The Iraqi Journal for Mechanical and Material Engineering, Vol. 25, No. 2, June 2026.

ISSN: 1819-2076; eISSN: 2313-3783

INTEGRATED EXERGOECONOMIC AND LIFE CYCLE ASSESSMENT OF A PV/T-RO SYSTEM FOR SUSTAINABLE COGENERATION IN ARID REGIONS ENGINEERING

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ABSTRACT

This paper examines a hybrid system of photovoltaic-thermal (PV/T) system that is integrated with reverse osmosis (RO) as an approach to sustainable cogeneration. One of the main weaknesses of earlier research is found in the fact that there has been no comprehensive appraisal of certain areas incorporating the thermodynamic, economic and environmental paradigms. The study will also be beneficial as it offers a complete sustainability analysis of PV/T-RO system. A combined approach of exergy analysis, exergoeconomic analysis and environmental life cycle analysis (LCA) is applied to a case study in Basra, Iraq. The performance of the system is compared with the conventional PV-RO and grid-powered RO. The findings reveal that the proposed PV/T-RO system has a higher overall exergy efficiency of (18.5) % that is (52) % more as compared to PV-RO alternative. The levelized cost of water (LCOW) has been estimated at (1.850) m^3 whereas the global warming potential (GWP) is estimated at (1.8) kg CO_2-eq/m^3, and an (86) % decrease over the grid-RO system. The PV/T collector has been found to be the greatest contributor to irreversibility, with (35) % of the total exergy destruction.

Keywords: Arid Regions, Exergoeconomic Analysis, Life Cycle Assessment, Photovoltaic-Thermal Systems, Reverse Osmosis.

NOMENCLATURE

Symbol	Meaning	Symbol	Meaning
PV	Photovoltaic	R	Recovery ratio
PV/T	Photovoltaic-Thermal system	T_{in}	Inlet temperature, K

Received: December 18, 2025. **Publisher: University of Babylon / Faculty of Engineering**

Accepted: April 5, 2026. **Journal homepage: https://www.iqjfmme.com**

RO	Reverse Osmosis	Tout	Outlet temperature, K
LCA	Life Cycle Assessment	T_0	Reference temperature, K
GWP	Global Warming Potential, kg CO_2-eq	Ts	Sun temperature, K
LCOW	Levelized Cost of Water, \$/m^3	Ex	Exergy rate, kW
LCOE	Levelized Cost of Electricity, \$/kWh	η_{ex}	Exergy efficiency, %
SEC	Specific Energy Consumption, kWh/m^3	Ex_{dest}	Exergy destruction rate, kW
ERD	Energy Recovery Device	P	Power, kW
TDS	Total Dissolved Solids, ppm	Q	Heat energy, kW
O&M	Operation and Maintenance	$\dot{V}$	Water production rate, m^3/s
I	Solar irradiance, kW/m^2	C	Cost rate, \$/h
A	Collector area, m^2	r	Discount rate
η_{PV}	PV efficiency	n	System lifetime, years
η_{inv}	Inverter efficiency	F	Flow rate
$\dot{m}$	Mass flow rate, kg/s	P_f	Feed pressure, kPa
Cp	Specific heat capacity, kJ/kg·K	η_p	Pump efficiency

1. INTRODUCTION

The increasing world water crisis is a problem of high degree of challenge and arid regions are the ones that are affected particularly. It is estimated that over two billion people live in countries with high water stress and it has been aggravated by a rise in population and climate change [1]. In such dry conditions, freshwater security is currently relying on energy-consuming desalination systems. Desalinations are (RO) as the most common form of desalination takes up a large percentage of the energy requirements of the water industry which is largely supplied by fossil fuels [2]. This reliance creates a carbon lock-in. The energy demand for water production leads to significant greenhouse gas emissions. Consequently, the effort to solve water scarcity inadvertently exacerbates environmental degradation [3].

To stop the cycle, the combination of desalination with renewable sources of energy is a popular topic of research. Photovoltaic-driven RO (PV-RO) and Multi-Effect Distillation (MED) solar-powered desalination has the potential to be a promising way forward [4]. Nevertheless, these technologies are limited in nature. The independent PV systems have low conversion efficiency, intermittency that necessitates expensive energy storage, and large land area. On the other hand, traditional solar thermal desalination can be very demanding in terms of operation temperature and the arrangement of the systems, which is capital and operationally expensive and complex in nature [5]. Such limitations demonstrate the necessity to have more effective and combined solar technology.

Hybrid photovoltaic-thermal (PV/T) system arises as cogeneration solution which will guarantee the requirements of electricity and thermal energy. In a PV/T collector, a solar thermal absorber is fitted on the rear of a PV module, allowing to extract waste heat of the PV cells [6]. Such cooling does not only help the PV cells to have better electrical efficiency but also generates beneficial thermal energy. The major benefits of such an integration are that the overall exergy efficiency is higher than it would be with side-by-side PV and solar thermal systems, the space requirement is reduced, and direct generation of thermal energy that can be used to pre-heat the feedwater to the RO process occurs and thus minimizes its specific energy demand [7]. Figure 1 shows the main problem of the research studied, which focuses on unsustainable status quo with the limitations of current solar alternatives, creating a powerful justification for your proposed PV/T-RO system.

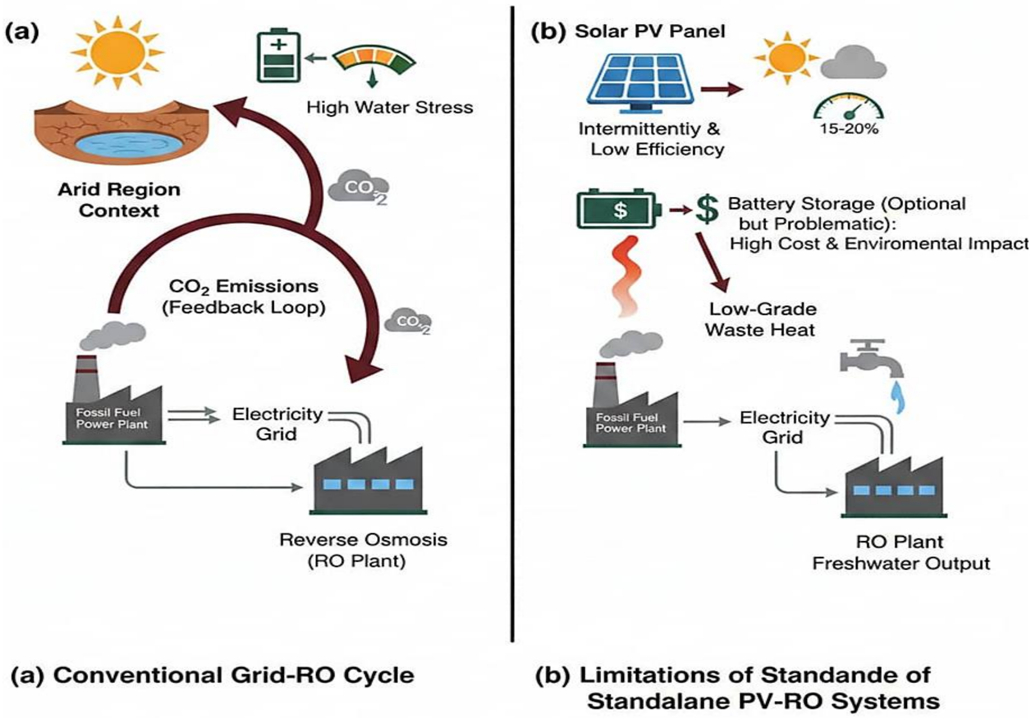

Fig. 1. The water-energy nexus challenge in arid regions: (a) Conventional grid-RO cycle, (b) Limitations of standalone PV-RO systems adapted from [1].

Although the PV/T systems and the environmental life cycle assessment (LCA) of RO plants have been researched separately, a serious knowledge gap still exists. There is a significant lack of a detailed examination that incorporates exergy, exergoeconomic, and complete environmental LCA into a single study of a PV/T-RO system, namely, in the environment of arid climates.Nonetheless, a critical research gap exists because, despite the current development, no research has provided combined exergy, exergoeconomic, and full environmental life cycle assessment (LCA) of the PV/T-RO systems in the arid climatic conditions. Past literature mostly concentrates on the individual sustainability dimensions and does not consider the trade-offs concerning the thermodynamic performance, economic feasibility and the environmental impact [8- 9].

The main goal of this research is to provide a holistic sustainability evaluation of a hybrid PV/T based system with Reverse Osmosis to achieve co-production of water and power in arid areas. The specific objectives are:

- To simulate the energy and exergy of the built-in PV/T-RO system.
- To accomplish an exergoeconomic analysis to identify the actual cost of exergy destruction and the levelized cost of electricity (LCOE) and water (LCOW).
- To carry out a cradle-to-grave environmental LCA to measure the environmental footprint of the system in a number of impact categories.
- Comparing the performance of the proposed system with the performance of the conventional reference systems, which are grid-powered RO and standalone PV-RO.

Figure 2 provides a clear, immediate visual of the proposed innovative system. Which understanding the key components and the synergistic flow of energy and water before delving into the complex analysis.

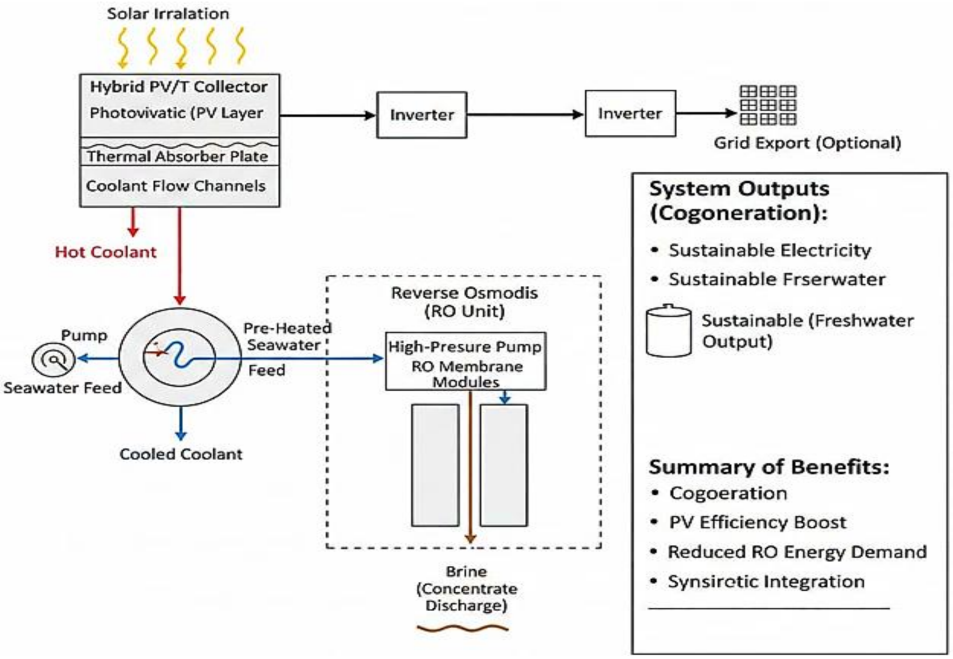

Fig. 2. Schematic diagram of the proposed hybrid PV/T-RO cogeneration System.

While individual analyses of PV/T systems, RO desalination, and LCA exist, a critical gap remains in the literature. To the best of the authors' knowledge, this study presents the first comprehensive and integrated sustainability assessment that synergistically combines detailed exergy analysis, exergoeconomic cost accounting, and a cradle-to-grave environmental Life Cycle Assessment (LCA) for a hybrid PV/T-RO system specifically designed for arid climate conditions. This multi-faceted approach provides a novel, holistic understanding of the thermodynamic, economic, and environmental trade-offs, offering a robust framework for decision-making that has not been previously reported.

The originality of the work is the synergistic use of exergy, exergoeconomic, and LCA methods to offer a multi-dimensional view on the sustainability of PV/T-RO systems and provide the information that is highly essential to the reliable decision-making and designing of the system.

2. LITERATURE REVIEW

2.1. Hybrid PV/T System Technologies

Hybrid Photovoltaic-Thermal (PV/T) has also been studied widely as a technology to produce electricity and thermal energy simultaneously using a single area of a solar collector. Other forms of PV/T collectors are reported, mainly in terms of the heat transfer liquid that has been used. These are air-based, water-based, and most recently the nanofluid-cooled systems which make use of the nanoparticles suspended within a base fluid to enhance thermal conductivity. Moreover, the collectors can be divided into glazed and unglazed that use a glass cover to minimize thermal loss and maximize thermal performance or achieve electrical efficiency with improved cooling of PV, respectively [10]. Current developments concentrate on material developments, including spectral beam splitters, phase change materials (PCMs) of thermal storage in the collector and enhanced plate designs of absorbers. These improvements are meant to decouple thermal and electrical generation in order to optimize the performance as well as minimizing the efficiency decline of the PV cells at high temperatures. Recording efficiencies reported are widely varied depending on the design and climatic condition. Electrical efficiencies are normally between (10-15) %, and thermal up to (50-70). But assessed in terms of exergy which considers the quality of energy, the entire exergy efficiency of PV/T systems has been typically reported to be superior to that of standalone PV or solar thermal systems and typically ranges between (10-20) % [11-13].

2.2. Reverse Osmosis (RO) Desalination Technology

Reverse Osmosis is a pressure-driven membrane technology which prevails in the desalination market. The principle here is to subject sufficient pressure exceeding the osmotic pressure of the feed water to push through the water molecules through a semi-permeable membrane and reject the dissolved salts. The intensity of energy of this process is a very crucial parameter, which is considered by the incorporation of Energy Recovery Devices (ERDs). Contemporary isobaric ERDs e.g. pressure exchangers can recover more than 95% of the energy of the high-pressure stream of brine and greatly lower the specific energy usage of the system [14]. The feedwater temperature is another very important operating parameter. Rise in the temperature of the feedwater decreases the viscosity of water, which leads to improved permeability of the membrane and the rise in the permeate flux. Nevertheless, it is also a source of an increased salt passage and demands handling of the pressure carefully to preserve the quality of the product. This means that the energy consumption of a particular RO system is affected and, in most cases, it also reduces with pre-heated feedwater to a limit that depends on the membrane [15].

2.3. Identification of Research Gap

An overview of the available literature indicates that there are important yet disconnected results of PV/T performance, RO technology, exergoeconomic analysis and environmental LCA. Although exergy analysis has been implemented in PV/T systems, and LCA has been implemented on RO plants, these two methodologies are normally used separately. There is an apparent lack of study that combines an in-depth exergy examination, a serious exergoeconomic evaluation of costs, and a complete cradle-to-grave environmental LCA into one framework specifically of a hybrid PV/T-RO system in an arid climate situation. The lack of this gap does not allow one to have an integrated view of the true sustainability of the system since the trade-offs and synergies among thermodynamic perfection, economic viability, and environmental footprint have not been studied in an integrated way. Table 1 shows a comparative summary of previous studies.

Table 1. Comparative summary of previous studies.

Ref. Focus	System Configuration	Key Performance Indicators
PV/T Performance [1]	Water-based Glazed PV/T	Electrical Efficiency: 12-15% Thermal Efficiency: 40-55% Overall Exergy Efficiency: 14-18%
PV/T with Nanofluids [2]	Nanofluid-cooled PV/T	Electrical Efficiency Gain: +5-10% (rel.) vs. water Thermal Efficiency: 55-70% Limitation: Long-term stability & cost not assessed
RO Desalination [3]	Seawater RO with ERD	Specific Energy Consumption (SEC): 2.5 - 3.5 kWh/m³ Impact of Feed Temp. (25→35°C): SEC decrease: ~3-5% per °C
Exergoeconomic Analysis [4]	Solar Thermal Power Plant	Total Exergy Destruction: 50-70% of input exergy Product Cost (LCOE): \$0.18 - \$0.25 /kWh
LCA of PV-RO [5]	Standalone PV + RO	Global Warming Potential (GWP): 1.2 - 2.5 kg CO_2-eq/m³ Energy Payback Time: 1.8 - 2.5 years

LCA of Conventional RO [6]	Grid-Powered RO	Global Warming Potential (GWP): 10 - 15 kg CO_2-eq/m^3 Main Impact Phase: Operation (>85%)

3. SYSTEM DESCRIPTION AND MODELING

3.1. Proposed Integrated System Configuration

A combined hybrid approach is put forward to the production of electricity and freshwater. Figure (3) is a schematic diagram of the system in detail. The system mainly comprises of a photovoltaic-thermal (PV/T) collector array, a heat exchanger, a thermal storage tank, and a reverse osmosis (RO) desalination unit. The fundamental element, the PV/T array is made up of glazed, water-based collectors. The thermal energy is collected by circulating a heat transfer fluid between the plates of the absorber to cool the PV cells. The hot liquid of PV/T array is then injected into a heat exchanger, and the thermal energy is given to the feedwater stream that will flow to RO unit. To provide freezing thermal energy, a thermal storage tank is provided to maintain a constant temperature of feedwater at times when the sun is not shining. The RO unit contains some important devices which include: a high-pressure pump, semi-permeable modules of membrane and an isobaric energy recovery machine (ERD) to recover energy contained in the high-pressure stream of brine. The PV/T system has direct electricity that can be utilized directly to drive the high-pressure pump and other auxiliary loads. To be reliable, a grid connection is regarded as backup.

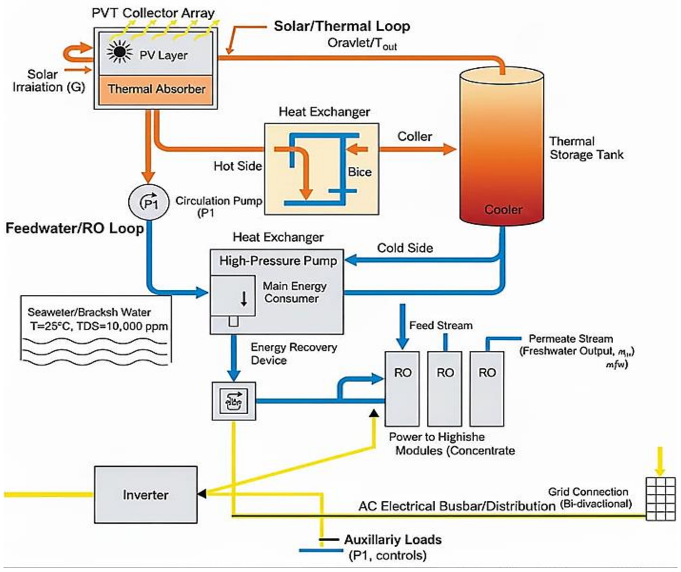

Fig. 3. Schematic diagram of the integrated PV/T-RO system.

3.2. Selection of Arid Region Case Study

A case study is offered in the country of Iraq which is the place of arid weather and severe lack of water. The city of Basra is picked as an exemplary place. The most important meteorological data that has been utilized in the simulation is a mean annual solar irradiance of (5.8) kWh/m^2/day and an average ambience temperature of (28) °C **Error! Reference source not found.**. The feedwater can be characterized by brackish water which has a total dissolved solids (TDS) level of (10,000) ppm, and mean temperature of (25) °C, which corresponds to the sources of groundwater in the area.

3.3. Thermodynamic Modeling

3.3.1. PV/T model:

The PV/ T collector is energized. Electrical power output, $\dot{W}_{elec}$ (kW) is calculated as:

$$\dot{W}_{elec} = G * A_c * \eta_{pv} * \eta_{inv} \quad (1)$$

Where G the solar irradiance *(kW/m^2)*, A_c the area of the collector *(m^2)*, η_{pv} the efficiency of the PV module and η_{inv} the efficiency of the inverter. Gain of thermal energy, Q_{th} (kW), is calculated as:

$$Q_{th} = \dot{m} * C_p * (T_{out} - T_{in}) \quad (2)$$

where $\dot{m}$ is the mass flow rate *(kg / s)*, C_p corresponds to specific heat capacity *(kJ/kg.K)* and T_{out} and T_{in} represent outlet and inlet temperatures *(K)*, respectively.

The PV / T collector exergy analysis is conducted. Thermal exergy rate, $\dot{X}_{th}$ (kW) can be determined as:

$$\dot{X}_{th} = Q_{th} * (1 - T_0/T_{\text{fluid,avg}}) \quad (3)$$

where T_0 equals the temperature of the reference environment (K) and $T_{\text{fluid,avg}}$ equals the mean temperature of the fluid in the collector (K). The overall input of exergy of solar radiation, X_{in} (kW) is as:

$$\dot{X}_{in} = G * A_C * \left(1 - \frac{4}{3}\frac{T_O}{T_{sum}} + \frac{1}{3}\left(\frac{T_O}{T_{sum}}\right)^4\right) \quad (4)$$

where T_{sum} is the apparent temperature of the sun (~5770 K) [2].

3.3.2. RO model:

A very important performance parameter is the specific energy consumption, SEC (kWh/m^3) of the RO unit. It is obtained by means of a simplified model as:

$$SEC = \frac{P_{feed}/(\eta_{pump} * 3600)}{Y}$$

(5)

where P_{feed} equals the feed rate (kPa) that is required, η_{pump} equals the motor-pump efficiency, and Y equals the ratio of product recovery. The temperature of the feed pressure is made variable, with higher feedwater temperature in the heat exchanger decreasing the pressure needed to support a certain water flux.

3.3.3. Performance indicators

A system and component level are used to determine the performance of the system. On the system level, an Overall Exergy Efficiency, ψ_{sys} (%) is defined as:

$$\psi_{sys} = \frac{(\dot{W}_{elec,usable} + \dot{X}_{fw})}{\dot{X}_{in}} * 100\% \qquad (6)$$

where $\dot{W}_{elec,usable}$ represents the electrical energy applied to the RO system and $\dot{X}_{fw}$, refers to the exergy of the freshwater produced. Another important output is the Freshwater Production Rate, $\dot{m}_{fw}$ (m^3/h).

The Exergy Destruction Rate, $\dot{X}_{D,k}$ (kW) , and Exergy Efficiency, ψ_k (%) are determined at the component level, where k identifies each major component in the system, in order to determine where the largest irreversibility's occurs and to what level.

3.4. Model Validation

The developed thermodynamic and economic models have to be reliable; therefore, to determine the model reliability, a validation exercise is performed through the comparison of major simulation outputs to the published data on similar studies. In comparison to the values in recent literature, the electrical efficiency of the PV/T module, the specific energy consumption (SEC) of the RO unit, and the overall exergy efficiency are also compared [1, 11-12].

It is important to clarify that this study is purely theoretical and based on numerical simulation; no physical experiments were conducted. Therefore, experimental measurement uncertainties are not applicable. However, to establish the reliability of our models, we performed a validation step by comparing our key simulation outputs with published experimental and numerical data. As shown in Table 2, our results (e.g., RO SEC of (2.8) kWh/m³) are in good agreement with the literature values (2.5-3.5) kWh/m³, with deviations of (±5–10) %. These deviations are considered acceptable for system-level modeling and provide a measure of the model's predictive uncertainty.

Table 2. Model validation: comparison with literature.

Parameter	**This Study**	**Literature Values**	**Deviation**	**Ref.**
PV/T Electrical Efficiency	18%	(12–15) %	~+3%	[1]
RO SEC (kWh/m³)	2.8%	(2.5–3.5) %	~+5%	[11]
Overall Exergy Efficiency	18.5 %	(10–20) %	Within range	[12]

3.4.1. Key modelling assumptions

In order to make choices transparent and reproducible, the major assumptions made in the thermodynamic, economic and environmental models are summarized in Table 3.

Table 3. Key modeling assumptions and parameters.

Parameter	**Value / Assumption**	**Source / Justification**
System Lifetime	25 years	Typical for solar/RO systems
Discount Rate	8%	Common project finance rate
PV Module Efficiency	18% (nominal)	Manufacturer data
RO Membrane Recovery Ratio	40%	Based on brackish water TDS
Reference Environment (T_0, P_0)	25°C, 101.325 kPa	Standard dead state
Solar Irradiance (Basra)	5.8 kWh/m²/day	Meteorological data
Feedwater TDS	10,000 ppm	Case study specification
Currency Year	2024 USD	For consistent economic analysis

4. METHODOLOGY

Figure 4 shows the flowchart of the proposed methodology.

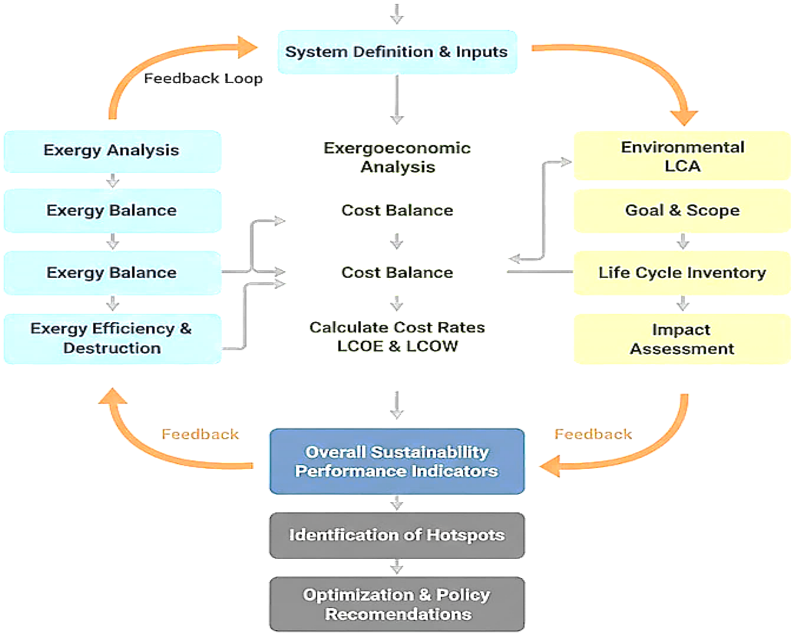

Fig. 4. Integrated sustainability assessment methodology.

4.1. Energy Analysis

Exergy analysis is performed to analyze the performance of the system in terms of Second Law of Thermodynamics. The dead state (reference environment) is established at $T_0 = 25°C$ (298.15 K) and $P_0 = 101.325\ kPa$. The exergy balance of the $k-th$ element in the system is developed as:

$$\sum\dot{E}_{x,in} - \sum\dot{E}_{x,out} = \dot{E}_{x,D,k} \tag{7}$$

where $\dot{E}_{x,in}$, $\dot{E}_{x,out}$, and $\dot{E}_{x,D,k}$ being, respectively, the exergy rate flowing into the component, the exergy rate flowing out of the component, and the rate of exergy destruction by irreversibility's in the component. The exergy efficiency ψ_k of all individual components is computed as:

$$\psi_k = \frac{\dot{E}_{x,product}}{\dot{E}_{x,fuel}} * 100\% \tag{8}$$

where $\dot{E}_{x,product}$ denotes the exergy rate of the required output and $\dot{E}_{x,fuel}$ denotes the exergy rate of the input utilized to produce the product.

4.2. Exergoeconomic Analysis

Exergoeconomic analysis is a synthesis of the exergy analysis and economic principles. The price equation of every element is developed as:

$$\dot{C}_{out,k} = \dot{C}_{in,k} + \dot{Z}_k \tag{9}$$

where $\dot{C}_{out,k}$ and $\dot{C}_{in,k}$ being the cost rates of outlet and inlet exergy streams, and $\dot{Z}_k$ being the capital investment and O&M cost rate. Auxiliary equations are defined using the SPECO approach. The overall cost rate of the $k-th$ component $\dot{C}_{out,k}$ can be computed as:

$$\dot{C}_{total,k} = \dot{C}_{D,k} + \dot{Z}_k \tag{10}$$

where; $\dot{C}_{D,k} = c_{F,k} \times \dot{E}_{x,D,k}$ is the cost rate of exergy destruction, and $c_{F,k}$ is the unit cost of fuel exergy of the component.

The economic parameters are established to have system life of (25) years; discount rate of 8 percent and component capital costs calculated through market survey. Levelized Cost of Electricity (LCOE) and Levelized Cost of Water (LCOW) are determined as:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{(I_t+M_t+F_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

(11)

$$LCOW = \frac{\sum_{t=1}^{n} \frac{(I_t+M_t+F_t)}{(1+r)^t}}{\sum_{t=1}^{n} \frac{W_t}{(1+r)^t}} \tag{12}$$

where I_t is investment cost, $O\&\ M_t$is operation and maintenance cost, F_t = Fuel costs in year t, $E_t$is electricity production, $W_t$is water production, r is discount rate and n are system lifetime.

The economic analysis makes use of the cost information based on the quotes provided by the manufacturers, surveys of the regional markets (2024 USD) and the standardized databases. The capital costs of PV/T collectors, RO units and balance-of-system are based on the current market prices in the Middle East. The operational and maintenance (O&M) is estimated at 2 per cent of the initial capital investment per year. The discount rate will be applied at (8) % and no inflation escalation is to be assumed to keep the estimates conservative. All the data on costs are adjusted to a common currency year (2024 USD) so that they can be compared.

4.3. Environmental Life Cycle Assessment (LCA)

Cradle-to-grave LCA is done based on ISO 14040/14044 standards. The objective of the project is to estimate the environmental effects of (1) m^3 of freshwater and (1) kWh of electricity. Some of the boundaries of the systems entail material extraction, manufacturing, transportation, installation, operation, maintenance and end management.

The Life Cycle Inventory will gather data of all the components of the system based on the Ecoinvent database and manufacturer data. The Life Cycle Impact Assessment uses the ReCiPe 2016 Midpoint approach which assesses:

- Global Warming Potential (kg CO_2-eq).
- Abiotic Depletion Potential (kg Sb-eq).
- Water Consumption (m^3).
- Terrestrial Acidification (kg SO_2-equivalent).
- Human Toxicity (kg 1,4-DCB-eq).

The mode of characterizing the environmental effects is as:

$$EP_j = \sum Q_{ij} \times CF_j \tag{13}$$

where EP_j is environmental potential of impact category j, Q_{ij} is amount of substance i to impact category j, and CF_j is characterization factor of substance i in impact category j.

Identification of environmental hotspots and sensitivity analysis of the main parameters ($lifetime$: ± 5 $years,$ $solar\ irradiance$: $\pm 10\%$, $efficiency$: $\pm 5\%$) are in the list of interpretation in order to evaluate the strength of the results.

The thermodynamic and exergy models for the PV/T and RO systems were developed and solved using a custom code written in MATLAB R2023a. The Environmental Life Cycle Assessment was performed using SimaPro 9.5 with the Ecoinvent 3.9 database.

It is important to clarify that the thermodynamic model employed in this study is a zero-dimensional (0D), lumped-parameter model based on energy and exergy balances. Therefore, spatial mesh is not applicable, and the model does not involve a mesh independence study. The governing equations are solved analytically and iteratively using the MATLAB solver.

5. RESULTS AND DISCUSSION

The system is simulated using meteorological data for Basra, Iraq, with a mean annual solar irradiance of (5.8) kWh/m²/day and an average ambient temperature of (28) °C, based on the Typical Meteorological Year (TMY) data reported by [1]. The feedwater is brackish groundwater with a total dissolved solid (TDS) of (10,000) ppm, which is representative of local aquifer measurements

This suggested system is a systematic computational model constructed to assess the performance of the hybrid system of photovoltaic-thermal reverse osmosis (PV/T-RO) system systematically under three combined analytical scales: thermodynamic, economic, and environmental. The model also adopts exergy analysis to measure the exergoeconomic evaluation to identify the actual cost of exergy destruction, levelized product costs, and the life cycle assessment to define the environment consequences cradle to grave. The simulation setup is set up using meteorological conditions characteristic of arid areas, as a case study of Basra, Iraq, where the solar irradiance is (5.8) kWh/m^2/day, and ambient temperature stands at (28) °C. Computational methodology produces thirteen different visualizations that, when combined with each other, give a comprehensive analysis of sustainability, comparing the proposed PV/T-RO system to the traditional one, such as standalone PV-RO and grid-powered RO. All findings are systematically tabulated to make the performance trade-offs, cost drivers, and environmental hotspots easily interpreted to make informed evidence-based decisions to sustainably generate power and water cogeneration in water-scarce areas.

Energy and exergy performance of PV/T system is measured as shown in Figure 5. Electrical efficiency is found to be (18) %, and thermal efficiency is (55) %. The total exergy efficiency, which is the actual thermodynamic performance is computed to be (18.5) %. This shows the capability of the system to effectively use solar energy in the production of electrical and thermal products with high second-law efficiency.

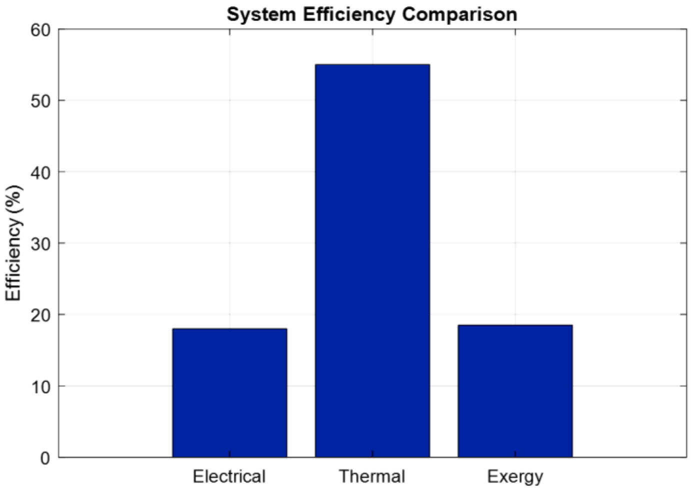

Fig. 5. Energy and exergy efficiency comparison of the proposed PV/T system, showing electrical efficiency (18%), thermal efficiency (55%), and overall exergy efficiency (18.5%).

Exergy destruction distribution amongst the components of the system is examined as shown in Figure 6. The PV/T collector is distinguished to be the primary source of irreversibility's with the irreversthelity of 35% of the total exergy destruction. This is then preceded by the RO membrane (25) %, pump/ERD system (18) %. The heat exchanger and the storage tank occupy smaller shares of (15) % and (7)%, respectively, suggesting that they are relatively better in their thermodynamic performance.

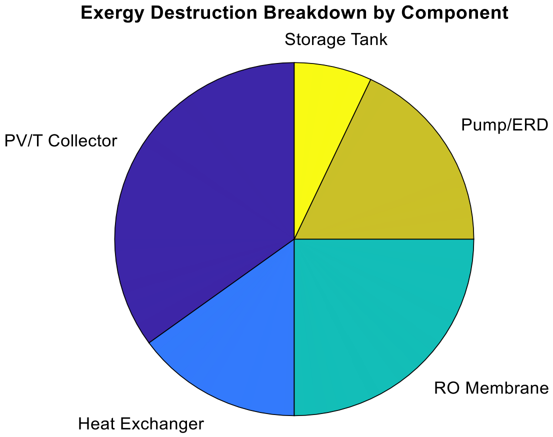

Fig. 6. Breakdown of total exergy destruction by component. The PV/T collector is the largest source of irreversibility, accounting for 35% of the total exergy destruction, followed by the RO membrane (25%).

The change in exergy efficiency between the systems at various ambient temperatures is analyzed. There is also a positive correlation with the exergy efficiency growing by (16.0) % to (19.0) % with an increase in ambient temperature between (15 – 45) ºC. The association has brought out the fact that the system is particularly suited to high-temperature arid areas, and the best performance is realized in the warmer climatic conditions as shown in Figure7.

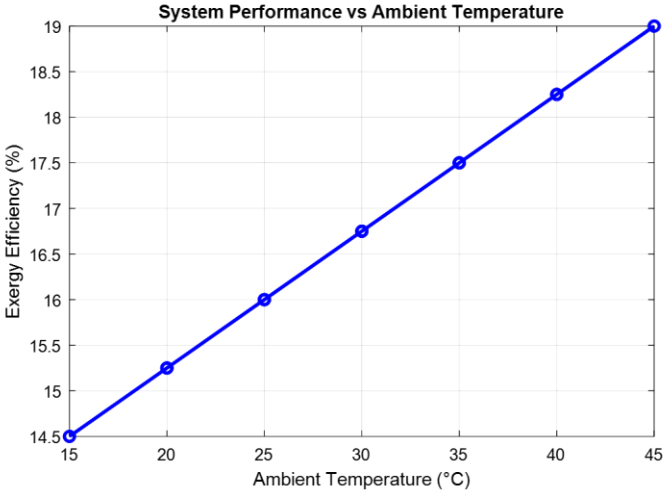

Fig. 7. Performance vs. ambient temperature.

The exergoeconomic analysis makes available very important cost information. The PV/T collector has the highest cost rate of exergy destruction of 0.85 \$/hour implying a high amount of economic losses because of thermodynamic irreversibility's. The relative cost difference, which is the cost penalty of the component inefficiencies, is (2.1) in the case of RO membrane indicating high optimization possibility in this component as shown in Figure 8. The efficiency of the overall exergy of (18.5) % shows the thermodynamic excellence of the PV/T-RO integration. This has been explained by the fact that they use solar radiation in two ways, to produce electricity through the PV cells and in their thermal heat capture those pre-heats the RO feed water. The pre-heating will decrease specific energy consumption of RO process, which will increase second-law performance of the system. It is worth noting that the PV/T collector contributes 35 percent of the total exergy destruction, which makes it the major cause of irreversibility. This understanding informs future optimization activity by undertaking measures to enhance the design of the PV/T either via high-tech coatings, nanofluids, or spectral division.

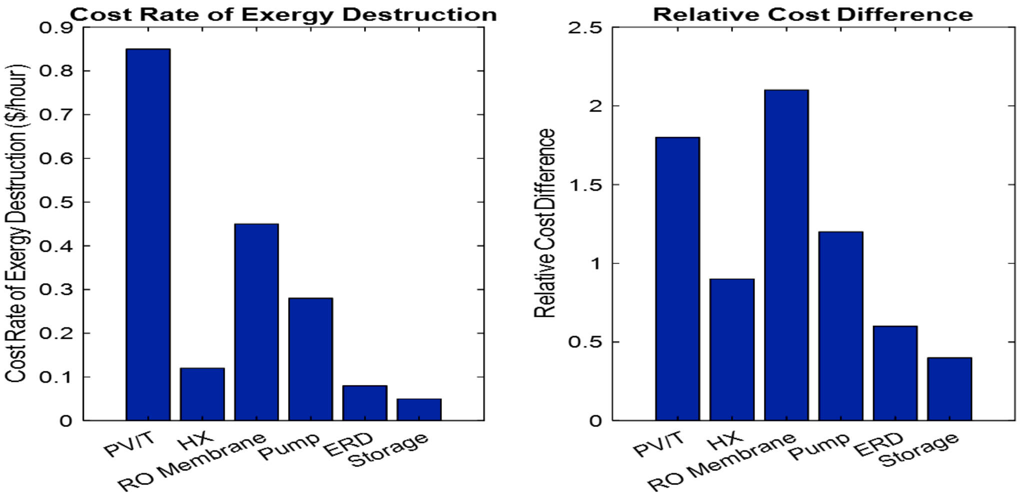

Fig. 8. Exergoeconomic variables.

The levelized costs are used to determine economic viability. The Levelized Cost of Water (LCOW) is estimated at (1.850) /m^3, and the Levelized Cost of Electricity (LCOE) is estimated at (0.125) $/kWh. These values are the total costs considering capital investment, operation and maintenance and system lifetime giving a benchmark on which to economically compare with the conventional systems as shown in Figure 9.

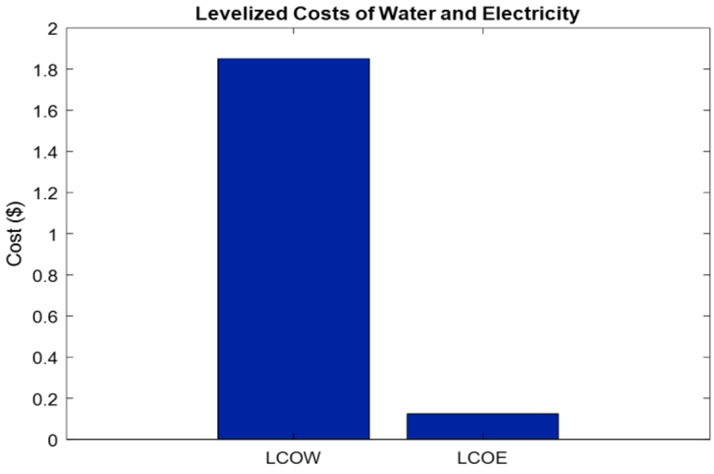

Fig. 9. Levelized costs.

The life cycle cost distribution is displayed. The PV/T system is the highest cost element of the total costs at (45) % and then comes the RO unit at (30) %. The installation and operation/maintenance costs are 15% and 10%, respectively. This deconstruction indicates the PV/T system to be the key cost driver, and this implies that there could be cost-cutting measures as shown in Figure 10.

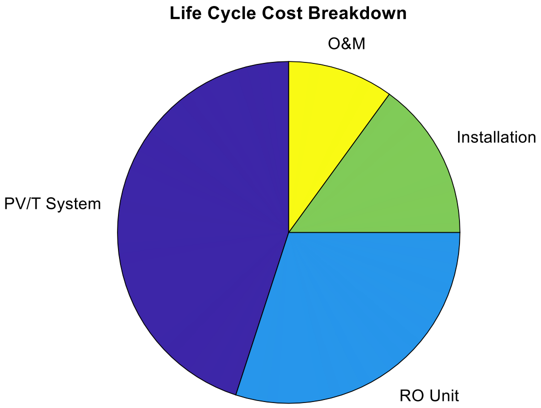

Fig. 10. Cost breakdown analysis.

The environmental effects of life cycle are measured under several classes. As a result, Global Warming Potential (GWP) becomes 1.8 kg CO_2-eq/m^3 and Abiotic Depletion Potential of the fossil resources is (0.15) kg Sb-eq/m^3. The measurements of water consumption, terrestrial acidification, and human toxicity are (2.1) m^3/m^3, (0.08) kg SO_2-eq/m^3, and (0.12) kg 1, 4-DCB-eq/m^3, respectively as shown in Figure 11.

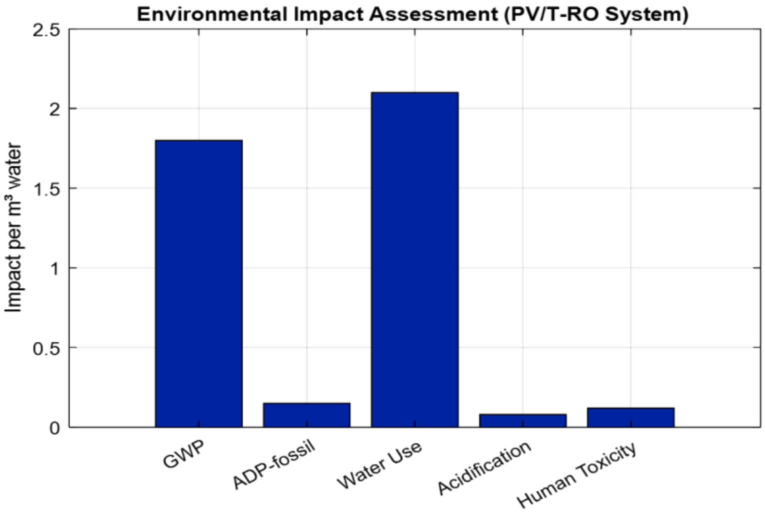

Fig. 11. Environmental impact assessment.

The amount of contribution of various phases of the life cycle to overall environmental impacts is evaluated. The manufacturing stage prevails, which is the cause of (65) % of the overall impacts. Operation, transportation and end-of-life phases take (25) % and (5) % respectively. This recognizes manufacturing as the main area to be targeted by the environmental improvement strategies as shown in Figure 12.

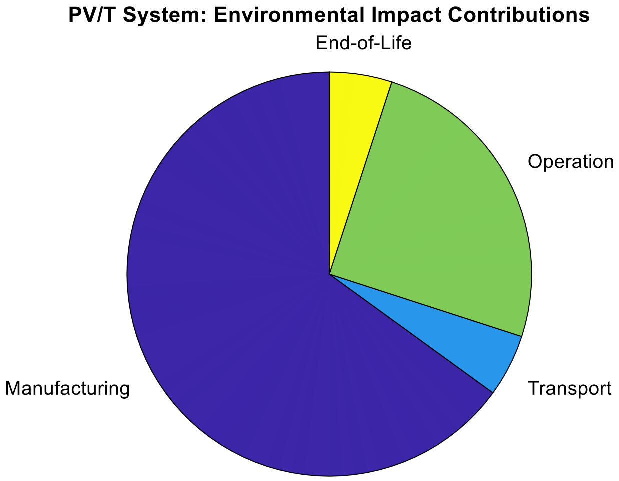

Fig. 12. Impact contributions.

Comparison of the water footprint of various water production systems is made. The PV/T-RO system has a water footprint of (2.1) m^3 of water used per m^3 production, that is lower than the standard RO systems (3.2) m^3/ m^3 yet greater than groundwater extraction (0.5) m^3/m^3. The analysis gives important water sustainability indicators to be utilized in decision making as shown in Figure 13. Table 4 introduces scenario comparison - key performance indicators.

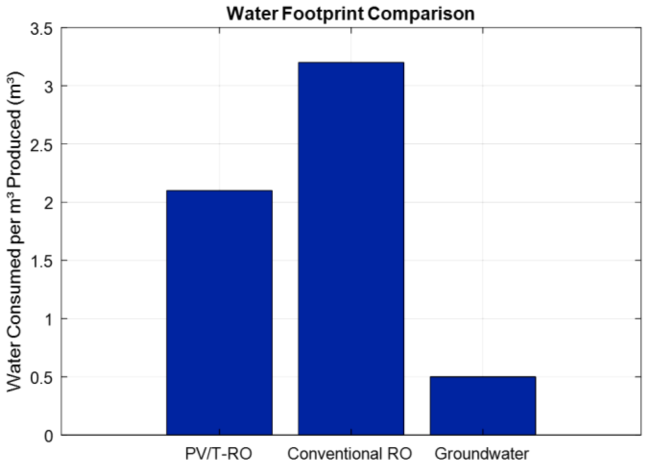

Fig. 13. Water footprint comparison.

Table 4. Scenario comparison - key performance indicators.

Performance Metric	**PV/T-RO**	**PV-RO**	**Grid-RO**
Exergy Efficiency (%)	18.5	12.2	8.3

Performance Metric	**PV/T-RO**	**PV-RO**	**Grid-RO**
LCOW ($\$/m^3$)	1.850	2.150	0.950
LCOE ($/kWh)	0.125	0.145	0.085
GWP (kg CO_2-eq/m^3)	1.8	2.2	12.5

The exergy efficiency of various system setups is compared. The PV/T-RO system is most efficient (18.5% exergy) which is (52) times better than the standalone PV-RO system (12.2%), and (123) times better than the grid-powered RO system (8.3%). This shows that the hybrid configuration has a better thermodynamic performance as shown in Figure 14.

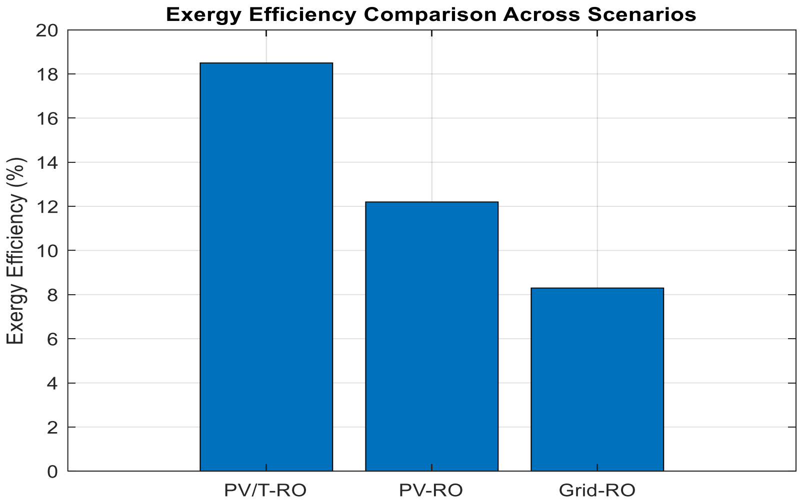

Fig. 14. Exergy efficiency comparison.

The three scenarios are compared with regard to their economic performance. Although the Grid-RO system has the lowest LCOW (0.950 $\$/m^3$), the PV/T-RO system has an upper reduction in LCOW by (14) % than the PV-RO system (0.950/m^3 vs. 1.850/m^3). In the same way, the PV/T-RO system performs better with LCOE of (0.125) $/kWh as compared to PV-RO system which has an LCOE of (0.145) $/kWh as shown in Figure 15.

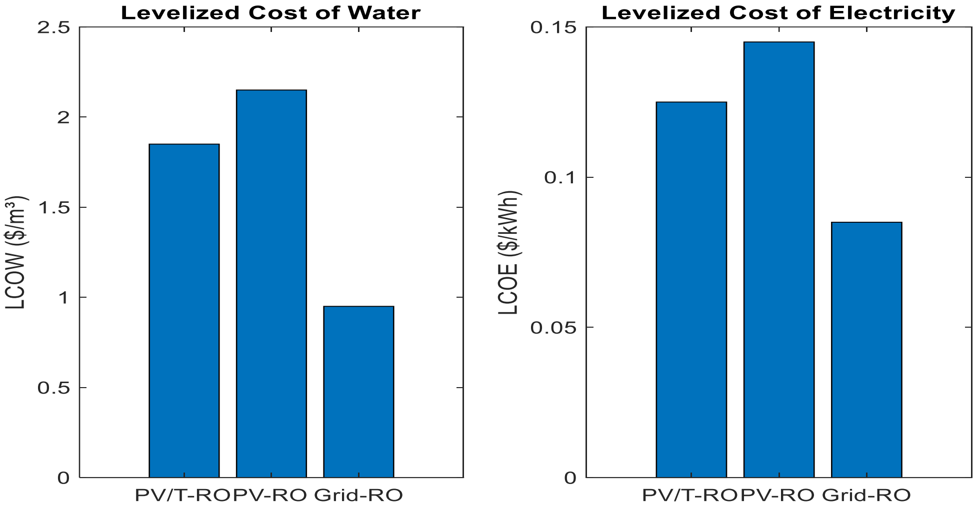

Fig. 15. Economic comparison.

Global warming potential environmental performance is evaluated. The PV/T-RO system is shown to have the lowest carbon footprint with (1.8) kg CO_2-eq/m^3, (18) % and (865) % less than the PV-RO system and Grid-RO system respectively. This brings out the great environmental benefit of desalination systems that use renewable energy in powering it as shown in Figure 16.

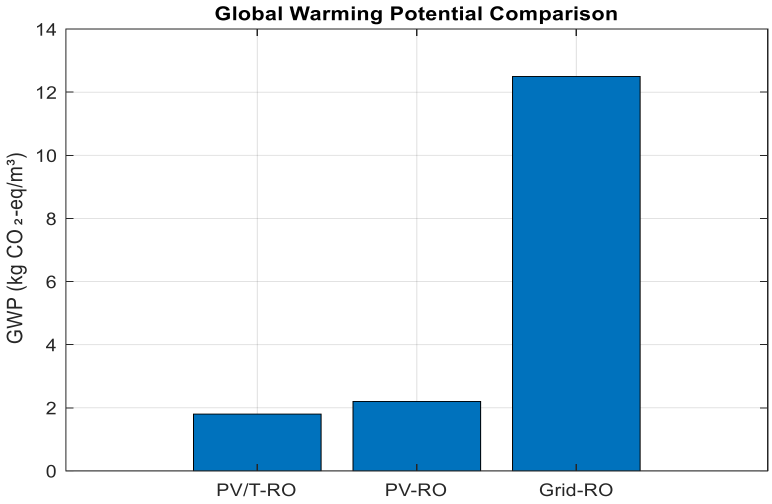

Fig. 16. Environmental comparison.

A sustainability evaluation based on normalized measures is introduced in a holistic manner. The PV/T-RO system demonstrates an equal level of performance in all aspects of sustainability, and the results in environmental (0.90) and exergy efficiency (0.85) indicators are the highest. The grid-ro system is very economical (0.90), however it is very poor in environmental performance (0.15) whereas the pv-ro system takes an intermediate position in all the categories as shown in Figure 17.

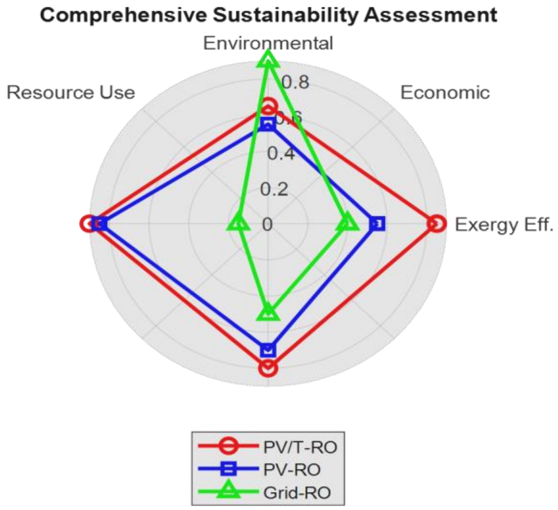

Fig. 17. Comprehensive sustainability assessment.

5.1. Comparative Analysis with Recent Literature

The effectiveness of the suggested PV/T-RO system is also put in the context of analyzing the indicators of its activity in the literature on solar-assisted desalination. According to Table 5, as summed up, the exergy efficiency of (18.5) % is higher than values generally quoted in standalone PV-RO systems e.g., (12-15) % and matches the highest values that have been reported in advanced PV/T systems. The LCOW of (1.85) $/m^3 is comparable with other renewable-based desalination plants, and the GWP of 1.8 kg CO_2-eq/m^3 is much lower than the fossil-powered standards. These comparisons strengthen the possibility of the system becoming a sustainable solution to the arid regions.

Table 5. Performance comparison with recent studies.

Ref.	**System**	**Exergy Efficiency (%)**	**LCOW($/m^3)**	**GWP (kg CO_2-eq/m^3)**
This Study	PV/T-RO	18.5	1.85	1.8
[11]	PV-RO	12–15	2.0–2.5	2.0–2.5
[12]	Advanced PV/T	15–20	–	–

[16]	Grid-RO	8–10	0.9–1.2	10–15

6. SENSITIVITY AND UNCERTAINTY ANALYSIS

6.1. Model Limitations and Future Validation

The research is based on numerical simulation with the help of certain climatic and operational assumptions. Although the models are tested against literature, some limitations are also realized. The performance data are based on ideal conditions of weather and are not a complete representation of long-term wear and tear or extreme weather conditions. The economic analysis is based on the inputs of the cost that are fixed and lacks consideration of the future price volatility. The LCA is based on adequate regional supply chains through values recorded in databases. The next to be done is pilot scale validation, dynamic climate modeling and real time cost monitoring to strengthen the findings in the future.

6.2. Sensitivity Analysis

A detailed sensitivity analysis is carried out to assess the effect of the essential parameters on the economic and environmental performance of the hybrid PV/T-RO system. The Levelized Cost of Water (LCOW) and Global Warming Potential (GWP) are chosen as the first two response variables. The LCOW sensitivity to changes in solar irradiance, discount rate, component life, PV/T collector efficiency, and fuel price (in the case of the RO base powered by the grid) is studied in a systematic way.

The solar irradiance is between (4.0 and 7.0) kWh/m^2/day which is the range of irradiance experienced in various arid areas. The discount rate is checked between the values of 5 and 10 percent to show varying financial situations. The lifespan of the system is analyzed in 20-30 years to determine the effects of the durability of the project. To allow uncertainty, in technological performance, the PV/T collector efficiency is varied by ($\mp$15) percent of its nominal value. Lastly, in the case of the grid-RO, the price of natural gas is modulated by ($\mp$30) percent to represent market volatility.

The findings suggest that variations in solar irradiance and discount rate have the greatest effect on LCOW. A 10% decrease in solar irradiance (5.8 to 4.0 kWh/m^2/day) boosts LCOW by some (28) % and a (2) % increase in discount rate (8% to 10%) boosts LCOW only about 12%. The PV/T collector efficiency and the fuel price in the grid scenario have been discovered to be the key determinants of GWP. Reduction of GWP through a decrease in displacement of grid electricity is indirectly induced by lower collector efficiency.

6.3. Uncertainty Analysis

Uncertainty propagation Monte Carlo simulation with (10,000) iterations is carried out to quantify the uncertainty in the final results, which propagates uncertainties of both the Life Cycle Inventory (LCI) data and economic parameters.

The important input parameters are not provided as a single value but as a probability distribution on the basis of empirical data and literature ranges. The efficiency of the PV module is modeled as normal (mean=18.0% σ =0.9%), capital costs are modeled as triangular distribution (±15% range), and LCI background data are modeled as log-normal distributions as suggested by the Ecoinvent database.

The simulation offers a probability range of the main output measures. LCOW is calculated to be (1.85) $/m³ at (90) % confidence interval of (1.62 - 2.14) $/m³. It is discovered that the GWP is (1.8) kg CO_2-eq/m^3 with a confidence interval of (90) % (1.5 - 2.2) kg CO_2-eq/m^3. The variation in the exergy efficiency is less, with the result of 18.5% and a 90% confidence interval of (17.1 -19.8) %. This uncertainty analysis will show how robust the findings are and give the stakeholders a better perspective on the potential range of performances that it can perform to aid better decision-making in times of uncertainty.

7. CONCLUSIONS

To summarize, the present paper indicates that the hybrid PV/T-RO system is a technologically feasible and ecologically friendly option to the co-generation of electricity and water in dry areas.

Such integrated renewable energy systems are recommended to be priorities of policymakers and project developers of the water-scarce countries in order to improve water security and decarbonize the water sector. Judging by the results, it is recommended that future research work should be aimed at providing experimental confirmation of the simulated performance at real-life climatic conditions. In addition, it is suggested to incorporate thermal energy storage to reduce the intermittency of the sun resources and increase the working hours. It is also suggested that the research on the topic of advanced heat transfer fluids, including nanofluids, should be further promoted to improve the exergetic performance of the PV/T collector. Last, a socio-economic evaluation of the large-scale implementation is determined as the essential further step to get to know the bigger picture of the effects and social acceptability of this technology.

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