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Optimizing Photovoltaic and Battery Integration for RO Desalination Using Differential Evolution Algorithm

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ABSTRACT

Access to clean water is a basic human right, and reverse osmosis (RO) is a common method for producing potable water from seawater. However, the high energy demands of RO systems make them expensive to operate. Renewable energy sources (RES), such as photovoltaic (PV) systems, can reduce the energy costs associated with powering RO systems. In this paper, a novel approach that uses a differential evolution (DE) algorithm to optimize PV-Battery systems for RO desalination is proposed. (DE) is a heuristic, population-based algorithm that searches for the global optimal solution. The approach aims to minimize the Cost of Electricity (COE), and Cost of Water (COW) and ensure that Desalinated water costs are within an appropriate range. The algorithm was used in a case study of the city of Dhahran, Saudi Arabia, which faces significant water scarcity challenges. The results show that for an RO load demand of 1 kW, the optimized hybrid system's configuration includes a PV generation capacity of 9.145 kW and a battery size of 64.65 kWh. The COE is 0.425 \$/kWh for Dhahran city, and the COW falls between 2.41 and 2.6 \$/m^3.

Keywords: Photovoltaic system, Reverse Osmosis Desalination, Differential Evolution Algorithm, Cost of Electricity, Cost of Water.

NONMENCLATURE

Abbreviations	
$B_{soc}(t)$	The Available Energy Storage (kWh)
C_{ann}	Annualized Cost (\$/year)
COE	Cost of Electricity (\$/kWh)
COW	Cost of Water (\$/m^3)
DE	Differential evolution
$P_{load}(t)$	Hourly Load Demand (W)
$P_{pv}(t)$	Power generated by PV (W) hourly
PSSP	Power Supply Shortage Probability
PV	Photovoltaic
RO	Reverse Osmosis
Symbols	
η_B	Battery Efficiency (%)
η_C	Converter Efficiency (%)
Δt	Time step (1 hour)
σ	Self-Discharge Rate of the Battery (%)

1. INTRODUCTION

Water scarcity affects a significant 25% of the global population despite freshwater accounting for only 3% of the world's water [1]. This critical issue, exacerbated by population growth and economic development, demands sustainable solutions. The integration of renewable energy sources such as wind and solar power with desalination technology presents a promising approach to combat water scarcity [2]. However, environmental challenges persist, given the high energy

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consumption and fossil fuel reliance in desalination processes.

Reverse osmosis (RO) is the most commonly used method for desalination today. This method employs a semi-permeable membrane and hydraulic pressure to remove impurities and produce fresh water. As of 2016, RO accounted for 65% of the world's desalination capacity [3]. Small-scale RO desalination plants powered by renewable energy have been built in different regions worldwide, and research has shown that they operate effectively with low maintenance requirements [4].

Several studies have been conducted on RO desalination in conjunction with RES including wind [5] and solar energy [6]. Ahmad et al. [7] looked at using photovoltaic systems to power reverse osmosis water desalination and examined the influence of the slope and azimuth angle of the Photovoltaic (PV) panel on the permeate flow rate. Qiblawey et al. [8] considered the combination of reverse osmosis water desalination with photovoltaic energy generation, including backup battery storage. Ayou et al. [9] conducted study to determine the feasibility of a small-scale photovoltaic (PV) integrated reverse osmosis (RO) desalination system on Madura Island from an economic and technical standpoint. 11.6 m^3/day were intended for the plant's daily capacity. According to the results, it would be fiscally possible to build a grid-connected PV-RO facility at a community scale in the area that would produce salt and drinking water.

Several optimization strategies have been used to estimate the optimal size of the photovoltaic (PV) system required to power the reverse osmosis (RO) desalination facility. In the remote region of Khorasan, Iran, heuristic techniques are suggested for the optimal stand-alone Reverse osmosis desalination system with a hybrid photovoltaic, diesel, battery, and power source design by Wu et al. [10]. The suggested hybrid system optimizes the size of the battery bank, the area of the solar array, and the fuel consumption of the diesel engine to minimize the system's overall life cycle costs. Harmony search optimization is used by Maleki et al. [11] to find the optimal size of stand-alone PV system with battery storage to satisfy the case study's electrical needs while targeting the lowest Total Life Cycle Cost (TLCC) feasible. The Improved Harmony Search (IHS) method is utilized to find cost-effective variables throughout the optimization procedure values for satisfying electricity demands. The technique also incorporates a reliability constraint for power loss. To enable the operation of a small-scale reverse osmosis (RO) water desalination system in Tehran, Iran, the study by Mousavi et al. [12] utilized HOMER Pro software for optimizing a standalone PV system with battery storage. Two distinct scenarios were evaluated to identify the most cost-effective approach. Both scenarios were designed, simulated, and subjected to comprehensive techno-economic analysis using HOMER Pro. Also, Karavas et al. [13] employed a fuzzy logic approach to determine the optimal size and configuration of a standalone PV system that powers a reverse osmosis (RO) plant on an island situated in the Cyclades, Aegean Sea, Greece. Yahiaoui et al. [14] used the Grey Wolf Optimizer (GWO) methodology to determine the optimum arrangement of a PV-Diesel Generator-Battery system, with the main objective of minimizing expenses for the hybrid power generating system located in a remote rural village in southern Algeria. According to the findings of the study, the GWO efficiently balances exploration and exploitation, resulting in both local optima avoidance and rapid convergence for problem-solving. Fodhil et al. [15] described a complete method for optimizing and performing sensitivity analysis on an independent hybrid energy system that includes PV, diesel, and batteries. In order to minimize system costs generally, unmet load, and carbon dioxide (CO2) emission simultaneously, Particle Swarm Optimization (PSO) and the -constraint technique were utilized in tandem. Following that, from among the possible solutions, one was picked as the optimal for in-depth investigation. Liu et al. [16] investigated the impact of dispatch techniques on optimizing a hybrid system (PV/energy storage/diesel/RO desalination) to satisfy the electricity and freshwater needs of a remote locale. Berbaoui et al. [17] implemented Virus Colony Search (VCS) algorithm to efficiently size and position a standalone hybrid power system that includes photovoltaic solar panels (PV) and a battery bank. The minimization of the equalized cost of the system (an economic goal) and the reduction of the equalized CO2 equivalent life cycle emissions (an environmental goal) are the two main goals that have been defined. For the eastern part of Iran, Cai et al. [18] established a flexible model for PV system optimization with battery storage. Their method mixes socioeconomic, technical, and environmental considerations to decide on the best location and size for PV systems, concentrating on TLCC minimization for standalone hybrid systems combining batteries, solar energy, and diesel generators. Additionally, they present an innovative hybrid optimization methodology for off-grid PV systems. The study investigates at interest rates as well as economic factors including the cost of fuel, batteries, and solar panels.

The aim of current study is to evaluate the feasibility of running a 1 kW continuous load RO desalination plant in the particular weather of Dhahran City. The most effective solution that minimizes the cost of electricity (COE) and the cost of water (COW) using the Differential Evolution (DE) method will be determined by considering various arrangements of PV panels and battery storage systems.

To achieve this objective, the research will collect and employ Dhahran City's weather data to model the performance of PV-Battery system. Additionally, cost data for each component will be gathered, and the COE and COW will be calculated for each configuration. Subsequently, the Differential Evolution algorithm will be utilized to seek the optimal combination of PV panels and battery storage systems that lead to the lowest COE and COW.

2. MATHMATICAL MODELING AND SYSTEM DESCRIPTION

In this study, a PV-powered RO desalination unit is considered for the production of freshwater. With a 1 kW power source, the RO unit produces a total daily flow rate of 5 cubic meters of water per day, equivalent to a rate of 0.208 m^3/h of water [19].

Figure 1's illustration of the study's configuration demonstrates how a PV panel, battery storage, and a DC/AC inverter are all included. The main source of power is a PV panel, and solar radiation influences how much power it produces. A battery stores extra energy to assure year-round stability, and a system converts DC power to AC to generate dependable, sustainable electricity.

2.1 PV model system

This study employs 295 W monocrystalline PV modules with an efficiency of 18.02%. These modules have a 25- years lifespan, a capital cost of $1200/kW, and an annual operating cost of $100 [20]. The hourly production of power is calculated [21]:

$$\mathrm{P_{PV}(t)} = \mathrm{P_R} \times f_{pv} \times \left(\frac{\mathrm{G_T(t)}}{\mathrm{G_{ref}}}\right) \times \left[1 + \alpha_p \times (\mathrm{T_C(t)} - \mathrm{T_{ref}})\right] \quad (1)$$

P_R is the PV module's rated capacity in kW, while f_{pv} is the derating factor in percentage. $G_T(t)$ represents hourly solar radiation on the tilted PV module in kW/m^2, with G_{std} denoting solar radiation under standard test conditions (1 kW for selected modules).

Additionally, α_p is the power temperature coefficient (0.0039/°C), T_{ref} is the PV cell temperature at standard test conditions (25°C), and $T_c(\mathrm{t})$ is the PV cell temperature during operation.

The operational PV cell temperature, which is calculated by:

$$T_C(t) = T_A(t) + \left(\frac{T_{NOCT}-20}{G_{NOCT}}\right) \times G_T(t) \quad (2)$$

where T_A refers to the ambient temperature (°C), T_{NOCT} represents the temperature under standard operating cell conditions (°C) and G_{NOCT} indicates the standard solar radiation at nominal conditions, which is equivalent to 0.80 kW/m^2. [22].

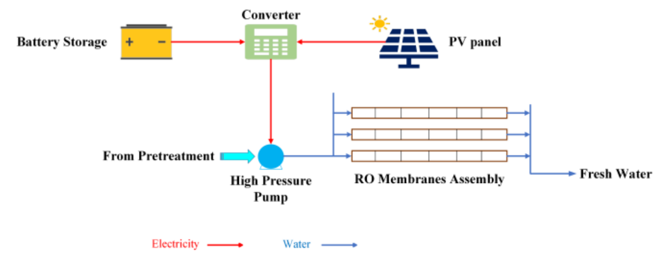

Fig. 1. *Photovoltaic-Powered RO Unit with Battery Storage*

2.2 Converter model

Converters are used in photovoltaic (PV) systems to transform DC power into AC. According to the converter efficiency formula, the AC power requirement is represented as follows:

$$P_C(t) = \frac{P_{Load}(t)}{\eta_C} \quad (3)$$

where $P_C(t)$ is the power converter, which reflects the amount of AC electricity needed to meet demand each hour (t), $P_{Load}(t)$ represents the hourly load requirement (kW), and η_C is the converter efficiency (%).

In this study, a 0.5 kW-rated converter with a 95% efficiency and a 15-year lifespan incurs capital and replacement costs of $650/kW and yearly operating and maintenance costs of $10 [23].

2.3 Battery model

Integrating battery backup into independent renewable energy sources is essential for reliability. The system produces energy to satisfy immediate demands while storing excess energy in batteries. An expression for the amount of energy that is accessible in the batteries during charge and discharge is also given [24].

$$B_{SOC}(t) = B_{SOC}(t-1) \times (1-\sigma) + \left[P_{PV}(t) - \frac{P_{Load}(t)}{\eta_C}\right] \Delta t \times \eta_B \quad (4)$$

$$B_{SOC}(t) = B_{SOC}(t-1) \times (1-\sigma) - \left[\frac{P_{Load}(t)}{\eta_C} - P_{PV}(t)\right]\Delta t \times \eta_B \quad (5)$$

$B_{SOC}(t)$ stands for the energy that was saved in the battery at time (t), whereas $B_{SOC}(t-1)$ stands for the energy that was stored at the previous time step. σ indicates the rate at which the battery discharges itself, which is specified as 0.16% annually, and η_B is the efficiency of battery charging. A 360 Ah battery made of lead acid with a 12 V voltage is employed in this study. It has a capital/replacement cost of 800 $/kW [25].

In this model, battery degradation is considered by incorporating the assumption of periodic battery replacement, typically occurring every 5 years, to address the natural degradation process. This approach ensures that the battery's performance is maintained at a specified level over the course of our study.

2.4 Reliability assessments

In order to assure reliability, Power Supply Shortage Probability ($PSSP$) must be considered while designing an off-grid PV system. The SPSP scale goes from 0 to 1, with 0 denoting no shortage and 1 signifying a 100% shortage. In order to determine SPSP based on system parameters, a specific formula, designated as [26], is used.

$$PSSP = \frac{\sum_{t=1}^{8760} PSS(t)}{\sum_{t=1}^{8760} P_{Load}(t)\Delta t} \quad (6)$$

where $P_{Load}(t)$ is the hourly power demand and $PSS(t)$ is the hourly power supply shortage. The power supply shortage ($PSS(t)$) is given by:

$$PSS(t) = P_{Load}(t)\Delta t - (P_{PV}(t)\Delta t + B_{SOC}(t-1) - B_{min})\eta_C \quad (7)$$

where $P_{PV}(t)$ is the hourly PV power generation, $B_{SOC}(t-1)$ denotes the battery capacity in the previous hour, B_{min} is the minimum battery capacity, and η_C is the converter efficiency.

2.5 Economic assessment

In assessing different PV/Battery configurations for a power generation system, the Cost of Electricity (COE) is employed as a metric for ranking their feasibility. COE represents the expense of producing one kilowatt-hour (kWh) of electricity through the PV/Battery system, denominated in $/kWh, and is formulated as [27]:

$$COE = \frac{C_{ann}}{\sum_{t=1}^{8760} P_{Load}(t)\Delta t} \quad (8)$$

where C_{ann} represent the overall annualized cost of the PV-Battery system in ($/year) which includes capital costs, O&M costs, replacement costs, etc. The total annualized cost (C_{ann}) can be expressed on the basis of Net Present Cost (NPC) as given:

$$C_{ann} = NPC \times CRF(i,n) \quad (9)$$

Capital recovery factor (CRF) is expressed by:

$$CRF(i,n) = \frac{i \times (1+i)^n}{(1+i)^n - 1} \quad (10)$$

where i refers to the interest rate (%) and n represents the lifetime of project (years).

Additionally, the Cost of Water (COW) [28] is a crucial indication that shows how much each m^3 of water produced by a RO desalination plant costs. It can be presented by [28]:

$$COW = \frac{C_{ann,RO} + COE \times \sum_{t=1}^{8760} P_{load}(t)\,\Delta t}{\sum_{t=1}^{8760} Q_{total}(t)} \quad (11)$$

where $C_{ann,RO}$ represents the total annualized cost of the desalination system in ($/year), and $\sum_{t=1}^{8760} Q_P(t)$ is the annual total of water produced on an hourly basis.

3. SIZING PV-BATTERY SYSTEM USING DIFFERENTIAL EVOLUTION ALGORITHIM

3.1 Differemtial Evolution Algorithim

Differential Evolution (DE) is a powerful heuristic algorithm used in engineering optimization for its robustness and effectiveness in single and multi-variable problems, guided by parameters like mutation factor (F) and crossover constant (CR). The four steps of DE algorithm are Initialization, Mutation, Crossover, and Selection.

In DE algorithm, the final step involves fitness evaluation, which measure solution quality based on the desired outcome. The best fitness value is stored for termination. Figure 2 illustrate the DE algorithim steps from the initialization to termination based on a consistent fitness level in a visual flowchart.

3.2 Optimzation function and constraints

The objective is to minimize the COE and COW of a PV- battery system for RO desalination while satisfying constraints on the PV panels, batteries, energy output, and $PSSP$, It is figuratively expressed as:

$$P_{pv}(t)\Delta t + B_{SOC}(t) \geq P_{load}(t)\,\Delta t \quad (12)$$

$$PSSP \leq PSSP_{min} \quad (13)$$

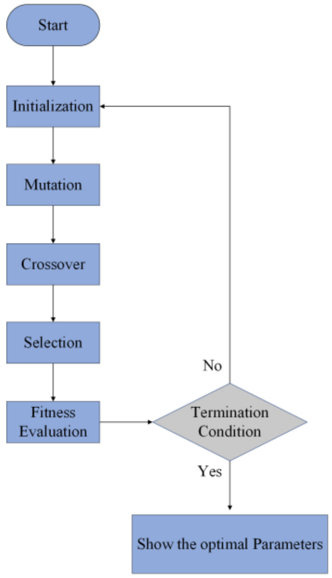

Fig. 2. Flowchart of Differential Evolution Algorithim phases

$PSSP_{min}$ is the minimum allowable Power Supply Shortage Probability which set to be zero in this study.

MATLAB was used for developing the mathematical model for the PV-Battery system for RO desalination. After that, the DE method was used to determine the optimal number of PV panels and batteries that minimize the COE and COW while satisfying the requirements for the PV panels, batteries, power output, and PSSP.

4. RESULT AND DISCUSION

In this study, The DE algorithm was used to optimize PV-Battery configurations, providing a constant 1 k load for an RO desalination system while ensuring a zero $PSSP$ constraint.

With PSSP set to zero Figure 3 illustrates the convergence curve of the DE algorithm, revealing its progress in searching for the optimal system configuration. After approximately 33 iterations, the curve reaches a convergence point where the Cost of Energy (COE) stabilizes at $0.425/kWh. Beyond this point, COE doesn't decrease further, indicating the discovery of an optimal and stable solution. This optimal configuration includes 31 PV panels, and 15 batteries to meet the energy and water production requirements of the RO unit while minimizing costs. Figure 4 shows the variation in sunshine causes the power produced to change throughout the day. But having a battery storage system allows for the storage of extra energy during times of high production for usage at a later time when energy creation is lower. The graph also shows the overall amount of power needed to run a 1 kW Reverse Osmosis (RO) desalination plant. Throughout the year, this consumption is shown as a steady value. Figure 5a presents the daily performance of the system, focusing on state of charge (loc) and excess power utilization.

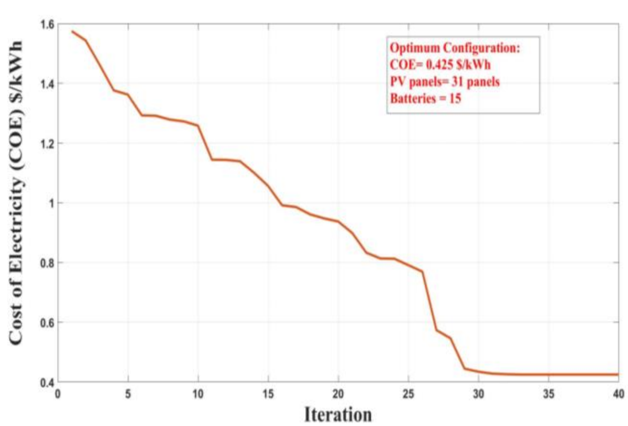

Fig. 3. DE Convergence Curve of Optimization Process for Optimal System Configuration.

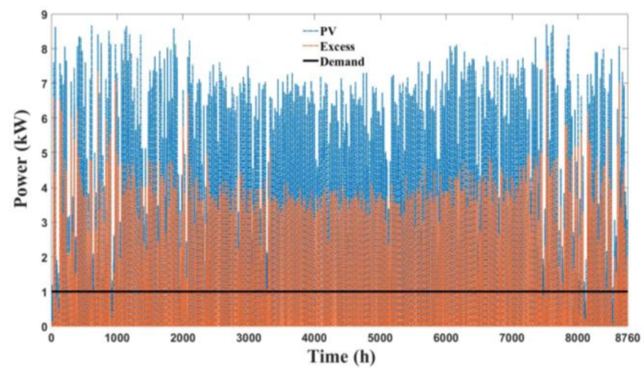

Fig. 4. Hourly power production and served to RO from the optimum PV system with battery storage configuration. during one year.

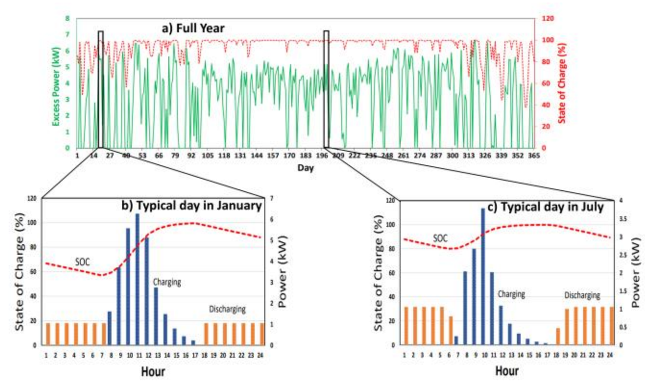

Fig. 5. Performance of the Optimized PV-Battery in terms of SOC and Excess Power, a) daily performance during one year, b) Hourly Charging and Discharging of battery with SOC: Typical Day in January, and c) Hourly Charging and Discharging of battery with LOC: Typical Day in July.

During winter, soc steadily declines, nearing the minimum for the battery storage, while in summer, it fluctuates between 70% to 100%. Excess power for pv varies depending on pv production and soc for battery. In figure 5b (representative january day), the state of charge (soc) fluctuates throughout the day, reaching its lowest point during nighttime when solar radiation is absent. Conversely, figure 5c (typical july day) illustrates soc variations, with soc consistently higher and reaching its peak during daylight hours. Winter days require more discharging operation due to limited sunlight, while summer days have shorter operating periods for battery.

Figure 6 Displays The Hourly Water Production From An Optimized Pv-Battery Powering A Reverse Osmosis (Ro) Unit. The Study's Water Demand Is 5 M^3/Day (0.208 M^3/H), With The Ro Unit Consuming 5 Kwh/M^3 And Aiming For A Daily Water Production Of 5 M^3/Day. In Figure 12.A, The Ro Unit Consistently Meets The Demand Throughout June. Figure 12.B Likely Illustrates Hourly Variations In Water Production For A Typical Day In July, Detailing Specific Hourly Ro Unit Outputs.

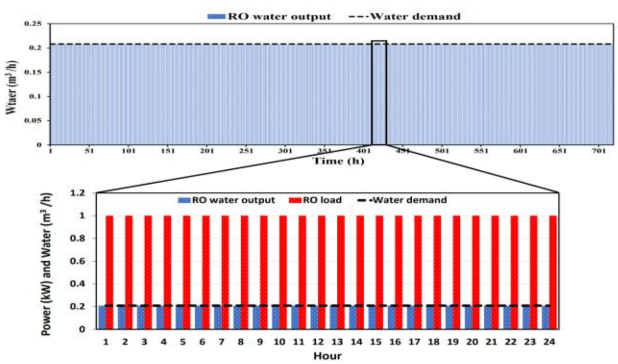

Fig. 6. Hourly Water Production and Demand Fluctuations for RO Unit Driven by Optimum PV-Battery system in: a) July, b) Typical day in July.

Figure 7 depicts the convergence pattern of the Cost of Water (COW) for different RO capital cost scenarios, with and without surplus energy sold to the grid.

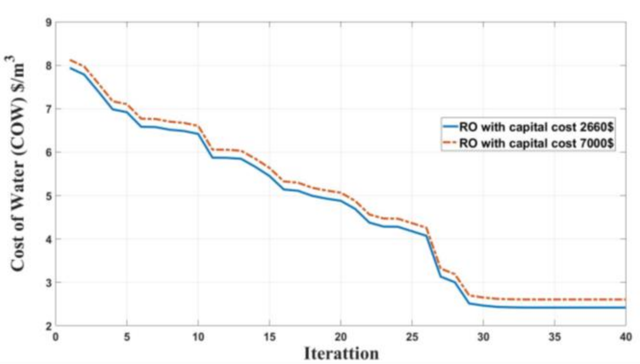

Fig. 7. Convergence of optimum Cost of Water (COW) for RO Units under Different Capital Costs.

Notably, around 33 iterations, the graph consistently shows a trend, signifying the attainment of the desired low desalinated water cost. The chart clearly indicates that RO units with capital costs ranging from $2660 to $7000 achieve optimal COW values of $2.41 to $2.6 /m^3.

5. CONCLUSIONS

In conclusion, this paper introduces an innovative approach to enhancing the efficiency and sustainability of an RO desalination system in Dhahran, Saudi Arabia, through the integration of a PV-Battery system. The utilization of a Differential Evolution (DE) algorithm for optimization, implemented in MATLAB, has resulted in a remarkably reliable system. By enforcing a loss of power probability constraint with a zero value, the system's reliability is guaranteed, paving the way for consistent performance.

The achieved 100% renewable contribution (RF) underscores the robust sustainability and environmentally friendly attributes of the optimized system. Comprising a PV generation capacity of 9.145 kW and a battery size of 64.65 kWh, this optimal configuration emerged as the pinnacle of efficiency and cost-effectiveness. With a Cost of Electricity standing at 0.425 $/kWh, the system demonstrates competitive cost parity with conventional energy sources. Notably, the Cost of Water production falls within the economically viable range of (2.41-2.6) $/m^3, solidifying its status as an economically sound water generation solution.

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DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

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