demand analysis provide valuable insights

for optimizing the design and operation of AWG systems, promoting water sustainability in various geographical locations.

## Conflicts of interest

Jim J John certifies that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Nithin Sha Najeeb that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Harry Apostoleris that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Kaushal Chapanerri that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Gerhard Mathiak that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article. Muhammad Alam that he has no financial conflicts of interest (eg., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article.

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## Data availability statement

This article has no associated data generated and/or analyzed / Data associated with this article cannot be disclosed due to legal/ethical/other reason.

## Author contribution statement

Methodology, Jim J John; Software, Kaushal Chapanerri; Validation, Jim J John, Gerhard Mathiak and Harry Apostoleris; Formal Analysis, Jim J John, Gerhard Mathiak and Harry Apostoleris; Investigation, Jim J John, Gerhard Mathiak and Harry Apostoleris; Resources, Nithin Sha Najeeb; Data Curation, Jim J John and Nithin Sha Najeeb; Writing – Original Draft Preparation, Jim J John and Harry Apostoleris; Writing – Review & Editing, Gerhard Mathiak

and Muhammad Alam; Visualization, Jim J John, Nithin Sha Najeeb and Kaushal Chapanerri; Supervision, Jim J John and Gerhard Mathiak; Project Administration, Jim J John; Funding Acquisition, Jim J John.

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