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Harnessing enhanced solar efficiency for green hydrogen production: A comparative analysis of PV and PV-T systems

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ABSTRACT

Green hydrogen, a critical element in the shift towards sustainable energy, is traditionally produced by electrolysis powered by solar photovoltaic (PV) systems. This research explores the potential of underexploited photovoltaic thermal (PV-T) systems for efficient green hydrogen generation. This paper compares this advanced technology performance and economic viability against conventional PV setups. This paper uses TRNSYS simulation software to analyze two distinct solar-based hydrogen production configurations – PV and PV-T – across diverse climatic conditions in Doha, Tunis, and Stuttgart. The paper's findings indicate that PV-T significantly outperforms PV in hydrogen generation across diverse climates (Doha, Tunis, Stuttgart). For instance, in Doha, PV-T systems increase hydrogen output by 78%, in Tunis by 59% and in Stuttgart by 25%. An economic assessment reveals PV panels as the most cost-effective option, with hydrogen production costs ranging from $4.92/kg to $9.66/kg across the studied locations. For PV-T collectors, the hydrogen cost range from $6.66/kg to $16.80/kg across the studied locations. Nevertheless, this research highlights the potential of PV-T technology to enhance the efficiency and economic viability of green hydrogen production. These findings offer valuable insights for policymakers, investors, and researchers pursuing more efficient solutions for sustainable energy.

1. Introduction

Green hydrogen, often hailed as a key player in the global push towards decarbonization, plays a crucial role as a sustainable energy source. Green hydrogen is produced through a process called electrolysis, where renewable energy sources such as solar or wind are used to split water into hydrogen and oxygen. The demand for green hydrogen is expected to grow approximately to 660 million metric tonnes annually by 2050 [1]. The significance of green hydrogen lies in its potential to address environmental and energy challenges.

Solar energy is one of the desired renewable energies to be coupled with an electrolyzer in the form of photovoltaic (PV) panels to produce green hydrogen. The share of energy generated by solar PV is expected to reach 12.6% of the total renewable energy utilized by 2028 [2]. It is desired for several reasons: (i) the abundance availability of solar energy across a wide range of locations and its consistency. It is especially effective in regions with high levels of sunlight. (ii) The dropping prices in the PV panels, which declined by almost 50% year-on-year up to 2023, with manufacturing capacity reaching three times 2021 levels [2]. Furthermore, the ongoing evolution of PV panel technologies represents a significant opportunity for assigning hydrogen production a pivotal role in accelerating the energy transition. Indeed, technologies like photovoltaic thermal (PV-T) collectors may significantly contribute to the ongoing evolution of renewable energy systems via integration with hydrogen production to address both electricity and thermal energy needs synergistically. Indeed, PV-T collectors act like solar collectors and PV panels. They capture solar energy from the sun and convert it to thermal energy like solar collectors. Also, they convert solar energy to electrical energy like PV panels. The PV-T collectors also have the feature of cooling down their temperature by exchanging the heat with the in-flowing water. This leads to reducing the collectors' temperature, increasing their efficiency. Moreover, using the heated water that flows out of the PV-T as a water feedstock for hydrogen electrolysis will enhance the efficiency and performance of the electrolyzer, thus producing more hydrogen.

Several studies have been published adopting a simulation approach to investigate the performance of solar (i.e., PV panels and PV-T collectors) driven hydrogen systems to investigate their performance. Such papers are carried out by Gül and Akyüz [3], Touili et al. [4], Khelfaoui et al. [5], Bahri and Harrag [6], Holmes-Gentle et al. [7], Chen et al.

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[8], Liu et al. [9], Li et al. [10], Zhang et al. [11], Cao et al. [12], Atiz et al. [13], Hassan et al. [14], Zou et al. [15], Shin et al. [16], Gutiérrez-Martín et al. [17], and Atiz et al. [18]. Most studies have simulated PV panel-driven hydrogen production systems using various software, such as Greenius, MATLAB, Simulink, Aspen Plus, and the TRaNsient SYstem Simulation tool (TRNSYS). However, few researchers, such as Li et al. [10], Atiz et al. [13], and Atiz et al. [18], have examined PV-T collector-driven hydrogen systems, primarily using software like Aspen. These studies typically focused on only one geographical location and a specific PV-T collector area. Additionally, they did not explore the concept of supplying the electrolyzer with heated water from the PV-T collectors. The only authors who investigated this concept were Gül and Akyüz [3], who developed a numerical model for their analysis. None of the reviewed studies, however, provides a comprehensive comparison between PV and PV-T systems – specifically, the electricity and thermal energy generation of each when coupled with an electrolyzer – in terms of performance and cost across different geographical locations.

Considering the contributions and limitations of prior studies, the present paper aims to address the following objectives:

- investigating the impact of using PV panels and PV-T collectors for hydrogen production via electrolysis across three locations at different latitudes and for varying panel and collector areas. Specifically, it examines how supplying heated water from PV-T collectors to the electrolyzer affects hydrogen production, using TRNSYS simulation methods. Previous studies, such as Li et al. [10], Atiz et al. [13], and Atiz et al. [18], have analyzed PV-T collector-driven hydrogen systems, primarily with Aspen software. However, these studies focused on a single geographical location and a fixed PV-T collector area, without considering the use of heated water from the PV-T collectors to enhance electrolyzer performance. The only work that investigated this concept is by Gül and Akyüz [3], who developed a numerical model for a specific location (Turkey).
- Performing an economic analysis of two systems – the PV panel-driven hydrogen production system and the PV-T collector-driven hydrogen production system – to determine which is most cost-effective at each selected location, based on simulation results from TRNSYS. Previous studies, such as Touili et al. [4], Hassan et al. [14], Srettiwat et al. [19], Shin et al. [16], and Gutiérrez-Martín et al. [17], have conducted economic analyses exclusively for PV panel-driven hydrogen production systems, focusing on specific system sizes and single geographical locations, and using various simulation tools. However, Gül and Akyüz [3] is the only study that performed an economic analysis on a PV-T collector-driven hydrogen production system, using a numerical model.

To this end, this paper adopts a simulation approach for energy system analysis, using the TRNSYS, while secondary data is used for economic analysis. TRSNSYS is selected over the other simulation software due to the various benefits, (i) it offers specialized libraries for renewable energy and thermal systems, (ii) it has robust capabilities to handle detailed solar models such as solar irradiance modeling, and tracking solar position, which is key for accurately simulating solar-based hydrogen production, (iii) it has dynamic simulation capabilities where conditions (like irradiance or temperature) change over time. It simulates transient processes in real-time, which is particularly useful for understanding how solar irradiance fluctuations impact hydrogen production throughout the day, and (iv) it provides graphical interface which allows us to better visualize the system through the feature of connecting the various system components together. This modular setup makes it easier to customize each part of the hydrogen production system, providing flexibility as we explore different configurations.

2. Literature review

This paper presents a summary of related work. Table 1 summarizes the scope and findings of each paper. The existing literature has limited work published in this area, and comprehensive comparative techno-economic analysis of different systems is still missing. Numerous studies have used simulation approaches to analyze the performance of solar-powered hydrogen systems, specifically those driven by PV panels and PV-T collectors. Notable works in this area include Touili et al. [4], Khelfaoui et al. [5], Bahri and Harrag [6], Chen et al. [8], Liu et al. [9], Li et al. [10], Zhang et al. [11], Cao et al. [12], Atiz et al. [13], Hassan et al. [14], Zou et al. [15], Shin et al. [16], Gutiérrez-Martín et al. [17], and Atiz et al. [18]. Most of these studies modeled PV panel-driven hydrogen systems using various simulation tools such as Greenius, MATLAB, Simulink, Aspen Plus, and TRNSYS. Touili et al. [4] studied the impact of the PV panels orientation on hydrogen production. Khelfaoui et al. [5] discussed the impact of the ambient temperature and the solar irradiance on the performance of the PV panels. Bahri and Harrag [6] studied the impact of changing the temperature, voltage, and faraday efficiency on the electrolyzer performance. Chen et al. [8] studied the hydrogen production through different seasonal climate. Liu et al. [9] and Zhang et al. [11] studied the impact of the ambient temperature on the PV panels efficiency, and the impact of different locations (i.e., solar resources and environmental conditions) on the system performances. Hassan et al. [14] optimized the electrolyzer size while considering the PV system size. Gutiérrez-Martín et al. [17] investigated the concept of coupling the PV panels-driven hydrogen system with a battery to reduce the electrolzyer size.

In contrast, only a few studies, such as Li et al. [10], Atiz et al. [13], and Atiz et al. [18], focused on PV-T collector-driven hydrogen systems, primarily using Aspen for simulation. Atiz et al. [13] studied the effect of water flow rate on the outlet and surface temperature of the PV-T collectors, the amount of electricity and thermal generation, and the amount of the hydrogen produced. Atiz et al. [18] investigated the effect of PV-T collectors area on hydrogen production and the thermodynamic efficiency, electricity and hydrogen production of PV-T collectors and PV panels. These works were limited to a single geographical location and specific PV-T collector areas, and none explored the potential benefits of supplying hot water from PV-T collectors to the electrolyzer. The exception is Gül and Akyüz [3], which developed a numerical model to study this concept and they carried out experimental work to compare between numerical and experimental results. However, none of the reviewed studies provided a comprehensive comparison of PV and PV-T systems – evaluating both electricity and thermal energy generation – when coupled with an electrolyzer in terms of performance and cost across different geographical locations.

To the best of knowledge, this paper is the first to (1) investigate the impact of using different PV technologies, namely PV panels and PV-T collectors on hydrogen production via electrolysis considering three locations at different lattiudes and (2) perform an economic analysis of different energy system configurations to determine which technology – namely PV panels and PV-T collectors – is the most cost effective for each considered location.

3. System description

3.1. Photovoltaic panels driven hydrogen production system

In this baseline system, as indicated in Fig. 1, the standard PV panels supply the required electricity to the hydrogen electrolyzer as an energy source. For the feedstock, room-temperature water is supplied to the hydrogen electrolyzer. This paper considers an Alkaline hydrogen electrolyzer.

Table 1
A summary of studies from the literature.

Author	Scope	Methodology	Location	PV technology employed in the study		Findings
				PV	PV-T	
[3]	Investigate the performance of two systems: PV and PV-T collectors-driven hydrogen systems.	Numerical Model	Turkey	✓	✓	* Develop a numerical model to evaluate the thermodynamic performance of the two systems. * Carry out experimental work to compare the results obtained from the numerical model and the experimental work.
[4]	Investigate the performance of PV panels-driven hydrogen system.	Simulation (Greenius) Model	Morocco	✓	X	* The two-axis PV produces the highest amount of hydrogen. * The one-axis PV is the optimal choice as it produces hydrogen close to two-axis PV at a lower cost.
[5]	Investigate the performance of PV panels-driven hydrogen systems.	Simulation and Experimental models	Algeria	✓	X	* The ambient temperature and the solar irradiance impact the performance of the PV. * The experimental results are compared with the modeling and simulation results.
[6]	Investigate the performance of PV panels-driven hydrogen system.	Simulation (MatLab Simulink) method	Not mentioned	✓	X	* Find the optimum operating point between PV and electrolyzer. * The performance of the electrolyzer is impacted by changes in temperature, voltage, faraday efficiency, and hydrogen production rate.
[8]	Investigate the performance of PV panels-driven hydrogen system.	Simulation (TRNSYS) method	Canada	✓	X	* The maximum power output is during Summer and Spring. * Hydrogen production is significantly related to the seasonal climate.
[9]	Investigate the performance of PV panels-driven hydrogen system connected to the grid.	Simulation (TRNSYS) software	Iran	✓	X	* The efficiency of the PV system decreases with increasing ambient temperature. * The system's performance, in terms of power generation and hydrogen production, varies across different locations due to varying solar resources and environmental conditions.
[20]	Investigate the performance of PV-T collectors-driven hydrogen system.	Numerical model	Iran	X	✓	* As the solar radiation intensity increases, the electrical efficiency of the system reduces, but hydrogen production is enhanced. * As the feedwater mass flow rate increases, hydrogen production is enhanced. * As the feedwater inlet temperature increases, the operating voltage of the electrolyzer is reduced. * The increase in the feedwater inlet temperature has a negative impact on hydrogen production.
[10]	Investigate the performance of PV-T collectors-driven hydrogen system coupled with organic Rankine cycle.	Simulation (Aspen Plus) and Mathematical models	China	X	✓	* The organic Rankine cycle completely satisfies the power demand of the auxiliary system operations. * This system is suitable for retrofitting PV plants as it has higher profitability than grid-supplied hydrogen production.

(*continued on next page*)

Table 1 (*continued*).

[11]	Investigate the performance of PV panels-driven hydrogen systems.	Simulation model	China	✓	X	* The system efficiency initially increases with higher solar radiation intensity but then decreases. * Efficiency decreases monotonically with higher ambient temperature.
[12]	Investigate the performance of PV panels-driven hydrogen systems.	Simulation model	Not mentioned	✓	X	* Propose electrical control and energy management strategies to manage issues related to power fluctuation.
[13]	Investigate the performance of PV-T collectors-driven hydrogen systems.	Simulation method	Not Mentioned	X	✓	* When the water flow rate increases, the outlet and surface temperature of the PV-T decreases. * The amount of electricity and thermal energy generation increases as the mass flow rate increases. * The amount of hydrogen produced increases as the mass flow rate increases.
[14]	Investigate the performance of PV panels-driven hydrogen system.	Simulation (MatLab) Model	Iraq	✓	X	* It is recommended to use two-thirds of the PV power to estimate the size of the electrolyzer. * Optimize the size of the electrolyzer in reference to the PV system size and use a location with a large potential for renewable energy.
[21]	Investigate the performance of two systems: PV and PV-T collectors-driven hydrogen systems.	Mathematical (MatLab) model	Not mentioned	✓	✓	* The operating voltage of the PV-T system is close to the PV system, while the operating current of the PV system is higher than that of the PV-T system. * As the number of PV-T collectors increases, the hydrogen production capacity increases. * The hydrogen production efficiency of the PV-T system is higher than that of the PV panels system.
[15]	Investigate the performance of PV panels-driven hydrogen system.	Simulation (Matlab and Simulink) and Mathematical models	Taiwan	✓	X	* The DC/DC buck converter with maximum power point tracking control can better adapt to PV and electrolysis.
[16]	Investigate the performance of PV panels and wind turbines-driven hydrogen systems.	Simulation (Python) Method	South Korea	✓	X	* The sensitivity analysis shows that the capacity factor of the renewable power plant has the most impact on the cost. * It is important to increase the efficiency of the renewable power plant or install it where there are abundant renewable resources. * When water electrolysis is coupled with the renewable power plant, the capacity optimization of the electrolysis should be achieved.
[22]	Investigate the performance of PV-T collectors-driven hydrogen systems.	Experimental method	India	X	✓	* Study the idea of incorporating nanofluid to mitigate the increase in the PV-T temperature. * Study the impact of flow rate on hydrogen production. * Find that 40 liters per minute produced more hydrogen than 30 liters per minute.

(*continued on next page*)

Table 1 (*continued*).

[17]	Investigate the performance of PV panels-driven hydrogen systems.	Simulation (Excel) model	Not mentioned	✓	X	* When the coupling of the PV and electrolyzer improves, the solar array size reduces, but the electrolyzer size becomes larger. * The PV panels-driven hydrogen system assisted with a battery reduces the electrolyzer size.
[18]	Investigate the performance of two systems: PV panels and PV-T collectors-driven hydrogen systems.	Simulation method	Turkey	✓	✓	* Hydrogen production increases as the cooling flow rate increases and the PV-T area decreases. * The thermodynamic efficiency, and electricity and hydrogen production of the PV-T system are higher than the PV system.

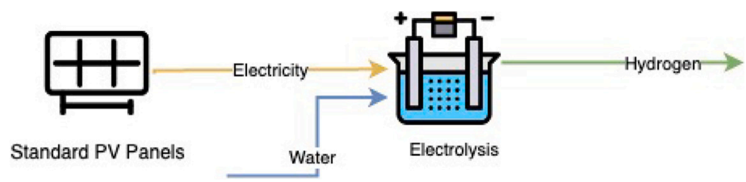

Fig. 1. The photovoltaic panels driven hydrogen production system.

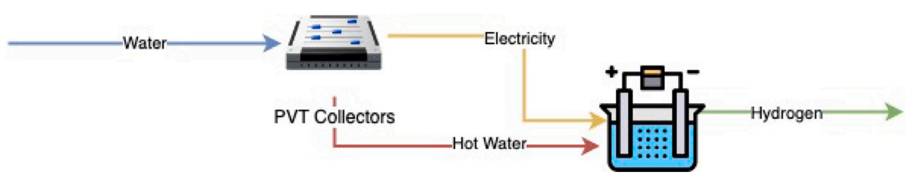

Fig. 2. The photovoltaic thermal collectors driven hydrogen production system.

3.2. Photovoltaic thermal collectors driven hydrogen production system

In this system, as indicated in Fig. 2, the PV-T collectors supply the required electricity to the hydrogen electrolyzer as an energy source. Also, the collectors supply the required hot water to the hydrogen electrolyzer as a feedstock — the hot water is generated from the thermal energy absorbed by the water in the collectors from the collector surface. Similarly, this paper considers an Alkaline hydrogen electrolyzer. In this system, the PV-T collectors function as both solar collectors and PV panels. They capture solar energy and convert it into thermal energy, similar to traditional solar collectors, while also generating electricity like PV panels. A key feature of PV-T collectors is their ability to cool down by transferring heat to the in-flowing water. This cooling effect lowers the temperature of the collectors, boosting their efficiency. The heated water that flows out of the PV-T collectors is then supplied to the hydrogen electrolyzer as feedstock. By pre-heating the water, the efficiency and performance of the electrolyzer are improved, leading to increased hydrogen production.

4. System simulation and analysis

4.1. Photovoltaic panels driven hydrogen production system

Fig. 3 shows the system configuration of the PV panels driven hydrogen production system simulated on TRNSYS software. The system consists of five components, namely: weather, PV panels, controller, power conditioning, and electrolyzer. Generally, the weather component (type 15) provides solar data such as solar radiation, ambient temperature, array slope, and wind speed. The PV panels component (type 190c) provides the power the electrolyzer needs. The controller component (type 100a) compares the electrolyzer's required power with the PV panels' output power. The power conditioning component (type 175b) converts power to the input current of the electrolyzer. Lastly, the alkaline electrolyzer (type 160a) consumes the input power from the PV panels and produces hydrogen. It is important to note that the electrolyzer is supplied with water at a constant temperature. Tables 2 and 3 highlight the parameters of the PV panels and alkaline electrolyzer used in the simulation, respectively. The electrolyzer has been intentionally designed to be oversized to ensure the system operates without bottlenecks. This design choice addresses potential constraints that might arise from the electrolyzer's capacity. By doing so, it ensures continuous and efficient operation regardless of variations in the input from the solar panels/collectors. The focus on varying the area of the panels/collectors allows for flexible adjustments to optimize energy capture without being limited by the electrolyzer's capacity. This approach ensures the system can handle fluctuations in solar energy availability, maximizing overall efficiency and output.

4.2. Photovoltaic thermal collectors driven hydrogen production system

Fig. 4 shows the system configuration of the PV-T collectors driven hydrogen production system simulated on TRNSYS software. The system consists of six components, four (i.e., weather, controller, power conditioning, and electrolyzer), of which are the same as the baseline system. This system employs a PV-T collectors component (type 50d), which provides the power and the hot water that the electrolyzer needs. Additionally, this system has a tank component (type 158) to temporarily store the water that is coming out from the electrolyzer and used again in the PV-T collectors, forming a closed loop system. In this system, the hydrogen production amount is impacted by two factors, (i) the amount of electricity generated by the PV-T collectors and (ii) the hot water supplied to the electrolyzer from the PV-T collectors. Table 4 highlights the parameters of the PV-T collectors used in the simulation. Similar to the previous system, the same design assumption for the electrolyzer was made in this system.

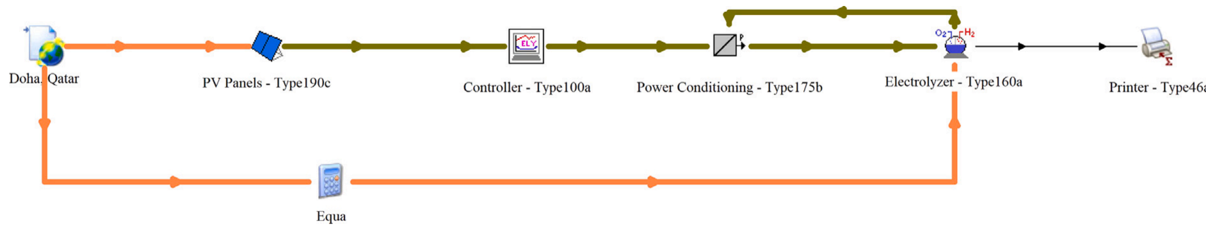

Fig. 3. The photovoltaic panels-driven hydrogen production system configuration with TRNSYS.

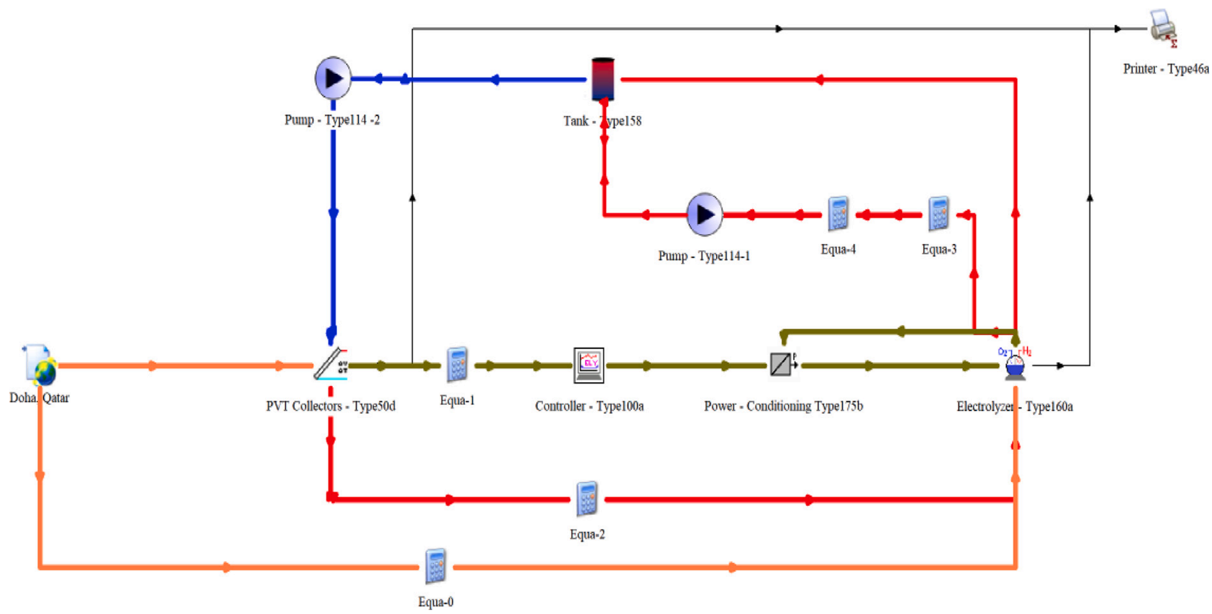

Fig. 4. The photovoltaic thermal collectors driven hydrogen production system configuration with TRNSYS.

Table 2
PV panels parameters.

Parameter name	Value	Unit
Module short-circuit current at reference conditions	8.8	A
Module open-circuit voltage at reference conditions	37.4	V
Reference cell temperature	298.15	K
Reference insolation	1000	W/m^2
Module voltage at max power point and reference conditions	30.2	V
Module current at max power point and reference conditions	8.28	A
Temperature coefficient of I_sc (ref. cond)	0.0295	A/K
Temperature coefficient of V_oc (ref. cond.)	−0.12544	V/K
Module temperature at NOCT	320.15	K
Ambient temperature at NOCT	298.15	K
Insolation at NOCT	800	W/m^2
Module area	1.65	m^2

Table 3
Electrolyzer parameters.

Parameter name	Value	Unit
Electrode area	0.25	m^2
Number of cells is series	60	–
Number of stacks in parallel	1	–
Maximum allowable current density	2000	mA/cm^2
Maximum allowable operating temperature	90	C
Minimum allowable cell voltage	1.229	V

Table 4
PV-T collectors parameters.

Parameter name	Value	Unit
Collector efficiency factor	0.7	–
Fluid thermal capacitance	4.19	kJ/kg K
Collector plate absorptance	0.9	–
Collector plate emittance	0.9	–
Loss coefficient for bottom and edge losses	20	kJ/h m^2 K
Extinction coefficient thickness product	0.03	–
Temperature coefficient of PV cell efficiency	−0.04	1/K
Temperature for cell reference efficiency	20	C
Packing factor	0.7	–

5. Results and discussion

This paper investigates hydrogen production in three locations, namely, Doha (Qatar), Tunis (Tunisia), and Stuttgart (Germany). They are selected to represent different solar latitudes to understand the behavior and performance of the three systems under different solar radiations, and air and water temperature conditions. The latitude and longitude of Doha are 25.286106 and 51.534817, respectively. Meanwhile Tunis's latitude and longitude are 36.80638 and 10.181667, respectively. Stuttgart's latitude and longitude are 48.783333 and 9.183333, respectively.

This paper considers panels/collectors area in the simulation instead of their peak capacity due to the crucial importance of space efficiency and availability. Panels/collectors come in various sizes and shapes, so considering their area helps optimize space utilization, especially in installations with limited space, such as small plots of land. Therefore,

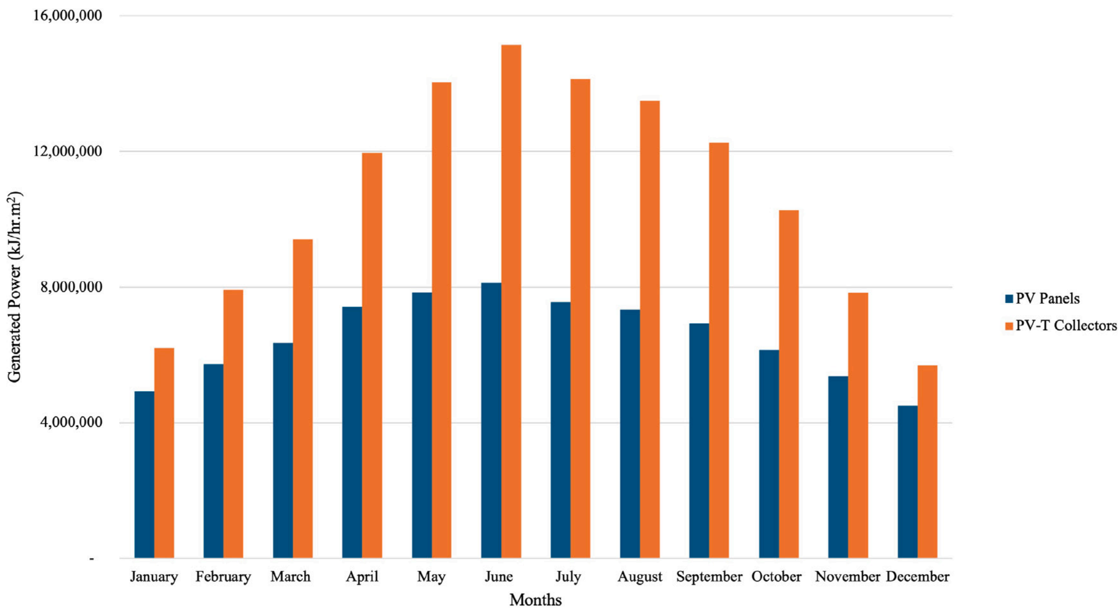

Fig. 5. The generated power from each panel/collectors throughout the year for Doha location.

space availability consistently serves as a key constraint in the efficient design of panels/collectors systems.

5.1. Power generation analysis

The PV panels and PV-T collectors collect beam incident radiations and diffuse incident radiations to generate electricity. Looking at the power generated from each panel/collector with an area of 90 m^2 for the three locations, Fig. 5 shows the power generated from each panel/collector throughout the year for Doha. The area 90 m^2 has been chosen arbitrarily for illustrative purposes only. The figure shows that the PV-T collectors generate power that is 64% more than the standard PV panels throughout the year due to the advancement in technological specifications that the PV-T collectors have over the PV panels. In other words, the additional generated power by the PV-T collectors is a result of the water flowing through the PV-T collectors, which cools down the temperature of the collectors (i.e., standard PV panels do not have this feature), enhancing their efficiencies significantly. For Tunis and Stuttgart, the PV-T collectors generate power that is 48% and 15% more than the standard PV panels throughout the year, respectively, for the reasons mentioned above.

Looking at all locations collectively, the PV panels in Tunis generate power that is 8% and 66% more than in Doha and Stuttgart, respectively, because of the moderate ambient temperatures in Tunis. The yearly average air temperature reported from the simulation is 18.39 °C close to the reported value in the literature, 18.9 °C [23]. PV panels are sensitive to temperature; their efficiency decreases as temperature increases. In Tunis, the average air temperatures are lower, by 8.6 °C, than in Doha. This allows the PV panels to operate closer to their optimal temperature, resulting in higher efficiency and, therefore, more power generation. In Doha, the yearly average air temperature reported from the simulation is 26.62 °C and from the literature is 27.5 °C [23]. On the other hand, the PVT collectors in Doha generate 3% more power than in Tunis and 118% more than in Stuttgart. This is due to three factors: (i) Thermal utilization: in Doha, the high average air temperatures allow the thermal component of the PVT collectors to effectively utilize excess heat, converting it into useful thermal energy. While the efficiency of PV panels alone is reduced in Doha due to the high temperatures, the combined energy output (electrical + thermal) is still greater than in Tunis. In contrast, the milder climate in Tunis means that the thermal component is less effectively utilized, leading to a lower total energy output than Doha. (ii) Average cell surface temperature: The average cell temperature of the PV-T collectors in Doha is 31.25 °C which is 4.24 °C more than in Tunis and 12.24 °C more than in Stuttgart. The high surface cell temperature can contribute to generating more power through the effective use of thermal energy in conjunction with electrical power generation. In other words, when the cell temperature of the PVT collector is high, more thermal energy is available. This thermal energy can be harnessed for various applications, effectively increasing the system's total power output (both electrical and thermal). So, the synergy between thermal and electrical power generation can lead to a higher combined power output, making the PVT system more efficient. (iii) Global incident radiations: Doha receives significantly more global incident radiation, with 2132.6 kWh/m^2 per year compared to 1753.3 kWh/m^2 per year in Tunis and 1167.5 kWh/m^2 in Stuttgart [23]. This higher global incident radiations contributes to the greater power generation in Doha.

5.2. Water temperature analysis

The PV-T collectors have the feature to cool down their temperature through the water that circulates within them. This water, at high temperature, can be supplied to the electrolyzer which enhances its efficiency and produces more hydrogen.

Fig. 6 shows the average output water temperature supplied to the electrolyzer from the PV-T with an area of 90 m^2 for Doha throughout the year. The water flow rate within the collector is constant which is 0.25 m^3/h. This is a standard water flow value given by the simulation software. The average output water temperature from the PV-T collectors is 34.2 °C.

In Tunis and Stuttgart, the average output water temperature from the PV-T collectors is 27.5 °C and 16.0 °C, respectively. Looking at the three locations collectively, Doha has the highest average output water temperature, by 6.71 °C in Tunis and 18.20 °C in Stuttgart. This is as a result that Doha receives the highest global incident radiations (i.e., 2132.6 kWh/m^2 per year in Doha Vs. 1753.3 kWh/m^2 per year in Tunis and 1167.5 kWh/m^2 in Stuttgart) and has the highest average air temperatures (i.e., 27.5 °C in Doha Vs. 18.9 °C in Tunis and 10.4 °C in Stuttgart) compared to the other two locations, which cause the surface cell temperature to increase significantly, hence the water that circulates the collector (i.e., heat exchange between the water and the cell surface).

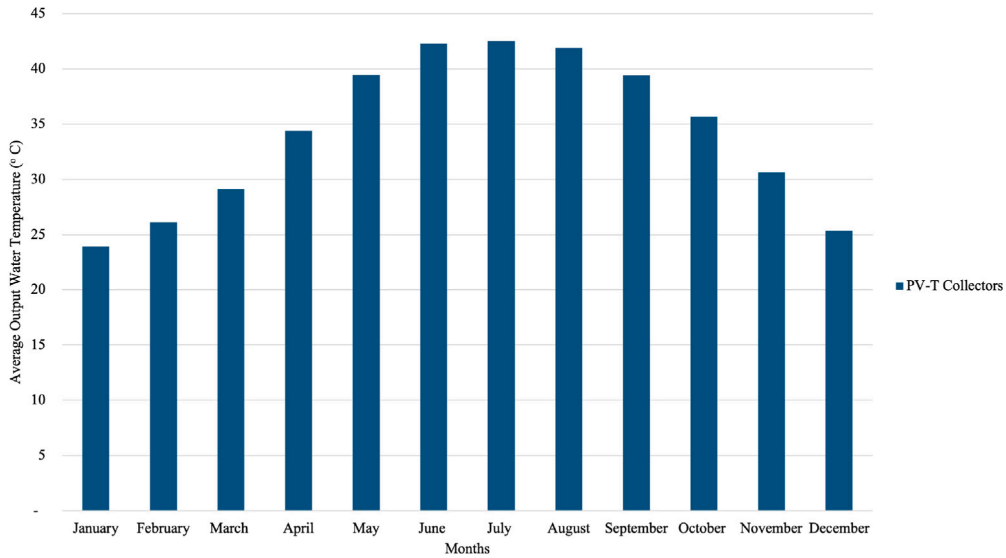

Fig. 6. The average output water temperature supplied from the PV-T collectors to the electrolyzer throughout the year for Doha location.

5.3. Hydrogen production quantity

The amount of power generated from the panels/collectors and the water temperature supplied to the electrolyzer significantly impact hydrogen production quantities. Fig. 7 shows the hydrogen production for each system (i.e., PV panels and PV-T collectors) at each location over a simulated period of 8760 h for different panels/collectors area (i.e., from 30 m^2 to 330 m^2). The figure shows that as the slope of the line increases, more hydrogen quantities are produced as the area of the panels/collectors increases.

Looking at each location independently, the hydrogen production increases on an average by 78%, 59%, and 25% when PV-T collectors are employed compared to the standard PV panels for Doha, Tunis, and Stuttgart, respectively, when the area increases from 30 m^2 to 330 m^2. This is a result of (i) more power being generated from the PV-T collectors than PV panels (i.e., 64% more power in Doha, 48% more in Tunis, and 15% more in Stuttgart) as a result of the water flowing through the collectors which help to cool down the collectors' temperature, and (ii) the hot water flowing out from the collectors, which is hot as a result of cooling down the collectors' temperature (i.e., The standard PV panels do not have this feature), is supplied to the electrolyzer increasing its efficiency, hence producing more hydrogen. The average output water temperature supplied to the electrolyzer from the PV-T collectors is 34.2 °C in Doha, 27.5 °C in Tunis, and 16.0 °C in Stuttgart. On average, the electrolyzer efficiency increases by 21% in the PV-T collectors-driven hydrogen system (71%) compared to the baseline system (50%).

Looking at all locations collectively, Fig. 7 shows the hydrogen production for panels/collectors for the three locations. The figure shows that the hydrogen production for Tunis, on average, is 8% and 77% more than in Doha and Stuttgart, respectively, when PV panels are employed, and the area increases from 30 m^2 to 330 m^2. As explained earlier, the PV panels in Tunis generate power that is 8% and 66% more than in Doha and Stuttgart, respectively, because of the moderate ambient temperatures in Tunis (i.e., the average air temperature is 18.9 °C). However, when PV-T collectors are adopted, the hydrogen production for Doha, on average, is 4% and 134% more than in Tunis and Stuttgart, respectively. As explained earlier, the PV-T collectors in Doha generate power that is 3% and 118% more than in Tunis and Stuttgart, respectively, due to (i) the highest global incident radiations in Doha (i.e., 2132.6 kWh/m^2 per year in Doha Vs. 1753.3 kWh/m^2 per year in Tunis and 1167.5 kWh/m^2 per year in Stuttgart), (ii) the highest average cell temperature in Doha (31.25 °C in Doha Vs. 27.01 °C in Tunis and 19.00 °C in Stuttgart), and (iii) the highest average air temperature in Doha (i.e., 27.5 °C in Doha Vs. 18.9 °C in Tunis and 10.4 °C in Stuttgart) compared to the other two locations. Additionally, the average output water temperature supplied to the electrolyzer in Doha (i.e., 34.2 °C) is higher than the average output water temperature in Tunis (i.e., 27.5 °C) and in Stuttgart (i.e., 16.0 °C). The high output water temperature supplied from the PV-T collectors to the electrolyzer contributes to producing more hydrogen.

The simulation results reveal that the energy efficiency of the PV-T collector-driven hydrogen production system surpasses that of the PV panel-driven system by 11% in Doha, 4% in Tunis, and 8% in Stuttgart. This higher efficiency explains the increased hydrogen production observed with PV-T collectors, as noted earlier. Comparing the three locations, the energy efficiency of the PV panel-driven hydrogen production system in Tunis is 5% higher than in Doha and 60% higher than in Stuttgart. The higher efficiency in Tunis explains why Tunis has a higher hydrogen production than Doha and Stuttgart when PV panels are installed. On the other hand, the PV-T collector-driven hydrogen production system in Doha achieves 2% greater energy efficiency than in Tunis and 57% higher efficiency than in Stuttgart. This points why the hydrogen production in Doha is higher than in Tunis and Stuttgart.

Figs. 8 and 9 show a snapshot of the simulated period (48 h) to display the impact of the water temperature and power generation on hydrogen production, respectively, when PV-T collectors are employed for Doha. Both figures show that the generated power, the water temperature, and hydrogen production follow a bell-curve behavior. In other words, when the generated power by the collectors increases, the hydrogen production from the electrolyzer increases. The same behavior can be explained by the output water temperature, which is as the water temperature increases, hydrogen production increases.

5.4. Variable water flow rate

The water flow rate of each panel/collector in the system is varied from 0.06 m^3/h to 0.30 m^3/h to understand its impact on the panels/collectors efficiency and the hydrogen yield from the electrolyzer. The selected range is based on the commonly reported values in the literature. Similar to the previous sections, Doha is selected as the case study, and the simulated area of panels/collectors is 90 m^2.

When the water flow rate of the PV-T collectors increases, the PV-T collectors are expected to generate more power, and the output water temperature from the collectors decreases. In other words, increasing the water flow rate helps to cool down the temperature of

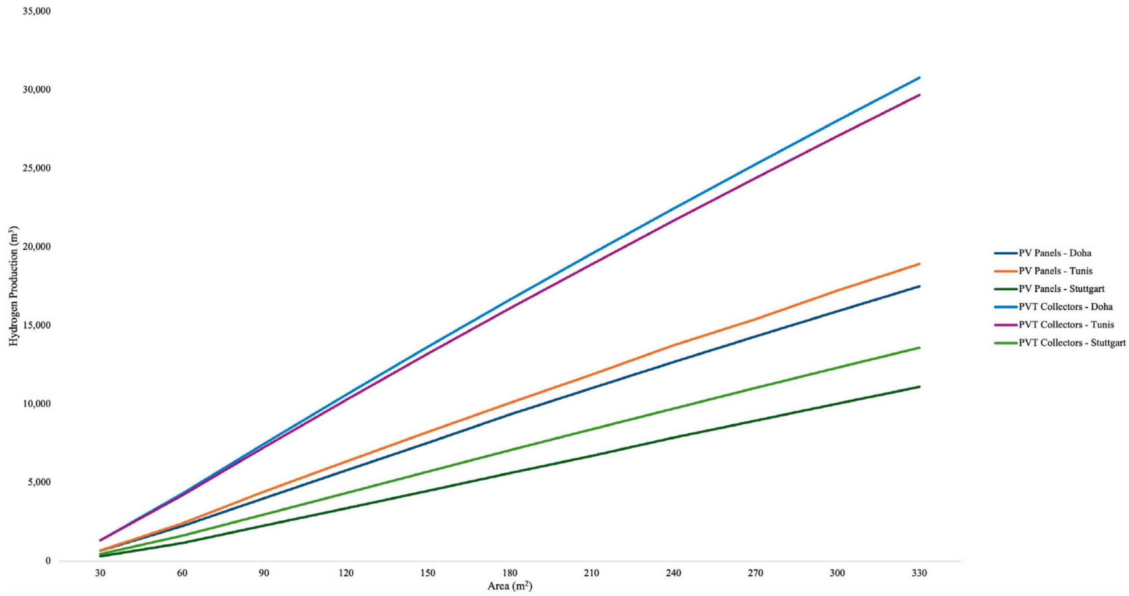

Fig. 7. The hydrogen quantity produced from the three panels/collectors for the three locations.

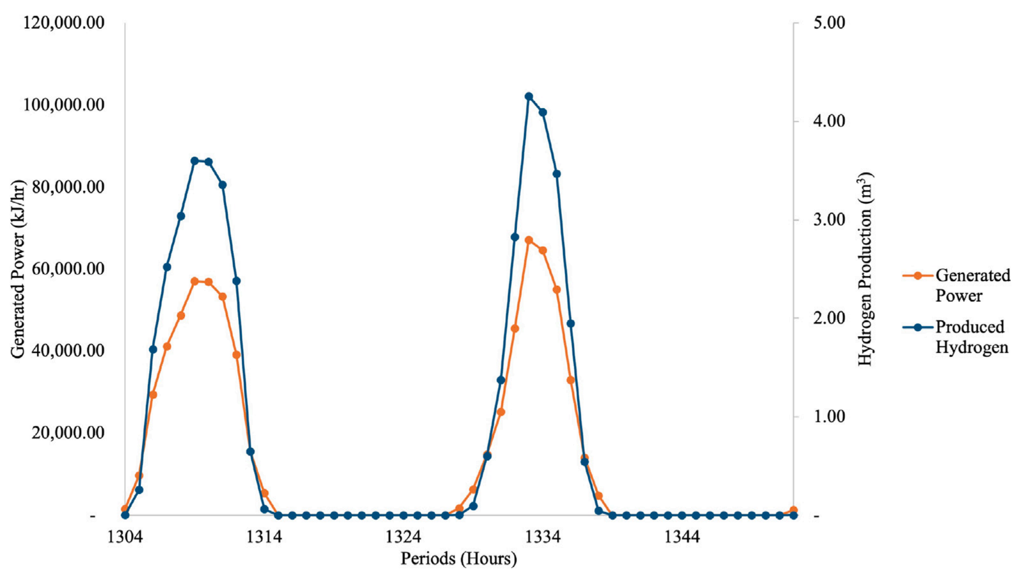

Fig. 8. The simulated hydrogen quantity and the generated power over the observed period for the PV-T collectors driven hydrogen system.

the collectors faster, hence the collectors generate more power. On the other hand, the output water temperature decreases as more water is passing through the collector per unit of time which means that the water absorbs less heat in a single pass through the collector. This results in a lower temperature increase compared to a situation with a lower mass flow rate. Thus, increasing the mass flow rate of the PV-T collector generally leads to a lower output water temperature, but it can increase the overall thermal efficiency of the system by improving heat extraction from the PV-T collectors. Indeed, Fig. 10 shows that increasing the water flow rate from 0.06 m^3/h to 0.30 m^3/h, the generated power by PV-T collectors increases by 15%, and the average output water temperature decreases by 5.62 °C.

As mentioned earlier, the hydrogen quantities from the electrolyzer are impacted by two factors: (i) the power generated quantities by the PV-T collectors and supplied to the electrolyzer, and (ii) the output water temperature supplied to the electrolyzer from the PV-T collectors. In other words, one would expect that the more power and the hotter the output water supplied to the electrolyzer, the more hydrogen is generated from the electrolyzer. Nevertheless, Fig. 11 shows that as the water flow rate increases from 0.06 m^3/h to 0.30 m^3/h, the average output water temperature decreases by 5.62 °C (i.e., as noted earlier), but the hydrogen quantities from the electrolyzer increase by 30.9%, which is unexpected. On the other hand, Fig. 12 points out that as the water flow rate increases from 0.06 m^3/h to 0.30 m^3/h, the generated power by PV-T collectors increases by 15% (i.e., as noted earlier), and the hydrogen quantities from the electrolyzer increase by 30.9%. From this, this paper concludes that when the water flow rate increases, the generated power increases, thereby increasing hydrogen quantities (i.e., positive effect). On the other hand, when the water flow increases, the output water temperature decreases, which has an adverse effect on the hydrogen quantities. This paper observes that the power generation effect largely dominates the water temperature in hydrogen production.

Fig. 12 can be used to determine the optimal water flow rate. The optimal water flow rate has a trade-off between the generated power by the PV-T collectors and the hydrogen quantities produced by the electrolyzer. Hence, the optimal water flow rate is 0.23 m^3/h, which is

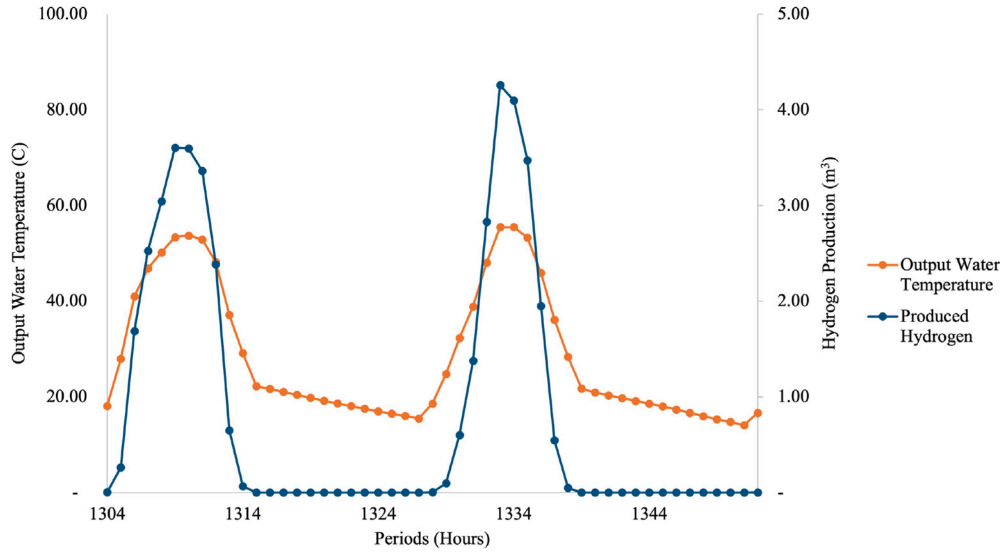

Fig. 9. The simulated hydrogen quantity and the water temperature over the observed period for the PV-T collectors driven hydrogen system.

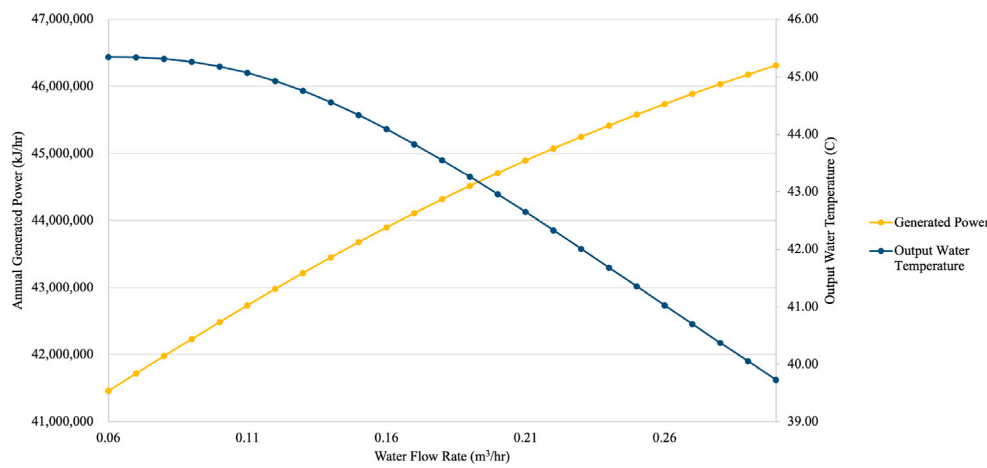

Fig. 10. The impact of water flow rate on the generated power by the PV-T collectors, and the average output water temperature.

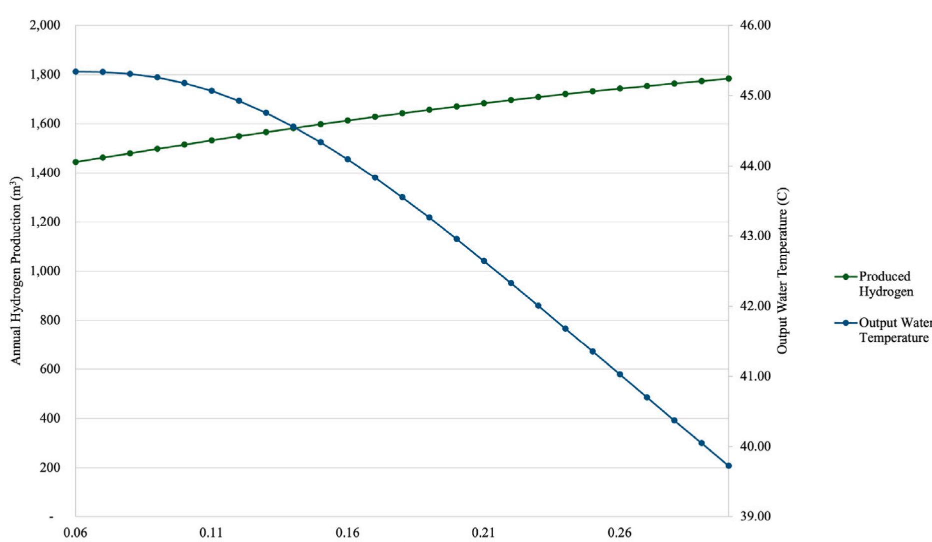

Fig. 11. The impact of water flow rate on the hydrogen production from the electrolyzer, and the outlet water temperature from the PV-T collectors.

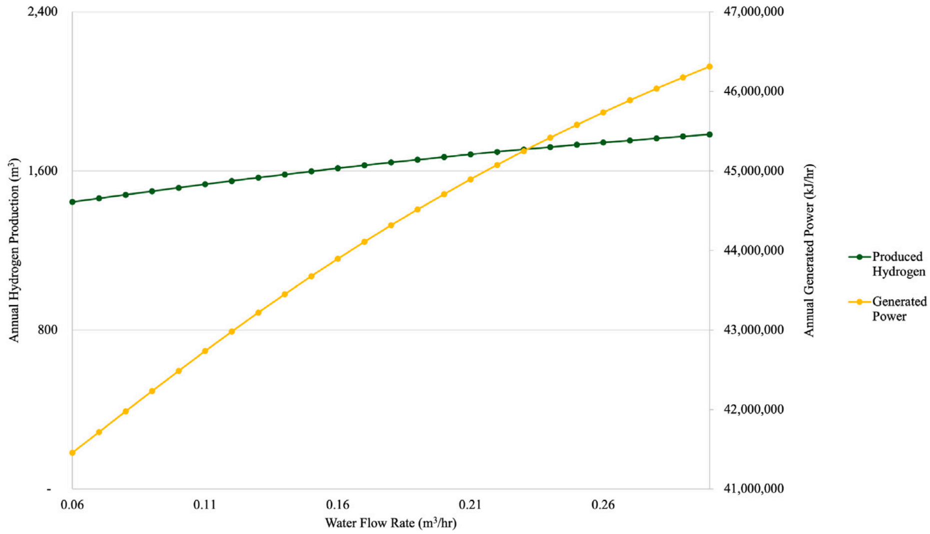

Fig. 12. The impact of water flow rate on the generated power by the PV-T collectors and the hydrogen production.

the intersection point between the two lines (i.e., the power generated by the PV-T collectors and the hydrogen quantities).

5.5. Economic analysis

The levelized cost of hydrogen (LCOH) of each system for the three locations is calculated to determine the most cost-effective system for each location. For that purpose, this paper makes the following assumptions:

- The installed area for each panel is 90 m^2;
- The useful life of each system is 30 years [24];
- The capital expenditures (CAPEX) include the investment cost (IC) of panels/collectors, and the installation cost (NC) of panels/collectors, which is assumed equal to \$3/Watt [25];
- The operating expenses (OPEX) include the annual maintenance and operation costs (M&OC) of panels/collectors, which represents 20% of the panels/collectors IC [26];
- The interest rate is 10% annual;
- The inflation is not considered.

Table 5 shows the reference figures (unit area, power and cost) for the considered types of panel and collector. The Net Present Value (NPV) was calculated for both PV panels and PV-T collectors according to Eq. (1):

$$NPV = [IC + NC]_0 + \sum_{t \in T}^{n} \frac{OPEX}{(1+i)^t} \quad (1)$$

where
n = the useful life of the system (30 years);
i = the annual interest rate (10%).

The IC is calculated by considering the number of panels installed to cover an area of 90 m2 and the price of one panel. The required number of panels for the two systems is 55 PV panels and 46 PV-T collectors, respectively. The NC is calculated by considering the number of panels installed to cover the 90 m^2, the total number of watts to be installed, and the cost to install one watt.

Finally, the LCOH for each system in the three locations was calculated according to Eq. (2):

$$LCOH = \frac{NPV}{\text{Total Hydrogen Production}} \quad (2)$$

where the Total Hydrogen Production was computed over the entire system's lifetime in the three locations.

Table 5
The area, power and cost of each panel.

Type	Gross area (m^2)	Power (W)	Price (\$) per panel
PV panel	1.65	250	110
PV-T collectors	1.96	Electrical: 280 W; Thermal: 450 W	250

Table 6
The LCOH of each panels/collectors for each location.

Panels/Collectors type	LCOH (\$/kg)		
	Doha	Tunis	Stuttgart
PV panels	5.44	4.92	9.66
PV-T collectors	6.66	6.86	16.80

Table 6 shows the LCOH results of each panel/collector for the three locations. The results point out that all locations exhibit the same behavior, which is that the PV-T collectors have the highest LCOH, while the PV panels have the lowest LCOH. For Doha, the PV-T collectors LCOH is 22% more than the LCOH of PV panels. While in Tunis, the PV-T collectors LCOH is 39% more than the LCOH of PV panels. Lastly, the PV-T collectors LCOH in Stuttgart is 74% more than the LCOH of PV panels.

Looking at all locations collectively, the LCOH of PV panels is the lowest in Tunis. The LCOH of PV panels in Tunis is lower than PV panels LCOH in Doha and Stuttgart by 9.56% and 49.07%, respectively. On the other hand, the LCOH of PV-T collectors is the lowest in Doha. The LCOH of PV-T collectors in Doha is lower than PV-T collectors LCOH in Tunis and Stuttgart by 2.92% and 60.36%, respectively.

Table 7 shows the LCOH values from the existing literature. The percentage of difference between the values reported in the literature and the values obtained in this paper does not exceed 30%, which is an insight that the obtained values in this paper are aligned with the existing literature. Most of the existing literature covered LCOH of PV panels-driven systems, but they tackled different research areas. In other words, they considered different system sizea, locations, and methodologies (i.e., simulation, mathematical, and experimental methods).

6. Conclusion

This paper analyzes the efficiency of two solar-driven hydrogen systems, namely a PV panels-driven hydrogen production system, and

Table 7
The LCOH from the literature.

Author	System	System size	Location	Methodology	Value ($/kg)	Percentage difference
This paper	PV and PV-T collectors driven system	Medium scale (90 m^2 - 55 modules)	Qatar; Tunisia; Germany	Simulation Model (TRNSYS)	PV: 4.92–9.66 PV-T: 6.66–16.80	–
[3]	PV panels and PV-T collectors driven system	Small scale (1.22 m^2)	Turkey	Numerical Model	PV: 4.87 PV-T: 5.61	1.02% for PV 17.11% for PV-T
[4]	PV panels driven system	Large scale (656,000 m^2 - 400,000 modules)	Morocco	Simulation Model (Greenius)	5.57	12.39%
[14]	PV panels driven system	Small scale (12 modules)	Iraq	Simulation Model (MatLab)	3.95–5.39	9.12%
[19]	PV panels driven system	Large scale (100 MW)	Belgium	Numerical and Simulation Models (Aspen Plus)	7.81–12.23	21.18%
[16]	PV panels driven system	Large scale (100 MW)	South Korea	Simulation Model (Python)	7.25–13.44	28.50%
[17]	PV panels driven system	Small scale (2.39 m^2)	Not mentioned	Simulation Model (Excel)	4.35–5.56	24.42%

a PV-T collectors-driven hydrogen system, for three different locations: Doha (Qatar), Tunis (Tunisia), and Stuttgart (Germany). In particular, this paper investigates the influence of power generation and water temperature on the hydrogen production from the electrolyzer under different system configurations and geographical locations. The two systems are modeled and simulated using the TRNSYS software. The simulation is carried out over an observed period of 8760 h for different areas (i.e., from 30 m^2 to 330 m^2 of panel/collector areas). Additionally, an economic analysis is carried out to determine the most cost-effective hydrogen production system configuration in each location.

The simulation results indicate that hydrogen production increases by 78%, 59%, and 25% when PV-T collectors are employed compared to the standard PV panels for Doha, Tunis, and Stuttgart, respectively. This is because (i) more power is generated from the PV-T collectors compared to the standard PV panels as a result of the water flowing through the collectors, which helps to cool down the collectors temperature, and (ii) the hot water flowing out from the collector's is supplied to the electrolyzer, increasing its efficiency and hence producing more hydrogen. Additionally, the simulation results point out that the hydrogen production for Tunis is 8% more than in Doha and 77% more than in Stuttgart when PV panels are employed. Additionally, when PV-T collectors are adopted, the hydrogen production for Doha is 4% more than in Tunis and 134% more than in Stuttgart. This is a result of the PV panels in Tunis generating power that is 8% and 66% more than in Doha and Stuttgart, respectively. While the PV-T collectors in Doha generate power that is 3% and 118% more than in Tunis and Stuttgart, respectively, due to (i) the highest global incident radiations in Doha, (ii) the highest average cell temperature in Doha, and (iii) the highest average air temperature in Doha compared to other locations. Additionally, the average output water temperature supplied to the electrolyzer in Doha (i.e., 34.2 °C) is higher than the average output water temperature in Tunis (i.e., 27.5 °C) and in Stuttgart (i.e., 16.0 °C).

The economic analysis of the two systems highlights that the PV panels achieve the lowest LCOH for all the locations: $4.92/kg for Tunis, $5.44/kg for Doha, and $9.66/kg for Stuttgart. On the other hand, the PV-T collectors have the highest LCOH for all the locations: $6.66/kg for Doha, $6.86/kg for Tunis, and $16.80/kg for Stuttgart.

The two solar panel technologies under consideration have varying degrees of development. While standard PV panels are a mature technology and widely commercially available, PV-T collectors are less mature thus they possess significant potential for performance improvement and cost reduction. This suggests that PV-T collectors could become even more economically attractive in the future. While CPV-T collectors offer high efficiency and generate both electricity and heat, their reliance on concentrated sunlight raises questions about land use and its negative impact on the ecosystem. Large-scale deployment of CPV-T collectors may necessitate significant land clearance, which imposes a significant deployment challenge for the user. Hence, investigating the CPV-T collectors-driven hydrogen production system as a third system is a future research work.

CRediT authorship contribution statement

Dana Alghool: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiheb Bouden:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Mohamed Haouari:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Conceptualization. **Paolo Trucco:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

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

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