



OPEN Bio-inspired computational intelligence metaheuristic-based optimization and sensitivity analysis approach to determine techno-economic feasibility of hydrogen refueling stations for fuel cell vehicles

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This study presents a comprehensive economic and technological evaluation of renewable hybrid power systems for hydrogen refueling stations (HRS) in Nizwa, Oman, leveraging cutting-edge optimization algorithms to determine the most cost-effective and efficient hybrid energy system configurations. Three hybrid energy systems of photovoltaic-wind turbine-battery (PV-WT-B), photovoltaic-wind-fuel cell-battery (PV-WT-FC-B), and wind turbine-battery (WT-B) were evaluated based on net present cost (NPC), levelized cost of energy (LCOE), and levelized cost of hydrogen (LCOH). The study employs advanced optimization techniques, including the Mayfly Algorithm, Genetic Algorithm, CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm to determine the most viable hybrid energy system for the HRS in Nizwa. The results indicate that CPSO consistently achieves the lowest NPC, LCOE, and LCOH, whereas HS and GWO yield higher costs due to convergence inefficiencies. Sensitivity analysis reveals a strong inverse correlation between PV capacity and cost metrics, highlighting the economic advantage of increased solar generation. Additionally, hybrid configurations integrating PV and wind turbine (PV-WT-B, PV-WT-FC-B) significantly reduce NPC compared to WT-B, reinforcing the role of solar energy in optimizing economic costs. Furthermore, fuel cell integration (PV-WT-FC-B) imposes additional economic burdens, making PV-WT-B the most viable solution for HRS deployment in Oman. More so, the annual worth and return-on-investment analysis demonstrated that the PV-WT-B is the preferred energy system to meet the needs of the HRS in terms of investment. The findings underscore the importance of renewable energy fraction and capacity factor in energy economics, demonstrating that higher PV integration enhances sustainability and cost-efficiency. This study provides a transformative framework for decarbonizing Oman's transportation sector, offering insights into optimal hydrogen production strategies to advance the global clean energy transition.

Keywords Hydrogen, Solar energy, Wind energy, Renewable energy, Refueling station

List of symbols

HRS	Hydrogen refueling stations
PV	Photovoltaic
WT	Wind turbine
B	Battery
PV	Photovoltaic

FC	Fuel cell
LCOE	Levelized cost of energy
LCOH	Levelized cost of hydrogen
MA	Mayfly Algorithm
GA	Genetic Algorithm
GWO	Gray Wolf Optimizer
CPSO	Constrained Particle Swarm Optimization
HS	Harmony Search
FPA	Flower Pollination Algorithm
REF	Renewable energy fraction
CF	Capacity factor
OPWP	Oman power and water procurement
HRES	Hybrid renewable energy systems
APSR	Authority for Public Services Regulation
HOMER	Hybrid optimization model for electric renewables
NREL	National Renewable Energy Laboratory
RFC	Regenerative fuel cell
DC	Direct current
AC	Alternating current
NPC	Net present cost
n	Duration of the project
C_{ann}	Total annual costs
i	Discount rate
n	Project duration
CRF	Capital recovery factor
C_{rep}	Present cost value of the component
M_h	Amount of hydrogen produced by the electrolysis process
C_{el}	Total cost of using energy to perform electrolysis
C_{elh}	Total cost of electrolysis
$C_{u,e}$	Electrolyser unit cost
η_e	Electrolyser efficiency
CF	Capacity factor
PE_e	Electric power needed to run electrolysis
NPV	Net present value
A	Amortization
r	Yearly interest rate
t	Number of years
V_f	Final value
V_i	Initial value
C_{cap}	Capital cost
C_{op}	Operational cost
C_{fuel}	Fuel cost
E_{gen}	Total energy generated
$C_{electrolyzer}$	Cost of the electrolyzer
$C_{storage}$	Hydrogen storage cost
C_{comp}	Compression cost
$E_{renewable}$	Renewable energy generation
E_{total}	Total energy demand
GHG	Greenhouse gas
ROI	Return on investment

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The utilization of fossil fuels for energy production by human activities has resulted in a rise in global warming and the widespread occurrence of air pollution. The hazards associated with global warming are projected to escalate in the forthcoming decades and are anticipated to attain perilous thresholds if the reliance on fossil fuels persists along its present trajectory¹. Thus, allocation of resources toward the development of developing renewable energy sources to mitigate the impacts of climate change is imperative². Renewable energy sources encompass various options, including wind, solar, tidal, geothermal, and others³. In recent decades, there have been several studies performed on new technologies that enable the production of electrical energy

and hydrogen from renewable energy sources⁴. Furthermore, electrical energy and hydrogen derived from sustainable energy sources is forecast to fulfill or surpass the energy demand forecast energy demand. Therefore, exploring renewable energy sources and applications in different sectors is necessary to address the impact of climate change and provide more sustainable energy.

Oman has had significant socioeconomic progress over the past thirty years, leading to a rise in the need for electricity and the depletion of gas resources⁵. This necessitates a quantitative evaluation of the solar energy potential in the country⁵. One of Oman's visions for 2040 aims to enhance the utilization of converted renewable energy sources for power generation, while simultaneously working towards reducing greenhouse gas emissions⁶. Oman's Vision 2040 emphasizes diversifying the energy mix with an important focus on renewable energy, with a goal of reaching 30% of electricity production from renewable energy by 2030. With this in mind, the government has introduced various policies, incentives, and subsidies. Oman renewable energy strategy includes a roadmap for increasing solar and wind energy projects, and notable institutions like Oman Power and Water Procurement Company (OPWP) have offered tenders for big projects related to renewable energy. Exemption from taxation, reduced tariffs, and other fiscal incentives are offered to facilitate investments in domestic as well as overseas investments for renewable projects. Furthermore, appropriate regulation, Oman's power market, and control of the land is overseen by the Authority for Public Services Regulation (APSR)⁷. Organizations, encompassing governments, authorities, and business sectors, have joined forces to guarantee the availability of essential renewable energy resources in Oman⁸. The utilization of sophisticated renewable energy technology, concerted research, and the implementation of sound policy directions are crucial for Oman to ensure future energy security and promote sustainable growth.

Hybrid Renewable Energy Systems (HRES) are electrical energy systems that use one or more additional sources in addition to at least one renewable source⁹. Studies on HRES have become increasingly important due to the need for sustainable, efficient, and reliable energy solutions that combine multiple renewable energy sources, such as solar, wind, hydro, and biomass, with energy storage systems^{10–24}. Studies have demonstrated that hybrid energy systems have been significantly employed in the quest for sustainable and alternative energy to meet the global energy demands²⁵. Researchers^{26,27} have investigated different HRESs for several applications and results presented. Studies have also shown that there is evidence that the hybrid system's efficiency and dependability can be improved by incorporating certain components²⁸. These hybrid systems aim to address challenges like intermittency, energy storage, and optimization of power supply to meet demand. Furthermore, the effects of hybridized systems on meeting the electrical needs of different communities and applications have been thoroughly studied in the literature^{29–33}. However, the electrical energy problems that one city has may be different from another's and call for a different solution.

Hydrogen production from renewable energy sources helps reduce environmental pollution and the effects of climate change³⁴. Renewable energy sources offer a hopeful possibility for the creation of green hydrogen³⁵. Nevertheless, the hydrogen generated by using electrical energy from conventional power sources, such as nuclear power plants and thermal power plants, remains costly. To promote the production and industrialization of hydrogen and the utilization of fuel cell vehicles, it is necessary to implement various policies that focus on investing in the infrastructure for hydrogen supply. Nonetheless, performing detailed research on hydrogen generation from sustainable sources, considering the upfront capital expenditure, ongoing operational and maintenance costs, and any additional charges, is an essential undertaking to assess the viability of the hydrogen production project and requires different techniques and approaches³⁶.

A software called HOMER, which stands for a hybrid optimization model for electric renewables, was created by the National Renewable Energy Laboratory (NREL)³⁷. Applications of hybrid energy systems, techno-economic evaluations, and feasibility studies have all been modeled and investigated with the help of the HOMER software³⁷. HOMER software has also been widely used in hybrid energy systems that are either off-grid or connected to the grid³⁸. The sustainable energy-based technology developed by HOMER has reportedly seen extensive application and has the potential to provide optimal techno-economic outcomes³⁹. HOMER Pro is especially well-suited for simulating intricate hybrid systems that combine storage, hydrogen production, and renewable energy. The capacity of HOMER to manage large-scale, multi-objective optimization problems that concurrently take technological, economic, and environmental factors into account is one of its main features. A thorough examination of energy options for hydrogen refueling stations has been made possible by the HOMER's capacity to model and optimize both grid-connected and off-grid systems. The comparison of HOMER Pro with other tools has been compared and reported in the literature^{32,40}. While other tools, such as RETScreen, MATLAB Simulink, and PVSyst, offer strong capabilities in energy modeling, HOMER's unique strength lies in its optimization algorithms and sensitivity analysis features, which are specifically tailored for determining the most cost-effective design and operational strategies for energy systems⁴¹. Despite the strengths of these tools, HOMER's focus on techno-economic optimization and its comprehensive approach to hybrid energy system analysis make it particularly suitable for the study of hydrogen refueling stations. Using HOMER software, Gökçek et al.⁴² investigated the possibility of setting up an HRS to refuel 25 vehicles on the island of Gökçada in Turkey. The analysis showed that the wind-photovoltaic-battery hybrid had a lower levelized cost than the alternative energy systems. Consequently, the hybrid energy system was chosen as the best option to meet the HRS's electrical and hydrogen needs. Another study by Ayodele et al.⁴³ used HOMER software to put up a wind-powered HRS in different cities in South Africa. While the produced hydrogen had a reasonable price per kilogram (ranging from \$6.34 to \$8.97), the results demonstrated that coastal cities in South Africa offered more possibilities for wind-powered HRS locations than mainland towns. Despite multiple HOMER studies evaluating renewable energy sources' ability to power HRSs and meet electrical load requirements, the results have demonstrated that environmental factors significantly impact electrical energy and hydrogen production⁴⁴. Notwithstanding Oman's wealth of solar energy, little is known about the most often used renewable energy

sources for producing hydrogen and using it in transportation. In addition, the economic implications of producing green hydrogen in Oman from renewable resources have not been fully considered.

The novelty of this study is for Nizwa's HRS to satisfy the city's demands for producing hydrogen and electricity through renewable energy sources as a potential substitute for conventional power generation. Another objective of this study is to further aid authorities and legislators in supporting and directing resources toward hydrogen production through a techno-economic evaluation of HRS using green hydrogen produced from renewable energy sources. Additionally, this study seeks to determine the most practical energy system by assessing the viability of several sustainable energy sources for Nizwa's HRS using HOMER software. More so, this novel research study engages the HOMER software's versatility to evaluate the effectiveness of several hybrid energy systems and determine the appropriate hybrid energy system to meet the energy demand of the HRS while considering Nizwa's economic and environmental limitations. Unlike traditional optimization techniques used in HOMER, which typically rely on deterministic or basic stochastic algorithms, this novel study mimics natural processes to explore complex solution spaces through application of the cutting-edge optimization algorithms. These algorithms can potentially find better solutions and handle more nonlinear and large-scale problems in HRS design.

Study's geographical position

Nizwa is a town located in the central region of Oman, exact location at the coordinates of Latitude: 22° 55'0.0" N Longitude: 57° 32.2" E as depicted in Fig. 1.

Nizwa is one of the countries commercial hubs and Oman has developed plan to set of energy farms in the city. The distance between the capital city of Muscat and the city of Nizwa is approximately 537 km. Throughout the year, Nizwa City usually has high levels of global radiation⁴⁵. To realize Oman's 2040 goal, the advantageous location and topography of Nizwa allow for the efficient and cost-effective use of ecologically benign and sustainable renewable energy sources⁴⁶. A cleaner and more sustainable environment can be promoted by using renewable energy to reduce the community's dependency on fossil fuels.

Energy system components

A hybrid power system is a configuration where multiple types of generation sources are integrated to generate electricity^{47,48}. The energy system components include photovoltaic (PV) panels, converters, wind turbine (WT), electrolyzer, fuel cell (FC), converter, hydrogen tank, and battery (B)⁴⁹.

PV panels and converters

A flat plate PV module connected to the direct current (DC) bus was used in the project. Through the function of the inverter-connecting system, the DC electricity is converted to alternating current (AC) to be used by the electric loads⁵⁰. The PV has a lifetime of 25 years and the converter has a lifetime of 15 years. The capital,

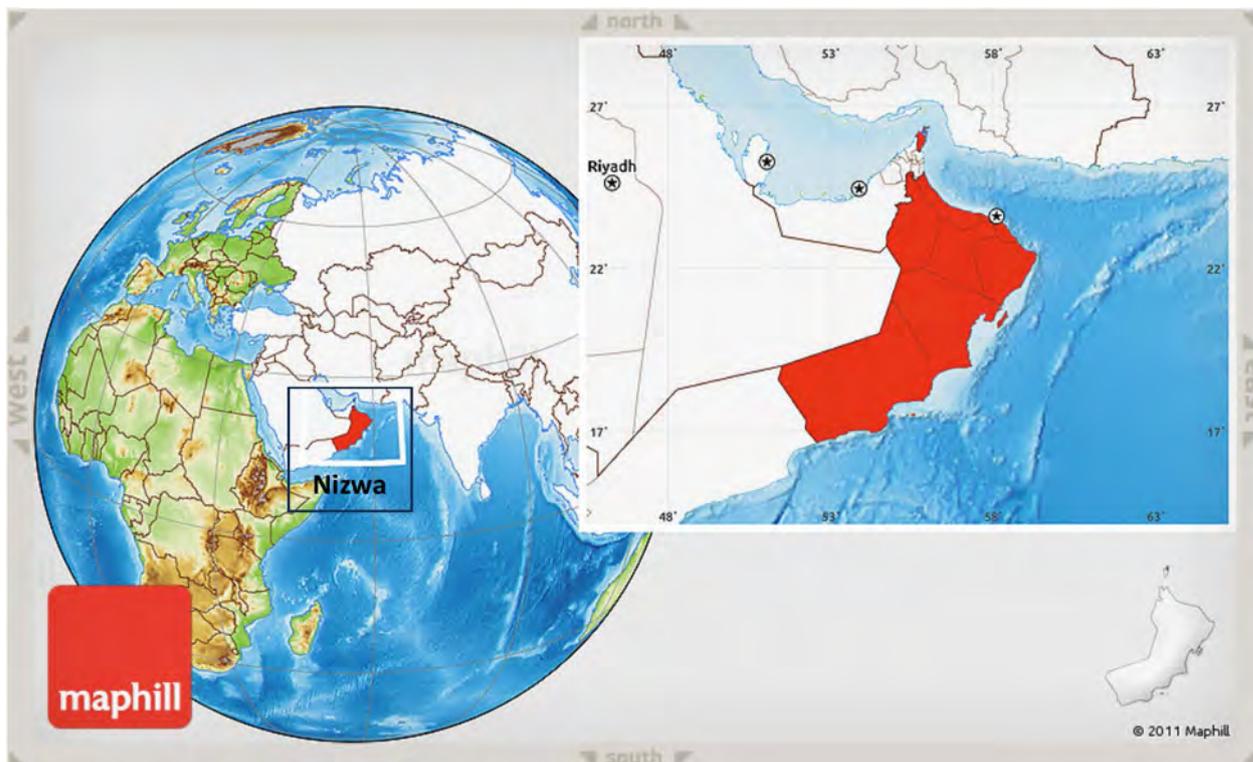


Fig. 1. The precise geographic coordinates of Nizwa in Oman.

replacement, and operation and maintenance costs of the PV are \$1200, \$1000, and \$20 per kW respectively, whereas the capital, replacement, and operation and maintenance costs of the converter are \$800, \$800, and \$10 per kW respectively.

Electrolyzer

The electrolyzer produces hydrogen through the process of electrolysis⁵¹. The chosen electrolyzer has an efficiency of 85% and a lifetime of 15 years. Upon completion of the simulation, after multiple iterations, the HOMER software determines the optimal size for the electrolyzer⁵¹. The electrolyzer costs \$/kW 2200 for capital, \$/kW 2000 for replacement, and \$/kW 50 for operation and maintenance.

Wind turbine

The wind turbine converts kinetic energy into electrical energy and the energy is used to power the electrolyzer. In the process of energy conversion, the wind turns the propeller that is connected to the shaft to generate electricity⁵². The wind turbine has capital, replacement, and operation and maintenance costs of \$/kW 1800, \$/kW 1500, and \$/kW 50 respectively.

Fuel cell

Fuel cells enable the electrochemical conversion of hydrogen generated by an electrolyzer into electrical energy. This model uses fuel cell technology as a fallback option if solar and wind energy sources are unavailable. Singla et al.⁵³ showed that a Regenerative Fuel Cell (RFC) system is frequently created by combining a fuel cell with a fuel-generating device, like an electrolyzer. This technology converts electrical energy into a fuel that can be stored and used in a fuel cell reaction to generate electricity when needed. The fuel cell used in the proposed project costs \$3500 per kW for capital, \$2500 per kW for replacement, \$5 per kW for operation and maintenance.

Hydrogen tank and battery

A hydrogen tank stores the hydrogen produced by the electrolyzer. Researchers⁵⁴ have shown that the hydrogen generated is often stored for future utilization in fuel cell-based power generation. When determining the energy storage method, the hybrid energy system considers the inclusion of a battery⁵⁵. The capital, replacement, and annual operating costs of the hydrogen tank are \$/kW 1000, \$/kW 900, and \$/kW 20. It is typical to have a battery with a lifespan of 15 years installed in a hybrid system. The capital cost, replacement cost, and annual operating cost of the battery are \$/kW 120, \$/kW 110, and \$/kW 20. This battery backs up the power source and helps alleviate the burden on the generator⁵⁶.

The technical specifications of the components used in the proposed study are displayed in Table 1.

Recourses present in the proposed project location

To perform a thorough feasibility analysis of an energy system, extensive examination of the accessible resources in the city of Nizwa in Oman is essential.

Pattern of wind velocity

Figure 2 displays the monthly average wind speed data for each location at a height of 70 m.

It can be seen in Fig. 2 that the monthly average wind speed in the city of Nizwa increased slightly from January to February. However, there was a sudden decrease from February to March before a significant increase from April to July occurred. Subsequently, the wind speed displayed a sharp decrease from July to October before a gradual increase from November to December, as shown in Fig. 2. From the data provided in Fig. 2, it is evident that the average wind speeds range from 4.54 m/s to 8.99 m/s, with the peak wind speed occurring in July. Figure 2 shows evidence that the chosen location has abundant wind speed, which can be harnessed to generate renewable hydrogen fuel for the road transport industry. Based on a detailed study by Kazem et al.⁵⁷, a location with an average wind speed of 4.99 m/s or higher is deemed appropriate for commercial wind energy generation. Consequently, the production of hydrogen will likewise fluctuate proportionally⁵⁸.

Solar radiation and clearness index

Figure 3 shows the mean monthly solar radiation obtained in the designated city of Nizwa. The statistics were obtained from the Department of Meteorology, Sultanate of Oman⁵⁹. The monthly average values over the 22 years period (1993–2015) were collected and utilized in the simulation. The data referenced from the Department of Meteorology, Sultanate of Oman, includes records of key meteorological parameters such as solar irradiance, wind speed, and temperature. From a single meteorological station in 1942, there are now

Components	Specification
PV panel	400 W—monocrystalline, generic flat plate PV with efficiency of 21%
Wind turbine	1 kW with cut-in wind speed of 5 m/s and 70 m (hub height)
Converter	1 kW microinverters with output voltage of 230 V AC (single-phase) and efficiency of 94%
Hydrogen tank	1000 kg metal hydride
Electrolyzer	1 kW PEM with efficiency of 85%
Battery	1 kWh—Lithium-Ion (Li-ion) and 6 V

Table 1. Technical specification of the system components.

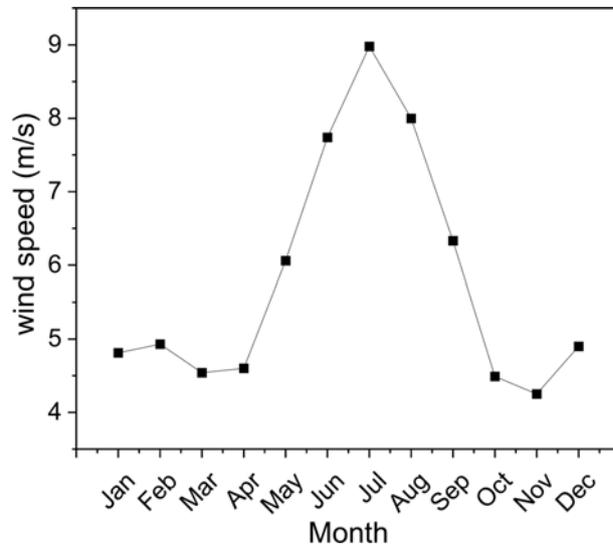


Fig. 2. Yearly wind speed in the city of Nizwa.

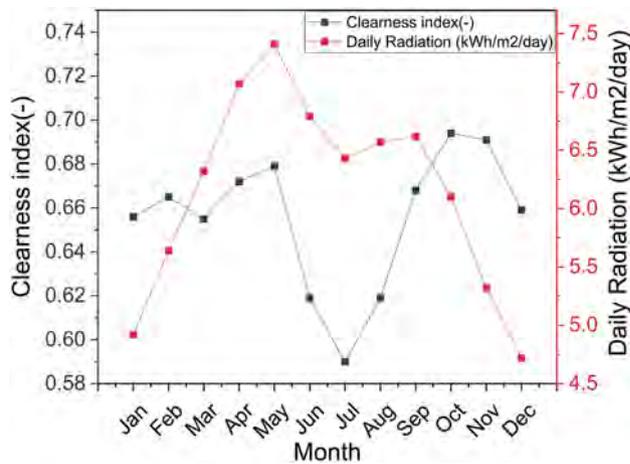


Fig. 3. Daily radiation and clearness index in the city of Nizwa.

about 20 stations in Oman, that monitor the above parameters in addition to atmospheric pressure, rainfall and evaporation. In this study data from twelve stations for the years 1993 to 2015 are compiled and analysed for ambient temperature, relative humidity, wind speed, sunshine hours and solar radiation. The data is presented as summary statistics that will provide handy reference for engineers and scientists involved in solar technology development in Oman. The mean, standard deviation, minimum and maximum values of the parameters are presented for the whole country, the twelve stations and the months of the year over the six-year period. The data have been subjected to rigorous statistical analysis to determine general weather patterns, and similarities and dissimilarities between the stations. Figure 3 displays the daily radiation and clearness index in the city of Nizwa.

The study identifies the country's climatic conditions as having a predominantly humid climate across most months of the year⁶⁰. As anticipated, there is a consistent fluctuation in monthly solar radiation as shown in Fig. 3. The HOMER software utilizes the data obtained from the coordinates of a planar surface to calculate the clearness index⁶¹. The monthly clearness index, denoting the proportion of solar energy at the earth's surface compared to that at the top of the atmosphere, ranged from 0.590 (in July) to 0.694 (in October). Riayatsyah et al.⁶¹ suggested that comprehension of a clarity index is necessary to ascertain the efficacy of solar energy in a specific area. Figure 3 shows that the monthly radiation cycle undergoes seasonal variations. Studies have revealed that multiple factors, such as precipitation, fog, wind, temperature, and sunlight, influence this phenomenon⁶². While the lowest solar radiation of 4.720 kilowatt-hours per square meter per day occurred in December, the highest radiation of 7.410 kilowatt-hours per square meter per day occurred in May with an annual average of 6.16 kilowatt-hours per square meter per day.

Temperature of the city of Nizwa

The temperature profile of the city of Nizwa is shown in Fig. 4.

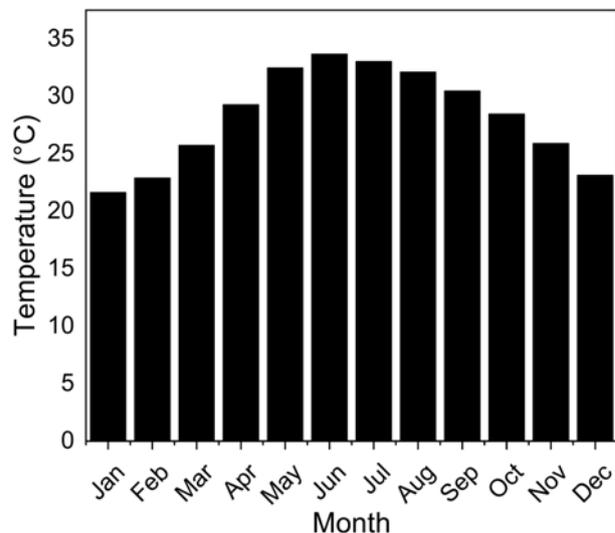


Fig. 4. The range of temperatures prevailing at Nizwa.

As displayed in Fig. 4, the peak measured temperature of 33.67 °C was recorded in June and the lowest temperature of 21.65 °C occurred in January. The HOMER software incorporates the average temperature of a specific area in its calculation of the efficiency of photovoltaic power⁶³. The solar radiation and temperature results displayed in Figs. 3 and 4 demonstrate that the productivity of sustainable renewable energy is significantly influenced by the prevailing ecological conditions. Furthermore, HOMER computes the efficiency of the PV system by considering the average temperatures specific to the local area⁶⁴.

Load specification and characterization

When developing a hydrogen refueling station (HRS), it is critical to accurately estimate costs and account for various factors, including the quantity of hydrogen to be stored and the accessibility of energy resources at the designated site. One thousand kilograms of hydrogen per day is estimated to be the utmost daily output required for implementing the HRS in the city of Nizwa. Approximately twenty fuel cell vehicles transporting personnel and students throughout Nizwa City refuel with this hydrogen. Owing to the City of Nizwa's location, it is essential to use renewable energy resources to produce a sufficient quantity of electricity and hydrogen for fueling fuel cell vehicles.

Analysis of HOMER and setup of hybrid energy system

Limitation and scope of the study

While HOMER Pro is a widely used and robust tool for energy system modeling and optimization and have been used by several researchers^{40,65,66}, this study focusses on employing the capabilities of HOMER Pro to explore the viability of establishing Hydrogen Refueling Stations for Fuel Cell Vehicles in the city of Nizwa, Oman. The study did not consider experimental or field data investigation and validation in our current study and can be ascribed to challenges of directly validating the model against real-world experimental data, particularly those utilizing fuel cell vehicle systems. More so, due to the nascent stage of hydrogen infrastructure development in this region and the complexity of operational variables, obtaining field data that can be directly compared to the outputs of the model is not always feasible. Nevertheless, the results generated by HOMER Pro have shown to provide valuable insights into the potential feasibility of hydrogen refueling stations under different scenarios, offering a foundational understanding for decision-makers and stakeholders³⁰. The use of HOMER Pro's optimization capabilities has also demonstrated that the model is grounded in recognized engineering and economic principles. Hence, this study will investigate the feasibility of setting up hydrogen refueling stations for fuel cell vehicles in the city of Nizwa, Oman, using HOMER Pro's capabilities and optimizing the result with selected advanced optimization tools.

Methodology and hybrid energy configuration

Optimization tools like Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm (FPA) are essential for hybrid energy optimization due to the complex and multi-faceted nature of hybrid energy systems. These systems combine renewable and conventional energy sources, requiring optimization techniques to balance various objectives such as minimizing cost, maximizing energy efficiency, and reducing emissions.

These algorithms are particularly useful because they can handle nonlinearities, multiple objectives, and constraints within hybrid energy systems, ensuring feasible and optimal solutions. They provide the ability to perform global exploration and local exploitation, allowing for fast convergence to high-quality solutions.

Optimization methods like CPSO and GWO are effective in navigating complex solution spaces, handling multiple constraints (e.g., energy production limits, budget, and system reliability).

Additionally, algorithms such as GA, FPA, and HS are adaptable, flexible, and scalable, allowing them to be customized for different system configurations and scenarios, including varying renewable resources and storage capacities. Their efficiency and scalability make them ideal for real-time optimization, ensuring cost-effective and reliable solutions across a wide range of hybrid energy systems. Ultimately, these optimization tools are crucial for improving the performance, efficiency, and sustainability of hybrid energy systems in an increasingly complex energy landscape.

The optimization tools—Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search (Cuckoo Search), Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm (FPA)—each exhibit distinct convergence behaviors when applied to complex optimization problems such as the HRS. While MA offers fast convergence by balancing exploration and exploitation, but may slow down in highly constrained problems, GA is robust and versatile but tends to converge more slowly, especially in high-dimensional or complex systems, and may face premature convergence. The CUKO Search excels in global exploration with Lévy flights and converges well but can require more iterations in complex scenarios compared to others. The GWO converges quickly in simpler problems but may struggle with complex landscapes, potentially getting trapped in local optima, while the CPSO is well-suited for constrained optimization problems, converging faster than standard PSO and maintaining feasibility while optimizing performance. Generally, HS generally has slower convergence rates, especially in large-scale or complex systems, but is effective in multi-objective optimization. The FPA optimization tool converges relatively fast into simpler problems but can experience slower convergence in more complex or nonlinear environments. Selectively, the choice of algorithm depends on the problem's complexity, dimensionality, and need for constraint handling.

Parameter setting for optimization algorithms

In the optimization, the population size and number of iterations were adjusted for more efficient exploration and exploitation of the solution space. The combination was performed to improve robustness and convergence of optimization.

The summary of the parameter settings for optimizing HOMER Pro results with each of the algorithms are shown below.

1. Mayfly Algorithm (MA)

- Population Size (N): 30 to 60
- Generations (G): 200 to 500
- Cognitive Component (c1): 1.5 to 2.0
- Social Component (c2): 1.5 to 2.0
- Inertia Weight (ω): 0.7 to 0.9
- Velocity Limit (v_{max}): 0.1 to 1.0
- Mutation Rate (μ): 0.05 to 0.1
- Reproduction Probability (P): 0.8 to 1.0

2. Genetic Algorithm (GA)

- Population Size (N): 50 to 100
- Generations (G): 100 to 500
- Crossover Probability (Pc): 0.7 to 0.9
- Mutation Probability (Pm): 0.01 to 0.05
- Selection: Tournament or Roulette Wheel
- Elitism: 2 to 5

3. CUKO Search (Cuckoo Search)

- Population Size (N): 20 to 50
- Generations (G): 200 to 1000
- Discovery Probability (Pa): 0.25 to 0.5
- Step Size (α): 0.1 to 0.3
- Levy Flight Exponent (λ): 1.5

4. Gray Wolf Optimizer (GWO)

- Population Size (N): 30 to 50
- Iterations (T): 100 to 500
- C1, C2, C3: 1.5 to 2.0
- Inertia Weight (ω): 0.5 to 1.0
- Leadership Hierarchy (α, β, δ): 0.5 to 1.0

5. Constrained Particle Swarm Optimization (CPSO)

- Population Size (N): 30 to 60
- Iterations (T): 100 to 500

- Cognitive Component (c_1): 1.5 to 2.0
 - Social Component (c_2): 1.5 to 2.0
 - Constriction Factor (κ): 0.5 to 1.0
 - Penalty Parameter (β): 0.1 to 1.0
6. Harmony Search (HS)
- Population Size (N): 30 to 60
 - Iterations (T): 100 to 1000
 - Harmony Memory Size (HMS): 20 to 50
 - Harmony Memory Considering Rate (HMCR): 0.7 to 1.0
 - Pitch Adjusting Rate (PAR): 0.1 to 0.5
 - Bandwidth (BW): 0.1 to 0.5
7. Flower Pollination Algorithm (FPA)
- Population Size (N): 20 to 50
 - Iterations (T): 100 to 500
 - Step Size (β): 0.1 to 0.5
 - Pollination Probability (p): 0.2 to 0.8
 - Global Search Probability (p_g): 0.2 to 0.5
 - Scaling Factor (μ): 0.1 to 1.0

Sensitivity analysis derivatives for optimization algorithms

Sensitivity analysis measures how an optimization model's output reacts to variations in its input parameters. Sensitivity analysis aids in determining how responsive the performance of each optimization method is to variations in particular parameters, including population size, mutation rate, and convergence criteria. The following succinctly explains how each algorithm can benefit from sensitivity analysis:

1. Mayfly Algorithm (MA)

- Sensitivity Derivatives:
- Population Size (N): While a larger population may yield better results, it also raises the cost of computing. Sensitivity analysis aids in weighing the trade-off between computing efficiency and solution quality.
- Sensitivity to the Inertia Weight (ω) parameter shows how successfully the algorithm strikes a balance between exploitation and exploration. Exploration is favored by higher ω values, whereas exploitation is favored by lower values.
- Mutation Rate (μ): Diversity is determined by the rate of mutation. Sensitivity analysis demonstrates the algorithm's capacity to prevent premature convergence and how sensitive it is to fresh solutions.

2. Genetic Algorithm (GA)

- Sensitivity Derivatives:
- Crossover Probability (P_c): While a larger crossover rate could boost diversity, it might also make it harder for the algorithm to improve the answer. Sensitivity analysis aids in figuring out the best pace for searching the space.
- Mutation Probability (P_m): Although it may interfere with convergence, a higher mutation rate can support diversity. Sensitivity analysis demonstrates the impact of varying mutation probabilities on performance.
- Population Size (N): While a bigger population raises computing costs, it also improves solution quality. Sensitivity analysis aids in maximizing the harmony between effectiveness and quality.

3. Cuckoo Search (Cuckoo Search)

- Sensitivity Derivatives:
- Discovery Probability (P_a): This parameter controls the likelihood of exploration via Lévy flights. Sensitivity analysis reveals how exploration vs. exploitation affects convergence speed.
- Step Size (α): Sensitivity to this parameter indicates how much the search space is adjusted during each step, affecting convergence speed and solution quality.
- Levy Flight Exponent (λ): The sensitivity of the algorithm to this parameter shows how the randomness of step sizes influences the exploration of the search space.

4. Gray Wolf Optimizer (GWO)

- Sensitivity derivatives:
- C_1 , C_2 , C_3 (Coefficients): These parameters influence the balance between exploration (global search) and exploitation (local search). Sensitivity analysis determines the effect of these coefficients on convergence speed and solution quality.
- Population Size (N): Larger populations increase diversity but can slow down convergence. Sensitivity analysis helps find the ideal population size.
- Inertia Weight (ω): Affects the search behavior, with higher ω favoring exploration and lower ω favoring exploitation. Sensitivity analysis determines the optimal value for effective search.

5. Constrained Particle Swarm Optimization (CPSO)

- Sensitivity Derivatives:
- Constriction Factor (κ): This controls particle velocity and impacts convergence. Sensitivity analysis shows how κ affects stability and convergence speed.
- Penalty Parameter (β): In CPSO, the penalty parameter helps enforce constraints. Sensitivity analysis identifies how sensitive the algorithm is to constraint handling and whether the solution is feasible.
- Cognitive and Social Components (c_1, c_2): These parameters affect the balance between local and global search. Sensitivity analysis helps optimize exploration vs. exploitation trade-off.

6. Harmony Search (HS)

- Sensitivity Derivatives:
- Harmony Memory Considering Rate (HMCR): Higher HMCR values lead to more exploitation of the current best solution. Sensitivity analysis shows how it affects convergence speed and solution quality.
- Pitch Adjusting Rate (PAR): Controls the ability to refine solutions. Sensitivity analysis identifies how the rate affects exploration of the solution space.
- Bandwidth (BW): Controls the variation in pitch adjustment. Sensitivity analysis helps determine how changes in BW impact solution quality.

7. Flower Pollination Algorithm (FPA)

- Sensitivity Derivatives:
- Step Size (β): This parameter controls the distance between solutions. Sensitivity analysis shows how different step sizes influence the algorithm's ability to explore the search space and converge.
- Pollination Probability (p): This affects the likelihood of global vs. local search. Sensitivity analysis indicates how different values of p impact the search balance.
- Global Search Probability (p_g): Sensitivity analysis reveals how the algorithm behaves with different probabilities of global exploration versus local refinement.

HOMER Pro system design

Figure 5 depicts the hybrid configuration proposed and implemented in the Homer simulation software.

The system further consists of the electrolyzer, hydrogen tank, converter, and electric and hydrogen loads, as shown in Fig. 5. The PV and WT are designed to provide electrical power to the load in the arrangement. Nevertheless, if electricity produced surpasses the amount needed by the refueling station, the surplus energy is utilized to recharge the storage batteries that provide electricity to the refueling station when the demand for power demand exceeds the amount produced. The choice of each hybrid configuration is contingent upon its contribution and economic feasibility. HOMER optimizes the system components' sizes to find the hybrid energy system with the lowest levelized cost of energy (LCOE) or net present cost (NPC)⁶⁷. The most optimal hybrid energy system is chosen based on cost evaluation, data analysis on energy resources, energy loads, system size, and cost parameters for each component.

In HOMER Pro, a software tool used for optimizing microgrids and energy systems, load scheduling is an essential function for optimizing the energy consumption, system reliability, and cost-effectiveness of hybrid renewable energy systems (HRES). HOMER Pro allows for the integration of different dispatch strategies and the consideration of deferrable load sections to optimize how electricity is distributed, particularly in systems with variable renewable energy sources like solar or wind. These strategies are essential in ensuring that the energy system operates at peak efficiency while meeting the demands of users. The HOMER has two different modes of load scheduling⁶⁸. The dispatchable load scheduling approach was employed in this study so that certain loads can be considered flexible and can be controlled or dispatched in response to the availability of energy from different sources^{69,70}. Furthermore, the loads can be adjusted in real-time based on the needs of the system, the availability of renewable resources, and the system's operational constraints. The flow chart of the feasibility study is shown in Fig. 6.

Techno-economic performance

Economic evaluation

Economic appraisal takes the time value of money into account by reducing the value of future cash flow to their current worth. Techno-economic feasibility study is frequently used in the process of making financial judgments on whether a project is profitable and feasible.

The NPC offers decision-makers a quantifiable metric for evaluating and comparing various initiatives or investment opportunities. The economic parameter aids in evaluating the economic feasibility of projects by considering the concept of the time value of money and offering a holistic perspective on the associated costs and benefits⁶⁷. The calculation of NPC is performed using the following formula:

$$NPC = \frac{C_{ann}}{CRF(i, n)} \quad (1)$$

The variable " C_{ann} " represents the hybrid power production system's total annual costs (\$/year). While " i " is the discount rate, " n " denotes the project duration in years (years). The capital recovery factor, often known as CRF, is calculated using Eq. 2⁶⁷.

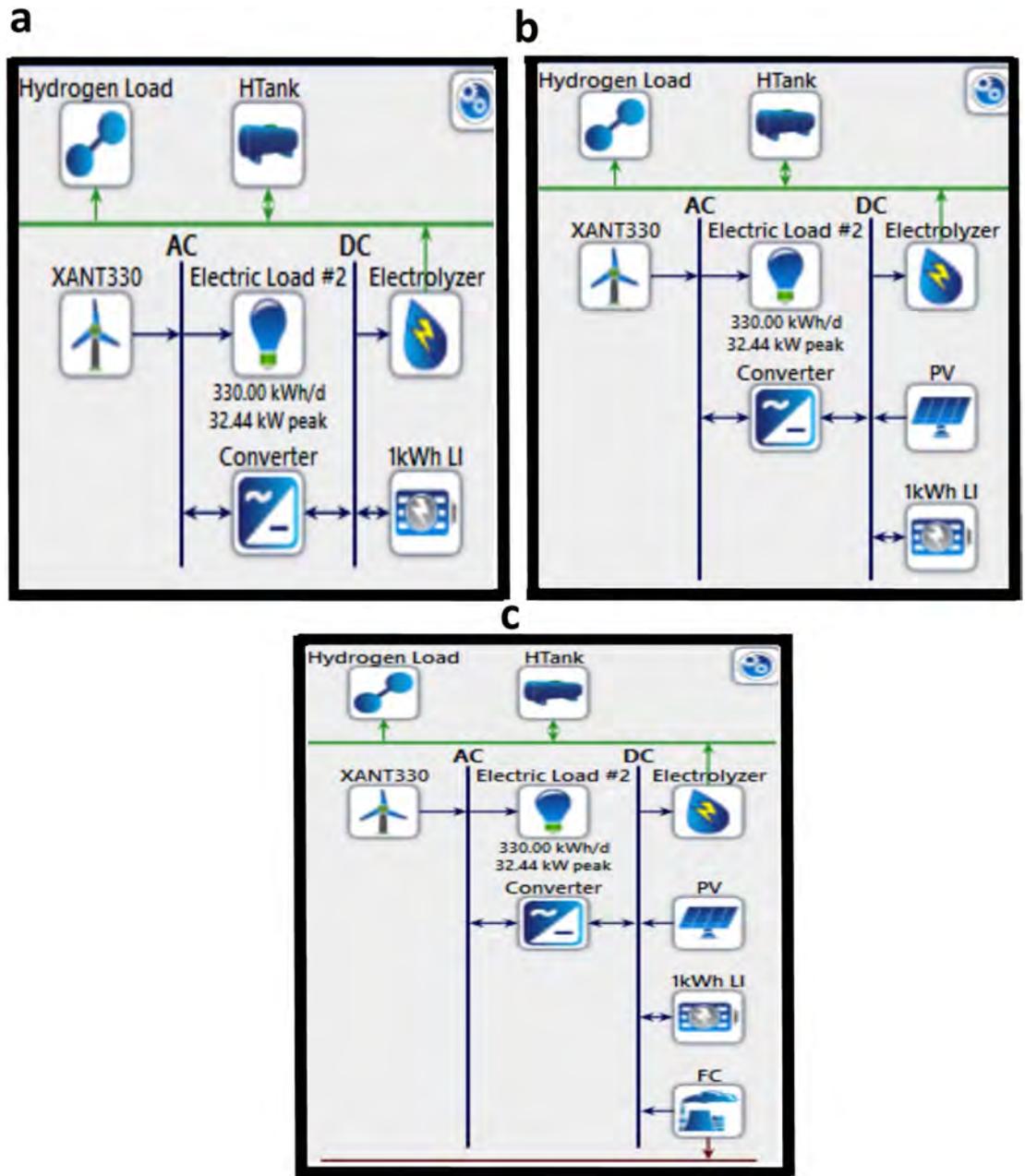


Fig. 5. Hybrid configuration (a) wind turbine (WT) combined with battery (B), (b) wind turbine (WT), photovoltaic (PV), and battery, and (c) photovoltaic (PV) combined, wind turbine (WT), fuel cell (FC), combined with battery (B).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

The actual discount rate is used to convert annual expenses. The subsequent Eq. 3 can be utilized to derive the actual discount rate⁷¹:

$$i = \frac{i^1 - f}{1 + f} \tag{3}$$

In Eq. 3, the variable “f” represents the assumed inflation rate, whereas “i” represents the nominal discount rate. The analysis establishes the inflation and discount rates at 2% and 8%, respectively.

The LCOE is computed by dividing the total annual cost by the total amount of energy the system produces in a given year. Equation 4 represents LCOE⁶⁷.

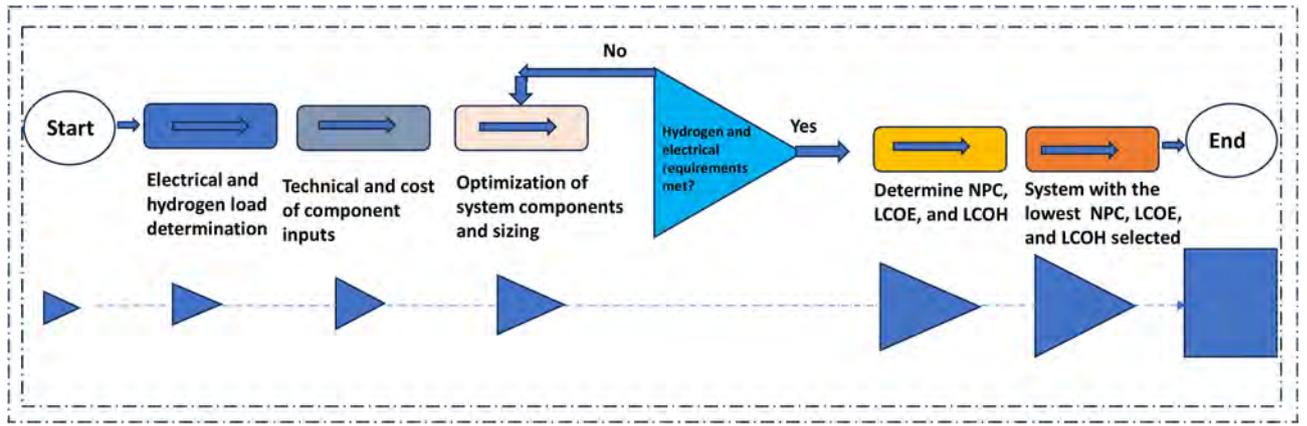


Fig. 6. Flow chart of the proposed study.

$$LCOE = \frac{C_{ann}}{E_s} \tag{4}$$

where E_s represents the quantity of electrical energy generated, measured in kilowatt-hours per year (kWh/year). Due to the varying lifespans of certain components in the HRS, replacement is necessary within the project’s duration. Equation 5 determines the yearly replacement costs⁶⁷.

$$C_{rep} = CRF \frac{C_{rep}}{(1 + i)^t} \tag{5}$$

The variable C_{rep} represents the present cost value of the component, whereas t represents the year of replacement.

When considering the viability of a hydrogen project, the levelized cost of hydrogen (LCOH) is another important factor to consider. By applying Eq. 6, we may determine the LCOH.

$$LCOH = \frac{C_{elh} + C_{el}}{\sum_1^t M_h} \tag{6}$$

The variable “ t ” here stands for the temporal duration, in this case, the lifespan of electrolyzers. “ M_h ” denotes the amount of hydrogen produced by the electrolysis process, expressed in kilograms. “ C_{el} ” indicates the total cost of using energy to perform electrolysis following Eq. 7.

$$C_{el} = LCOE_h \times \frac{\sum_1^t EWT_i}{t} \tag{7}$$

Furthermore, “ C_{elh} ” is the total cost of electrolysis, which may be calculated using Eq. 8.

$$C_{elh} = C_{u,e} \times \frac{M_h + PE_e}{t \times CF \times \eta_e \times 8760} \tag{8}$$

Some factors influence the levelized cost of electricity used to produce hydrogen, abbreviated as $LCOE_h$. Electrolyser unit cost (represented as $C_{u,e}$), electrolyser efficiency (represented as η_e), total electricity obtained after the year (measured in kilowatt-hours) (referred to as EWTi), capacity factor (represented as CF), and electric power needed to run electrolysis (represented as PE_e) are some of these important factors (measured in kilowatts)⁷².

The utilization of annual worth analysis is crucial in understanding a project’s financial condition and progress. Regular assessment of a project’s net value aids in identifying feasible projects and tracking progress towards financial goals and objectives. Equations 9 and 10 can be used to compute the annual worth and return on investment of the projects.

$$\text{Annual worth} = \frac{NPV}{A_{t,r}} \tag{9}$$

where A stands for annual interest rate and NPV for net present value. The capital recovery (amortization) factor is denoted by A , the yearly interest rate by r , and the number of years by t .

$$\text{Return on Investment} = \frac{V_f - V_i}{V_i} \tag{10}$$

where the dividends V_t implies the final value and V_i means the initial value invested in the project.

Validation of techno-economic performance using bio-inspired computational intelligence metaheuristic optimization algorithms and sensitivity analysis functions

Several studies on optimization algorithms in hybrid energy systems focusing on improving the efficiency, reliability, and cost-effectiveness of integrating multiple renewable energy sources have been performed by researchers^{40,73–77}. Different algorithms have been employed to optimize the operation, sizing, and dispatch of energy systems to meet varying demands while minimizing costs and increasing efficiency^{78–85}. In this study, a Python program was employed to execute the methodology for evaluating the techno-economic performance of hydrogen refueling stations (HRS) that utilize photovoltaic-wind hybrid energy systems with battery storage. Although other optimization tools have been used to study different hybrid energy systems, this approach integrates bio-inspired computational intelligence metaheuristic optimization algorithms (Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm (FPA)) and sensitivity analysis functions to assess cost-effectiveness and operational efficiency for different hybrid system configurations (PV-WT-FC-B, PV-WT-B, and WT-B). In contrast to HOMER's conventional optimization methods, which usually depend on deterministic or simple stochastic algorithms, the bio-inspired Computational Intelligence Metaheuristic-Based Optimization and Sensitivity Analysis approach explores complex solution spaces by simulating natural processes. These algorithms can potentially find better solutions and handle more nonlinear and large-scale problems in HRS design. By including sensitivity analysis, the study provides a deeper understanding of the system's robustness and helps identify critical parameters that influence the feasibility of HRS, which was often limited in earlier HOMER-based studies.

The Net Present Cost (NPC) is defined as follows:

$$NPC = \sum \frac{C_t}{(1+r)^t} \quad (11)$$

where C_t is the total cost at year t , and r is the discount rate, quantifies the lifetime economic feasibility of the system.

The Levelized Cost of Energy (LCOE), calculated using:

$$LCOE = \sum \frac{(C_{cap} + C_{op} + C_{fuel})}{\sum E_{gen}} \quad (12)$$

where C_{cap} is capital cost, C_{op} is operational cost, C_{fuel} is fuel cost, E_{gen} is total energy generated, assesses the economic viability of energy generation.

The Levelized Cost of Hydrogen (LCOH) is determined by:

$$LCOH = \sum \frac{(C_{electrolyzer} + C_{storage} + C_{comp})}{\sum H_2} \quad (13)$$

where $C_{electrolyzer}$ is the cost of the electrolyzer, $C_{storage}$ is hydrogen storage cost, C_{comp} is compression cost, and H_2 is the total hydrogen produced.

The renewable energy fraction (REF) is evaluated as:

$$REF = \frac{E_{renewable}}{E_{total}} \quad (14)$$

where $E_{renewable}$ is renewable energy generation, and E_{total} is the total energy demand. The capacity factor (CF) is given as:

$$CF = \frac{E_{actual}}{E_{rated} \times T} \quad (15)$$

where E_{actual} is actual energy output, E_{rated} is the rated power capacity, and T is total operational time.

The sensitivity analysis examines the impact of key design parameters, including PV capacity, wind turbine count, and battery storage, using sensitivity functions such as:

$$\frac{\partial NPC}{\partial PV}, \quad \frac{\partial LCOE}{\partial PV}, \quad \frac{\partial LCOH}{\partial PV} \quad (16)$$

$$\frac{\partial NPC}{\partial WT}, \quad \frac{\partial LCOE}{\partial WT}, \quad \frac{\partial LCOH}{\partial WT} \quad (17)$$

$$\frac{\partial NPC}{\partial B}, \quad \frac{\partial LCOE}{\partial B}, \quad \frac{\partial LCOH}{\partial B} \quad (18)$$

Partial derivatives indicate the rate of change in cost metrics resulting from fluctuations in system components. Optimization algorithms such as the Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and

Flower Pollination Algorithm (FPA) are utilized to determine the most economically and operationally feasible configurations. These bio-inspired computational intelligence metaheuristic optimization algorithms were used to determine and compare NPC, LCOE, and LCOH across various configurations, elucidating essential trade-offs and cost-reduction measures.

Results and discussion

Identifying the most efficient performance for individual components in a certain system depends on the distinct characteristics and qualities displayed by that system⁸⁶. Research has demonstrated that the optimization of the system is important to ascertain the most feasible energy system for the proposed project⁸⁷.

Optimization of the hybrid energy systems

The optimization method entailed thoroughly investigating all possible combinations of system components for the feasible production of energy and hydrogen. Table 2 presents the optimized outcomes from the three energy systems.

For the proposed HRS in Nizwa, the combination denoted as “2” in Table 2 is thought to be the best option for supplying the system’s electrical energy needs and generating the necessary quantity of hydrogen while lowering expenses. In comparison to all other energy systems, combination 2 is clearly the most cost-effective, as indicated by the numbers in Table 2. This is evident from the sharp declines in key economic metrics that are used to assess the viability of a renewable energy project, including NPC, LCOE, and LCOH⁸⁸.

The PV-WT-B energy system from combination 2 has the lowest NPC, LCOE, and LCOH values, which are \$33,618.44, \$0.02067 per kWh, and \$0.626 per kg, respectively. Similarly, the NPC, LCOE, and LCOH of the PV-WT-B energy system show that combination 2 performs noticeably better than the other three combinations of the PV-WT-B energy system. Thus, combination 2 in the PV-WT-B energy system is the most economically viable choice and is considered as the best choice for the city of Nizwa’s hydrogen refueling programme.

Figure 7 illustrates a state-of-the-art optimization analysis for a hydrogen refueling station (HRS) that incorporates a photovoltaic-wind hybrid energy system with battery storage, utilizing seven sophisticated metaheuristic algorithms: Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm (FPA).

Figure 7 consists of three separate subplots, each representing a single hybrid system configuration—PV-WT-FC-B, PV-WT-B, and WT-B—assessing their performance based on Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Levelized Cost of Hydrogen (LCOH). The findings demonstrate that CPSO regularly attains the lowest NPC, LCOE, and LCOH, establishing it as the most economical optimization method. Conversely, Harmony Search (HS) and Gray Wolf Optimizer (GWO) incur elevated costs, indicating constraints in convergence efficiency for this application. The result is attributed that CPSO generally achieves the lowest cost values faster than both GWO and HS due to its strong ability to handle constraints and balance exploration and exploitation, making it more efficient in terms of convergence speed. More so, GWO and HS can also achieve competitive solutions, but CPSO typically converges more quickly to optimal or near-optimal solutions in cost optimization scenarios. The optimization tools, MA, GA, CUKO, GWO, CPSO, HS, and FPA—each exhibit distinct convergence behaviors when applied to complex optimization problems such as the HRS. While MA offers fast convergence by balancing exploration and exploitation, but may slow down in highly constrained problems, GA is robust and versatile but tends to converge more slowly, especially in high-dimensional or complex systems, and may face premature convergence. The CUKO Search excels in global exploration with Lévy flights and converges well but can require more iterations in complex scenarios compared to others. The GWO converges quickly in simpler problems but may struggle with complex landscapes, potentially getting trapped in local optima, while the CPSO is well-suited for constrained optimization problems, converging

Hybrid system	Combination	System components							NPC (\$)	LCOE \$/kWh	LCOH \$/kg
		PV (kW)	WT (330 kW)	Electrolyzer (kW)	Hydrogen tank (kg)	Battery (1 kWh LA)	Fuel cell (250 kW)	Converter (kW)			
PV-WT-FC-B	1	1200	1	1	1000	120	1	800	33,902.21	0.02214	0.8712
	2	1200	1	2	1000	120	1	800	33,888.81	0.02178	0.8590
	3	1200	2	3	1000	100	1	800	34,115.02	0.02295	0.8853
	4	1200	2	4	1000	100	1	800	34,279.54	0.02311	0.8960
PV-WT-B	1	1000	2	1	1000	120	–	800	33,914.90	0.02186	0.6341
	2	1000	2	2	1000	120	–	800	33,618.44	0.02074	0.6263
	3	1000	1	3	1000	100	–	800	34,176.00	0.02192	0.6452
	4	1000	1	4	1000	100	–	800	34,280.43	0.02203	0.6576
WT-B	1	–	2	1	1000	120	–	800	36,505.58	0.02590	0.8703
	2	–	2	2	1000	120	–	800	36,421.39	0.02339	0.8625
	3	–	1	3	1000	100	–	800	36,911.81	0.02413	0.8865
	4	–	1	4	1000	100	–	800	37,013.11	0.02429	0.8912

Table 2. The optimization results of hybrid energy systems.

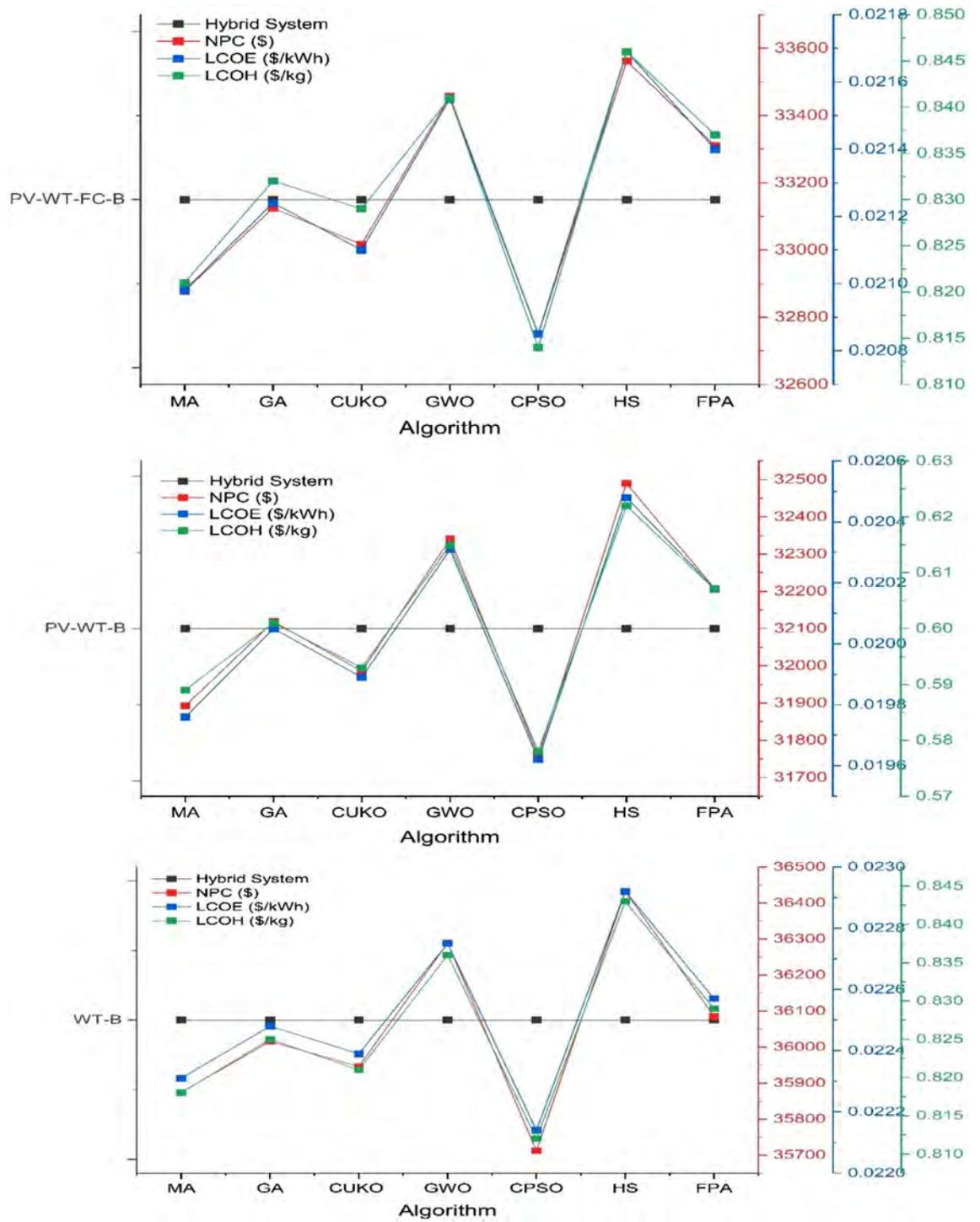


Fig. 7. Optimization of hybrid energy systems.

faster than standard PSO and maintaining feasibility while optimizing performance. Generally, HS generally has slower convergence rates, especially in large-scale or complex systems, but is effective in multi-objective optimization. The FPA optimization tool converges relatively fast into simpler problems but can experience slower convergence in more complex or nonlinear environments. Selectively, the choice of algorithm depends on the problem's complexity, dimensionality, and need for constraint handling. The patterns observed in Fig. 7 underscore the relationship between algorithmic efficiency and renewable energy integration, indicating that hybrid systems incorporating fuel cells (PV-WT-FC-B) impose a greater economic burden than PV-WT-B due to the supplementary expenses associated with fuel cell integration. The multi-axis graphic (Fig. 7) clearly illustrates the comparative effectiveness of each algorithm across many cost metrics, providing a comprehensive evaluation framework for the design and optimization of next-generation HRS. This novel methodology establishes the

groundwork for sustainable, high-efficiency hydrogen refueling infrastructure, essential for promoting green energy transition initiatives.

Figure 8 illustrates a precise sensitivity analysis assessing the influence of photovoltaic (PV) capacity (kW) on Net Present Cost (NPC), Levelized Cost of Energy (LCOE), and Levelized Cost of Hydrogen (LCOH) for three innovative hybrid system configurations: PV-WT-FC-B, PV-WT-B, and WT-B.

The sensitivity analysis indicates a distinct inverse correlation between PV capacity and cost metrics, showing that an increase in PV capacity results in a substantial decrease in NPC, LCOE, and LCOH, underscoring the economic advantages of augmenting solar generation in hybrid renewable energy systems. Figure 8 illustrates

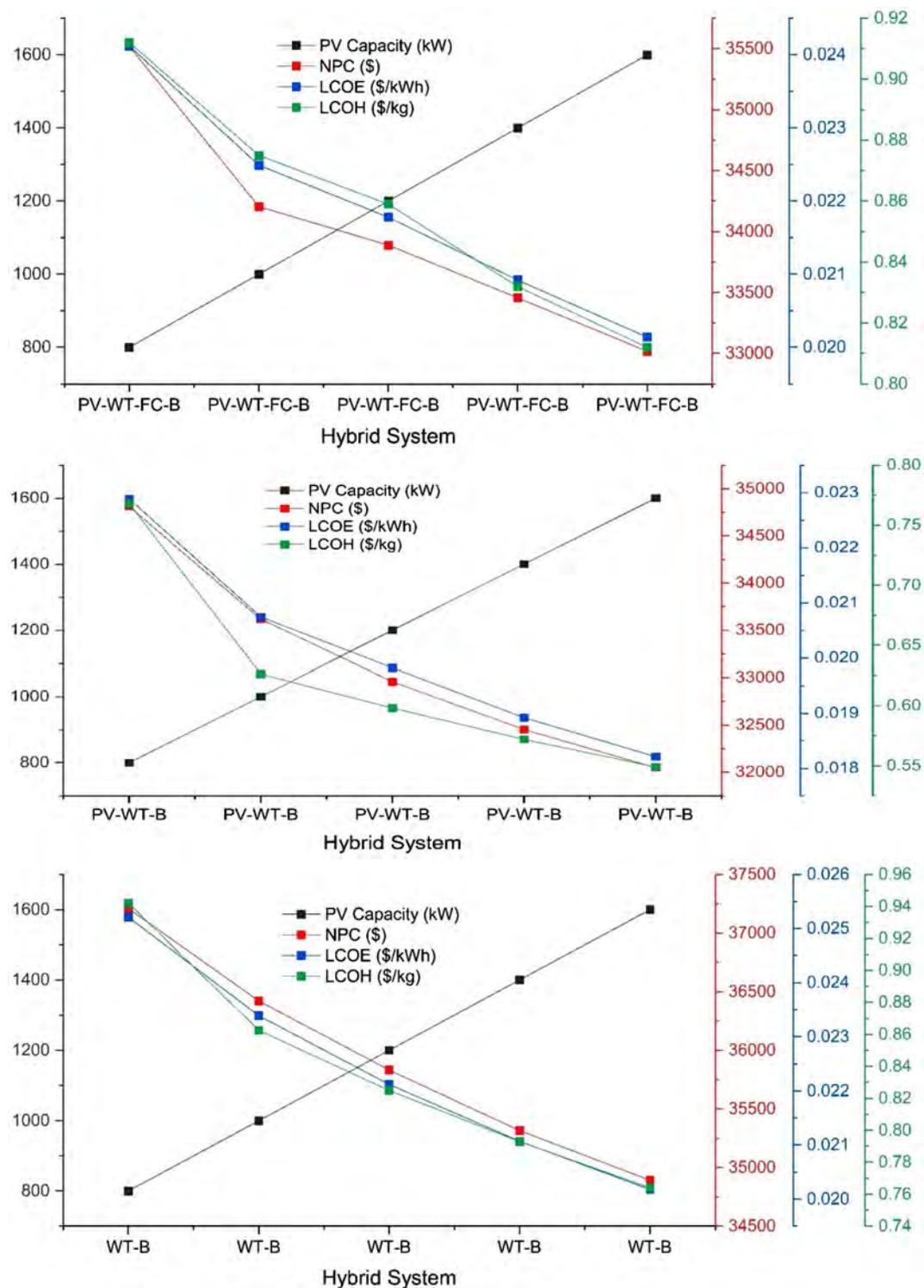


Fig. 8. Sensitivity analysis: impact of PV capacity on cost metrics.

that NPC undergoes a more pronounced reduction in PV-WT-B and PV-WT-FC-B relative to WT-B, signifying that systems integrating both photovoltaic and wind energy attain superior cost efficiency. The results emphasize the crucial importance of renewable energy fraction (REF) and capacity factor (CF) in optimizing energy economics, as increased photovoltaic (PV) integration improves overall system performance and sustainability. The trend in all configurations indicates a threshold beyond which increased PV capacity results in diminishing returns, highlighting the importance of multi-objective optimization to balance system cost and performance. These findings enhance the next-generation hydrogen refueling infrastructure by offering a comprehensive, data-driven methodology for policymakers and engineers to improve economical, sustainable hydrogen production.

Electricity generation from the energy system

Figure 9 illustrates the monthly electricity generated from combination “2” of the three hybrid energy systems. The similarity in the overall behavior is seen in the three energy systems regarding wind power’s contribution to electricity production. It is evident that electricity production generally increased from May to July and

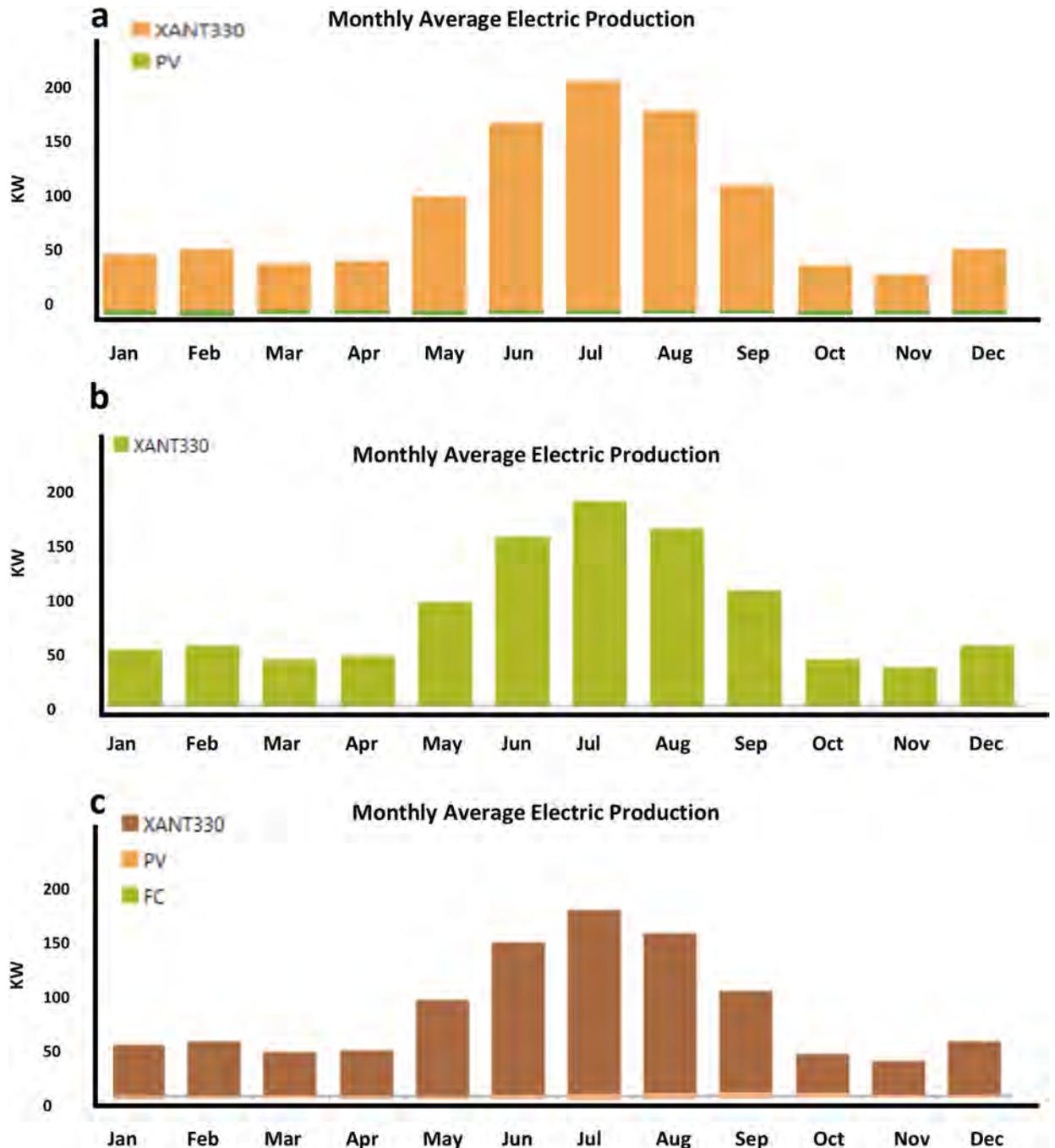


Fig. 9. Power generation from the three hybrid energy systems.

gradually decreased as the month progressed from August to November, with a slight increase in December, as shown in Fig. 9.

The trend in electric production can be attributed to the effect of the prevailing wind and solar radiation that occurs in Nizwa throughout the year. Nargeszar et al.⁸⁹ reported that increased wind speed and temperature could produce significant electricity. After an early increase in electricity generation from January to February, Fig. 9a shows a steady fall in electricity generation from February to April, followed by a notable increase in electricity output from May to July. Figure 9a demonstrates that the WT and PV contributed 776,993.58 and 7848.42 kWh/yr of the total electrical energy generated in the PV-WT-B energy system. However, as illustrated in Fig. 9b, the WT in the WT-B energy system generated 741,240 kWh of electricity energy annually. The energy system comprising WT, PV, and FC demonstrated that, although WT contributed 98.5% of the total electricity generated, PV produced 1.8%, or 76,522.095 kWh/year of the total power generated by the PV-WT-FC-B energy system, as shown in Fig. 9c.

The three energy systems shown in Fig. 10 exhibited comparable behavior in terms of electricity production, utilization, and excess electricity.

Although the PV-WT-B energy system produced the highest electricity of 805,427 kWh/yr, the WT-B energy system produced the lowest electricity of 741,240 kWh/yr as displayed in Fig. 8. While the required electrical energy needs of the hybrid energy systems are met, excess electrical energy is stored in the battery for future use as reported by other researchers⁹⁰. Furthermore, the fuel cell hybridization in the PV-WT-FC-B can act as a storage facility for the energy system.

Hydrogen production from the energy systems

Figure 11 shows the electrolyzer's monthly hydrogen production for each of the three energy systems over the course of the year. Though the electrolysis of water, the electrolyzers produce hydrogen using electrical energy.

The WT-B and PV-WT-FC-B energy systems shown in Figs. 11a,b produce more hydrogen in May, June, July, August, and September than in the other months of the year. However, the highest hydrogen production is observed in May and June for the PV-WT-B energy system shown in Fig. 11b. The primary cause of this phenomenon is the heightened availability of wind-generated electricity over a prolonged duration as observed in Fig. 9. The energy supplied by the three systems and the hydrogen generated by the electrolyzer are strongly correlated. The electricity generated by the PV-WT-B energy system agrees with the hydrogen produced by the same energy system, as evident in Fig. 10. Furthermore, the lowest hydrogen production observed in the WT-B energy system matches the quantity of electricity generated by the WT-B energy system. According to reports, the city of Nizwa experiences consistently high wind speeds, which can be utilized to increase the production of electrical energy and facilitate the creation of hydrogen⁹¹.

Figure 12 depicts the amount of hydrogen produced from each of the energy systems and then stored in the hydrogen tank.

Figure 12 shows that while the PV-WT-B energy system produced 41% of the total hydrogen produced by the entire electrolyzers, the WT-B energy system generated 29.3% of the total hydrogen. The remaining 3027 kg/yr. of the hydrogen is produced by the PV-WT-FC-B energy system as shown in Fig. 10. Salhi et al.⁹² reported that the amount of hydrogen produced is directly linked to the amount of electricity supplied, as power is necessary to activate the electrochemical process involved in water electrolysis.

The graph in Fig. 13 displays the fluctuation of the hydrogen tank level throughout the year for the three hybrid energy systems, as it relates to each day of the year.

The tank storage level steadily dropped from January to February before staying remarkably constant from March to April, as seen in Fig. 13a. But starting in March, the amount of hydrogen stored rose to a maximum of 1000 kg before falling from October to December. The pattern is comparable to the WT-B energy system's tank storage level, which is displayed in Fig. 13c. However, the hydrogen tank level dropped higher in December

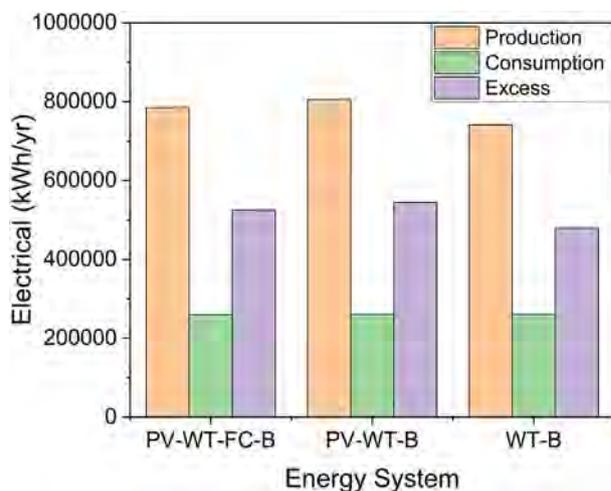


Fig. 10. A comparison of electrical energy production, utilization, and excess.

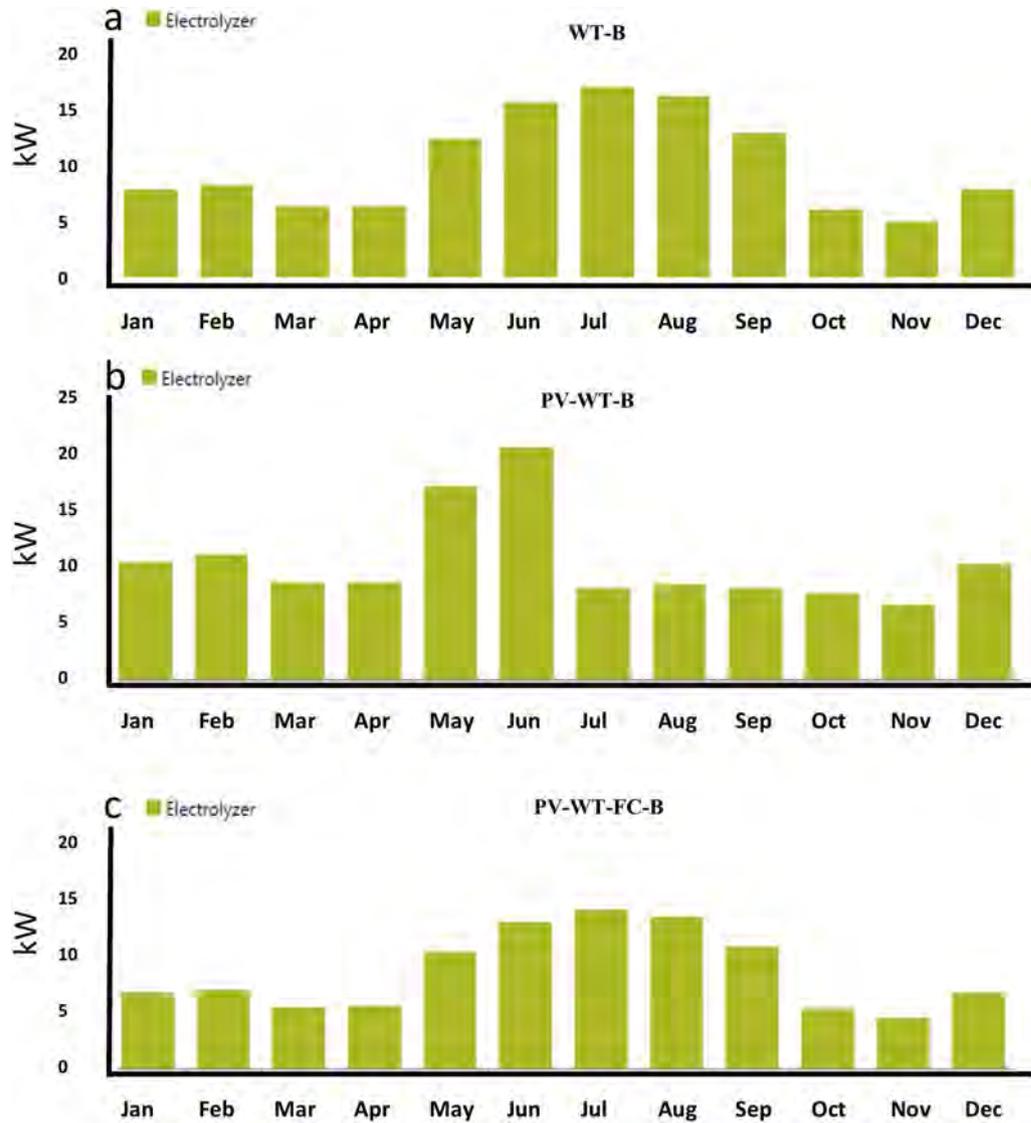


Fig. 11. Hydrogen production from the electrolyzer of the three-energy systems.

for the PV-WT-FC-B energy system than the WT-B energy system. From January to June, the hydrogen tank level progressively rose, as seen in Fig. 13b, before showing a noticeable level of stability from July to December. The patterns in local solar radiation, temperature, wind speed, and power generation seen in this study can be attributed to the hydrogen tank's stability and optimum production.

Cost analysis and economic indicators results

Table 3 displays the comprehensive expenses of all elements comprising the optimal hybrid energy system, including capital, replacement, operation, and maintenance costs. HOMER computes the cash flow to provide a summary of the system expenses⁹³.

It is also clear from Table 3 that the electrolyzer accounts for a significant portion of the total cost of each refueling station, followed by the fuel cell. The PV accounts for the least proportion of the costs. A crucial first step in choosing the optimal system for producing electricity and hydrogen is cost analysis. Using HOMER software, the analysis determines the yearly capital cost by dividing the capital and fixed operating expenses of the hybrid energy system components evenly across the systems' lifetimes⁹⁴. Figure 14 displayed the NPC, LCOE, and LCOH of the three-energy system.

Figure 14 shows that the PV-WT-FC-B has the highest NPC, LCOE, and LCOH of \$36,421.39, \$0.02339 per kWh, and \$ 0.862 per kg, while the PV-WT-B energy system has the lowest NPC, LCOE, and LCOH of \$33,618.44, \$0.02067 per kWh, and \$ 0.626 per kg respectively. On the other hand, the WT-B energy system has NPC, LCOE, and LCOH of \$33,888.81, \$ 0.02178 per kWh, and \$ 0.859 per kg. WT-B energy system has NPC, LCOE, and LCOH of \$33,888.81, \$ 0.02178 per kWh, and \$ 0.859 per kg, as depicted in Fig. 14. Since the three parameters are the basic economic requirements needed to determine the viability of the hybrid energy system, the HOMER consistently finds the system that satisfies the electrical load demands at the lowest NPC and COE

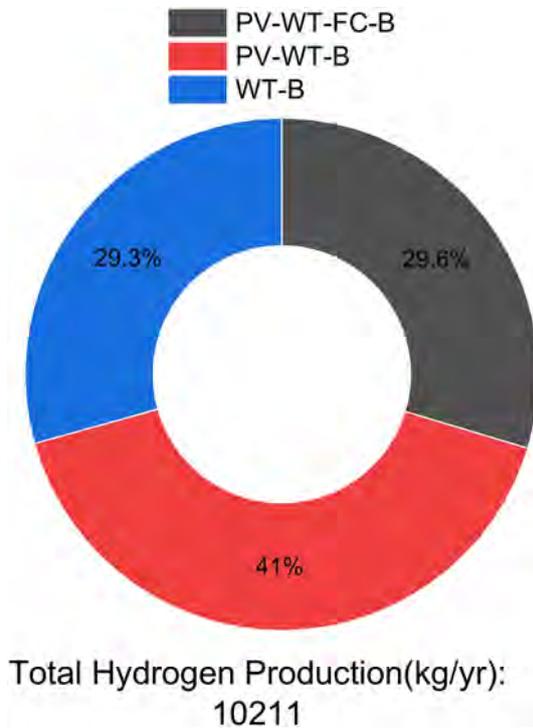


Fig. 12. Total hydrogen produced by the three-energy systems.

values⁹⁵. Other researchers have used these three standards^{96,97} to assess the feasibility of using renewable energy. According to the results, the hybrid energy system with the lowest NPC, LCOE, and LCOH is often selected as the best choice for supplying the system's energy needs.

Analysis of annual worth and Return on Investment (ROI)

The yearly worth analysis is an alternative method employed to evaluate the feasibility of a given project. Furthermore, the utilization of annual worth analysis yields substantial results in understanding a project's financial condition and advancement⁶⁶. Studies have shown that the use of yearly worth simplifies the assessment of the financial value of an investment over its entire duration, allowing for a direct comparison of different projects or investments⁹⁸.

An alternative measure used to evaluate an investment's profitability is return on investment (ROI), which compares the gain to the initial capital outlay⁶⁷. This metric is commonly expressed as a percentage. As highlighted earlier, it is crucial for the city of Nizwa, specifically in the hydrogen project, to meticulously select the most advantageous and economically efficient hybrid system. This challenge primarily concerns the choice between different options for renewable energy sources. The HOMER software considers projected fluctuations in load demand, whether they are expected to rise or fall when carrying out its operating procedures and computing the ROI. The yearly value and ROI outcomes for the three hybrid energy systems under consideration are shown in Fig. 15.

As seen in Fig. 13, the PV-WT-B energy system outperforms the other two energy systems in terms of efficiency during the course of the project, resulting in a higher return on investment and yearly value. Furthermore, the PV-WT-B energy system has a good return on investment of \$302 and an ROI of 39.1%. This contrasts with the PV-WT-FC-B and WT-FC-B energy systems, which have an ROI and annual worth of 30% and \$284 per year and 27% and \$176 per year, respectively. The result categorically demonstrates that the PV-WT-B energy system is the best choice for the HRS station in Nizwa because it continuously generates a profit over the course of the project.

Pollution and emission analysis

Completely renewable energy systems are intended to use natural and sustainable sources of energy, such as solar, wind, hydropower, and geothermal⁹⁹. In terms of direct emissions during operation, these systems can approach zero emissions, especially when compared to traditional fossil fuel-based energy systems. However, it's important to acknowledge that while the operational phase of HRES can produce little to no greenhouse gas (GHG) emissions, there are still life-cycle emissions associated with the production, transportation, and disposal of the components used in these systems. Despite the operational benefits of HRES, the overall life-cycle emissions associated with the components that make up these systems should not be overlooked. These include emissions from raw material extraction, manufacturing, transportation, installation, maintenance, and eventual disposal or recycling of the components at the end of their life. The main goal of these systems is to significantly reduce or even eliminate the environmental damage associated with traditional energy sources,

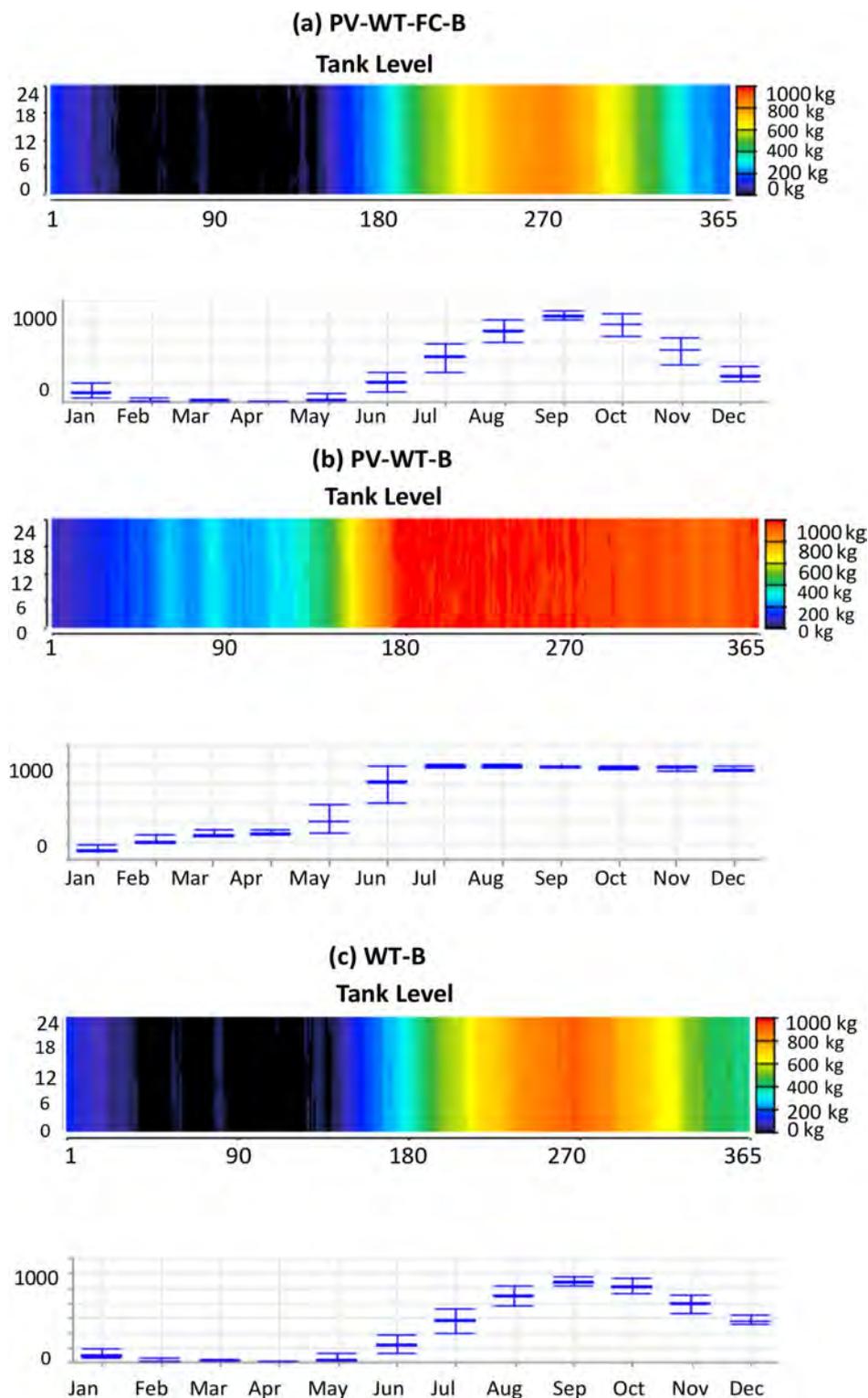


Fig. 13. Hydrogen tank level for (a) PV-WT-FC-B (b) PV-WT-B, (c) WT-B.

such as coal, oil, and natural gas. As shown in Table 4, renewable energy systems do not emit harmful emissions during operation¹⁰⁰.

Yet, whereas renewable energy systems in operation have negligible or no emissions, the production of technologies that support such systems can be a source of pollution. This is particularly evident in the production of materials for renewable energy infrastructure¹⁰¹. Fully renewable energy systems are a great leap toward the reduction of greenhouse gas emissions and, therefore, in the fight against climate change. There are also operational concerns, including noise pollution and the potential disruption of wildlife habitats. These can

Energy system	Component	Capital cost (\$/kW)	Replacement cost (\$/kW)	Operation and maintenance cost (\$/kW)	Life cycle (year)
PV-WT-FC-B	XANT 330	900	0.00	323.19	30
	PV Panel	6.93	0.00	2.98	30
	Battery	1078.80	419.56	1162.18	15
	Hydrogen Tank	1000	0.00	0.00	25
	Converter	100	42.43	0.00	15
	Electrolyzer	22,000	637.61	646.76	20
	Fuel Cell	3000	0.00	0.00	15
PV-WT-B	XANT 330	900	0.00	323.19	30
	PV Panel	20.16	0.00	8.69	30
	Battery	979.20	380.83	1054.89	15
	Hydrogen Tank	1000	0.00	258.55	25
	Converter	100	42.43	0.00	15
	Electrolyzer	22,000	637.61	646.76	20
	WT-B	XANT 330	900	0.00	323.19
-	-	-	-	-	-
Battery	1021.20	397.16	1100.13	15	
Hydrogen tank	1000	0.00	258.55	25	
Converter	53.69	22.78	8.68	15	
Electrolyzer	22,000	637.61	646.76	20	

Table 3. Total cost summary.

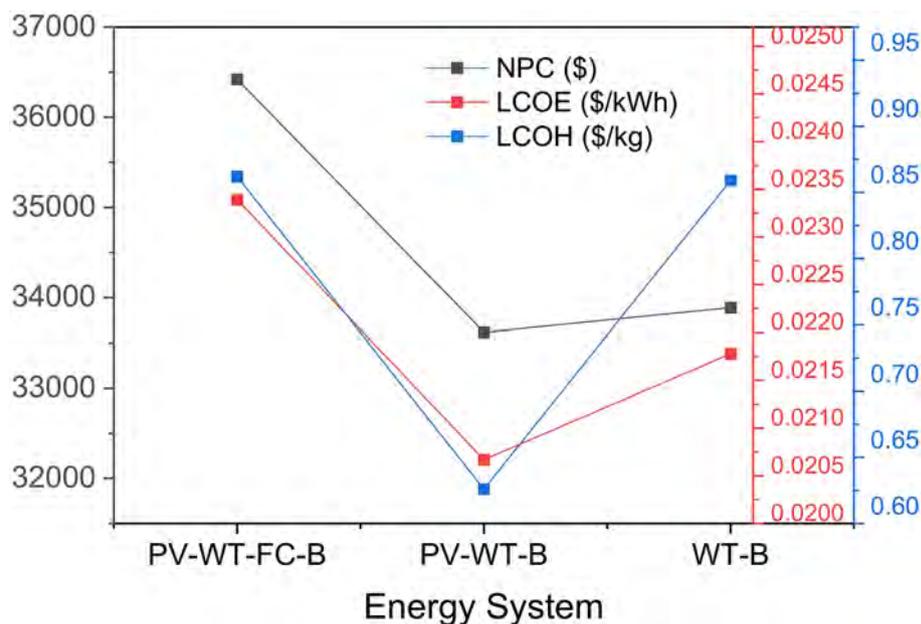


Fig. 14. Economic indicators of the three energy systems.

be minimized by developing better technologies, recycling methods, and sustainable practices. These ongoing improvements will help minimize the overall environmental footprint and enable renewable energy systems to fulfill their potential as eco-friendly, low-impact energy sources.

Prospects and suggestions

The results of this study clearly demonstrate the significant potential of wind and solar energy in Nizwa, Oman. The creation of hydrogen is contingent upon both the intensity of sunlight and the speed of the wind turbine. The production of environmentally friendly renewable energy could serve as a viable substitute for the current use of fossil fuel in transportation vehicles in the city of Nizwa. The components of the hybrid energy system, particularly the electrolyzer, considerably influence the cost of hydrogen production. Considering the affordable pricing of PV systems and wind turbines, as well as their projected decrease in cost, transitioning to renewable hydrogen fuel could be a more favorable choice for meeting the transportation sector's future environmental

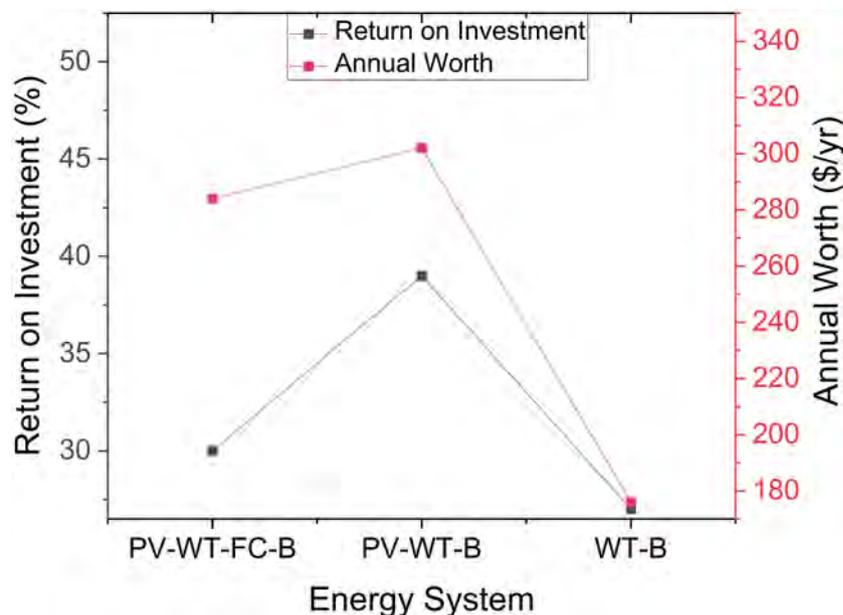


Fig. 15. Annual worth and return on investment (ROI).

	Hybrid energy system		
	PV-WT-FC-B	PV-WT-B	WT-B
Emission	kg/yr		
Carbon dioxide	0	0	0
Carbon dioxide	0	0	0
Carbon monoxide	0	0	0
Unburned hydrocarbons	0	0	0
Particulate matter	0	0	0
Sulfur dioxide	0	0	0
Nitrogen oxides	0	0	0

Table 4. Emission analysis from HOMER Pro.

and energy objectives in Nizwa. Currently, transportation vehicles in Oman rely on fossil fuels as their primary source of energy fuels as their primary source of energy source. However, per the objectives outlined in Oman Vision 2040, there is a strong emphasis on reducing the dependency on fossil fuel fuels by a substantial amount by 2040. By allocating funds towards implementing the planned renewable HRS and adopting hydrogen as a fuel source in the transportation industry, greenhouse gas emissions can effectively be mitigated, produce economic income for the nation, and save the environment. Oman has land use regulations for renewable energy projects governed by a combination of national laws and specific decrees aimed at promoting sustainable energy development. As the Authority for Public Services Regulation (APSR) permits the setting up of the HRS, the installation of HRSs in Nizwa, Oman can be achieved through short-term, mid-term, and long-term phases. This study examines the potential benefits of PV and Wind energy sources in Nizwa and Oman to achieve the country's goal of phasing out fossil fuels in the transportation industry. Moreover, the study's results can provide policymakers with the necessary information to establish PV-Wind-powered hydrogen filling stations in Oman.

Conclusion

The study verified that using renewable energy as the main source of electricity to meet the HRS's electrical and hydrogen needs in Nizwa is feasible. The results of this investigation show that Nizwa is an ideal location for producing renewable hydrogen fuel for transportation due to its sufficient sunlight and wind.

1. Though the three energy systems investigated showed no emission, it is evident from the examined and optimized results that the PV-WT-B hybrid energy system performs better than the others in terms of NPC, LCOE, and LCOH using Homer Pro software.
2. Optimization algorithms such as the Mayfly Algorithm (MA), Genetic Algorithm (GA), CUKO Search, Gray Wolf Optimizer (GWO), Constrained Particle Swarm Optimization (CPSO), Harmony Search (HS), and Flower Pollination Algorithm (FPA) were utilized to determine the most economically and operationally

feasible configurations based on the NPC, LCOE, and LCOH across various configurations (PV-WT-FC-B, PV-WT-B, and WT-B), elucidating essential trade-offs and cost-reduction measures. The findings demonstrate that CPSO regularly attains the lowest NPC, LCOE, and LCOH, establishing it as the most economical optimization method.

- Conversely, Harmony Search (HS) and Gray Wolf Optimizer (GWO) incurred elevated costs, indicating constraints in convergence efficiency for this application.
- The patterns underscore the relationship between algorithmic efficiency and renewable energy integration, indicating that hybrid systems incorporating fuel cells (PV-WT-FC-B) impose a greater economic burden than PV-WT-B due to the supplementary expenses associated with fuel cell integration.
- The sensitivity analysis indicates a distinct inverse correlation between PV capacity and cost metrics, showing that an increase in PV capacity results in a substantial decrease in NPC, LCOE, and LCOH, underscoring the economic advantages of augmenting solar generation in hybrid renewable energy systems.
- The study found that NPC undergoes a more pronounced reduction in PV-WT-B and PV-WT-FC-B relative to WT-B, signifying that systems integrating both photovoltaic and wind energy attain superior cost efficiency.
- The results emphasize the crucial importance of renewable energy fraction (REF) and capacity factor (CF) in optimizing energy economics, as increased photovoltaic (PV) integration improves overall system performance and sustainability.
- Implementing renewable HRSs is a practical way to reduce dependency on fossil fuels and encourage decarbonization in Oman's transportation industry, motivating Nizwa stakeholders to support hydrogen generation.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Received: 3 February 2025; Accepted: 2 April 2025

Published online: 11 April 2025

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Acknowledgements

Deep thanks and gratitude to the Researchers Supporting Project Number (RSP2025R351), King Saud University, Riyadh, Saudi Arabia, for funding this research article.

Author contributions

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Competing interests

The authors declare no competing interests.

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