Date of publication June 22, 2025, date of current version June 22, 2025.
Digital Object Identifier 10.21608/pesj.2025.395208.1037

Research article,

Integrated-Techno-Economic, Environmental, and Sensitivity Analysis of Hybrid PV/Wind Energy Systems for Powering a 3.5 MVA Tourist Resort in Ras Al-Hekma City, Egypt

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Abstract: This study presents an integrated techno-economic, environmental, and sensitivity analysis of hybrid photovoltaic (PV) and wind energy systems designed to supply a peak load of 3.5 MVA to a remote tourist resort in Ras Al-Hekma City, Egypt. Multiple configurations; PV- and wind-based; were examined, each incorporating combinations of battery storage (BS), fuel cells (FC), and hybrid FC/BS systems under off-grid conditions. The assessment evaluates system performance, cost of energy (COE), capital and operational expenditures, and resilience across different scenarios using real-site solar and wind resource data. Among PV-based systems, the PV/BS configuration demonstrated the lowest COE at $0.076/kWh, offering simplicity and economic efficiency, while the PV/FC/BS setup provided a balanced trade-off between reliability and cost. For wind-based systems, Wind/BS achieved the lowest COE at $0.067/kWh, making it the most cost-effective, whereas Wind/FC/BS offered the highest resilience at a higher cost. A comprehensive sensitivity analysis identified solar irradiance, wind speed, and component costs as the most influential parameters affecting system performance and COE. The findings underscore the feasibility of deploying hybrid renewable energy systems in coastal, off-grid locations and contribute to Egypt's strategic goals for renewable energy integration and sustainable development.

keywords: Hybrid Renewable Energy Systems (HRES); Techno-Economic Optimization; Cost of Energy (COE); Sensitivity Analysis; Climate-Resilient Energy; Systems Sustainable Energy for Tourism.

I. Introduction

The concept of cleaner production emphasizes the adoption of practices and technologies aimed at preventing environmental degradation. These initiatives support sustainable development by promoting the efficient use of energy and advancing innovative technologies that can also guide effective policymaking [1]. In 2015, the United Nations introduced the 2030 Agenda, which includes 17 Sustainable Development Goals (SDGs) [2]. Goal number 7 specifically targets the expansion of renewable energy's share in the global power supply, encouraging a shift toward environmentally friendly energy systems [3].

Unlike conventional fuels, renewable energy sources generate electricity without combustion, helping to reduce pollutant emissions and atmospheric particulates. This cleaner approach not only safeguards public health and biodiversity but also elevates the general quality of life. These benefits can serve as motivation for governments and investors to prioritize renewable energy infrastructure [4]. The European Union's carbon neutrality target; which Egypt has committed to following; can be realized through ongoing development in sustainable energy technologies. Among the most effective solutions are wind power installations and solar photovoltaic systems, which together are forecast to contribute 43% of the EU's electricity output by 2050. This energy transition is expected to provide positive environmental impacts and stimulate economic growth, including the generation of an estimated 1.5 million jobs over the next three decades in Europe [5].

Egypt's significance in the global energy landscape stems largely from its strategic geographic features [6]. The country, located in North Africa and the Arab region, has nearly 3,000 kilometers of coastline along key bodies of water such as the Mediterranean Sea, Red Sea, and the Gulfs of Suez and Aqaba. Its location also bridges three continents: Africa, Asia, and Europe [7]. Major global trade routes, including the Suez Canal and the Suez-Mediterranean Pipeline (SUMED), further strengthen Egypt's role in the international energy supply chain.

Despite these advantages, Egypt remains heavily dependent on conventional energy systems to meet increasing demand. This reliance has led to a significant rise in carbon emissions, projected to grow from about 800 million metric tons in 2012 to more than 1,800 million metric tons by 2035; a 125% increase. Data from 1971 to 2016, Figure (1) indicates a consistent pattern of dependence on fossil fuels for energy production [8].

II. Electricity Demand and Renewable Energy in Egypt

Over recent decades, Egypt has witnessed a sharp rise in electricity demand, primarily driven by factors such as population growth, urban expansion, industrial development, economic progress, and subsidized energy pricing. During the 2015/16 fiscal year, electricity consumption reached approximately 156,300 GWh [7]. Of this total, 66% were supplied by natural gas, 7% by hydropower, and just 8% by renewable sources [7]. Egypt contributes around 8% of Africa's total renewable electricity output, equating to 93 million tons of oil equivalent. By 2020, solar power accounted for 1.9% of Egypt's total electricity production, ranking it second in Africa; following South Africa; and 31st globally in terms of solar energy deployment [9].

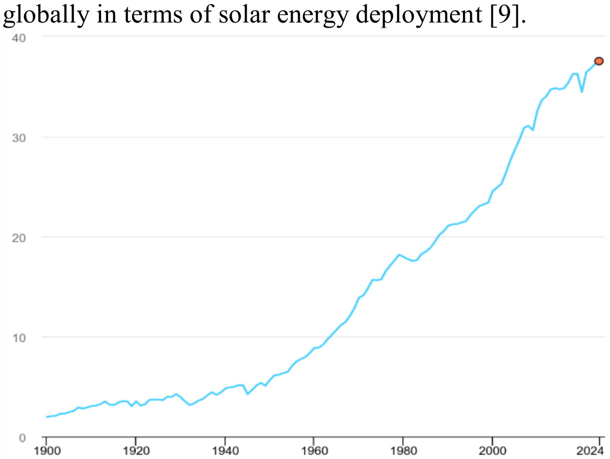


Figure 1: Electricity production from conventional energy sources and CO_2 emissions from gaseous fuel consumption (Mt) over the years from 1900 to 2024 [8].

In terms of wind power, Egypt has made significant strides. Wind energy projects began in 2001 with generation capacities of 5.4 MW in Hurghada and 545 MW in Zafarana. The Zafarana wind farm, completed in 2015 with a $6.8 billion investment, expanded its capacity to 340 MW by 2017 and 600 MW by 2018. A national strategy was introduced to expand wind power capacity to 7.2 GW by 2020. By that year, wind energy contributed 1.44% of the country's total electricity, making it the third-largest renewable energy source [10]. Approximately 90% of Egypt's hydroelectric power is produced by the Aswan High Dam on the Nile River, which has a capacity of 2,300 MW.

A. Renewable Energy for Desalination and Remote Areas

With the rising global awareness around environmental protection and emission reduction, shifting towards renewable-based electricity generation has become increasingly essential. In Egypt, this shift is particularly critical given the demographic concentration along the Nile and the limited freshwater availability in remote and rural areas. These regions face challenges in sustaining population growth and development due to insufficient freshwater access.

To tackle water scarcity, especially in isolated communities, desalination using alternative energy sources is becoming a viable option. However, desalination is energy-intensive, and relying on fossil fuels presents issues related to availability, cost, and environmental impact. Therefore, integrating hybrid renewable energy systems; primarily solar and wind; to power desalination processes is emerging as a practical solution. Several studies have been conducted both in Egypt and globally, evaluating the feasibility of various renewable-powered desalination technologies.

This article presents an updated overview of desalination techniques with a focus on membrane-based methods such as Reverse Osmosis (RO), Membrane Distillation (MD), and hybrid systems. It also explores the application of cutting-edge materials like plasmonic nanomaterials in solar-driven water purification processes. Furthermore, it highlights recent collaborative projects undertaken by the co-authors to implement hybrid RE-powered desalination in remote Egyptian areas [11].

B. Hybrid Systems and Smart Grid Integration

In recent years, renewable energy has gained increasing relevance worldwide due to the depletion of fossil fuels, their rising costs, and environmental implications. This has led to a growing shift toward renewable energy, particularly for electrifying remote or off-grid areas. Integrating multiple renewable sources along with energy storage and backup systems creates hybrid energy setups that are more cost-effective and dependable.

However, due to the unpredictable nature of renewable sources and the complex load variations, managing such systems efficiently requires advanced coordination. This is where smart grids come into play. A smart grid enhances the traditional power infrastructure through technologies that allow two-way communication and electricity flow, distributed energy generation, automated control systems, and predictive analytics [12-14].

Smart grids facilitate dynamic interaction between energy providers and consumers, allowing electricity usage to be optimized based on real-time conditions, costs, and environmental concerns. This results in a more secure, efficient, and reliable energy system [15, 16].

C. Installed Renewable Energy Capacity in Egypt

As of 2021, Egypt's installed renewable energy capacity reached approximately 19.2 gigawatts (GW). To meet future energy goals, the government has outlined plans to scale this capacity significantly - targeting 50.5 GW by the 2029/2030 period and ultimately reaching 62.6 GW by 2034/2035. Achieving this target would enable renewable sources to contribute around 42% of Egypt’s total electricity generation by 2035, according to projections from the World Energy Outlook. These figures are detailed in Table (1), which illustrates the projected growth in renewable energy installations over the coming years [17].

Table 1: Egypt’s renewable energy capacity in GW [18].

Types of power Station	Hydro (GW)	Wind (GW)	PV (GW)	CSP (GW)	Total (GW)
2009 - 2010	2.8	0.5	0.0	0.0	3.3
2021 - 2022	2.8	13.3	3.0	0.1	19.2
2029 - 2030	2.8	20.6	22.9	4.1	50.5
2034 - 2035	2.9	20.6	31.75	8.1	62.6

The growing global demand for sustainable energy solutions has led to increased interest in hybrid renewable energy systems (HRES) that combine multiple energy sources to enhance reliability, reduce environmental impact, and optimize energy costs. In remote and off-grid areas such as tourist resorts, the integration of renewable technologies becomes particularly vital, offering a clean and independent alternative to conventional fossil fuel-based generation

This research work presents the design and sizing of a hybrid renewable energy system intended to supply a peak load of 3.5 MVA for a tourist resort located in Ras Al-Hekma City, Egypt. The study evaluates three hybrid system configurations; (I) Photovoltaic (PV)-, and (II) wind-based HRES configurations. Each configuration consists of three hybrid systems with Battery Storage (BS), Fuel Cell (FC), and Fuel Cell/Battery Storage (FC/BS). Each configuration is analyzed to determine the optimal sizing of the photovoltaic array, wind turbines, battery storage, and FC components while considering energy availability, system efficiency, and economic viability through cost of energy (COE) calculations.

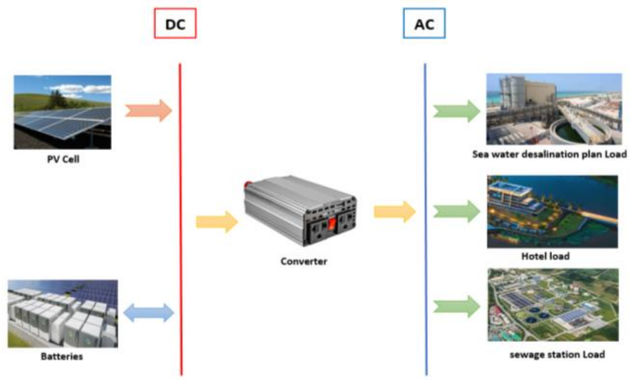
Ras Al-Hekma City, situated along Egypt's Mediterranean coast, exhibits favorable solar conditions with an average solar irradiance of approximately 5.5 kWh/m²/day and an annual irradiance of around 2,000 kWh/m²/year. These high irradiance levels, coupled with moderate ambient temperatures ranging between 20°C and 35°C, make the location suitable for solar energy exploitation. Average wind speed is ~6.5 m/s at 50 - 100 m. However, system design must account for efficiency losses; estimated at 25% for the overall system; and the distinct lifespans of each component: 25 years for PV modules and 10 years for both BS and FC systems

The objective of this research work is to provide a comprehensive methodology for the technical and economic assessment of hybrid renewable energy systems under off-grid conditions, tailored to the specific climatic and energy demands of Ras Al-Hekma City. The following sections will detail the energy requirement analysis, sizing procedures, system configurations, and the associated performance metrics that guide the development of a robust and sustainable energy solution for the targeted tourist resort.

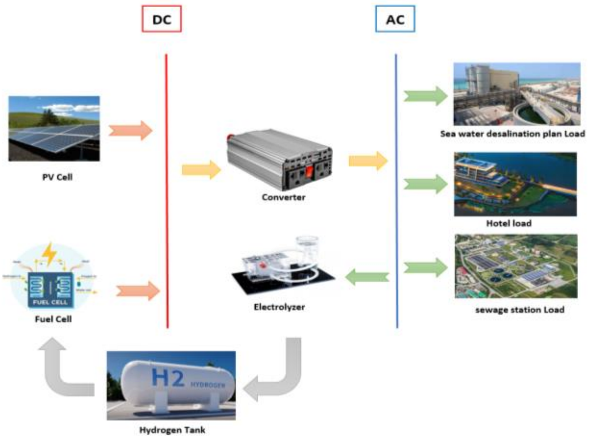
III. Results and Discussion

A. PV-Based HRES Configurations

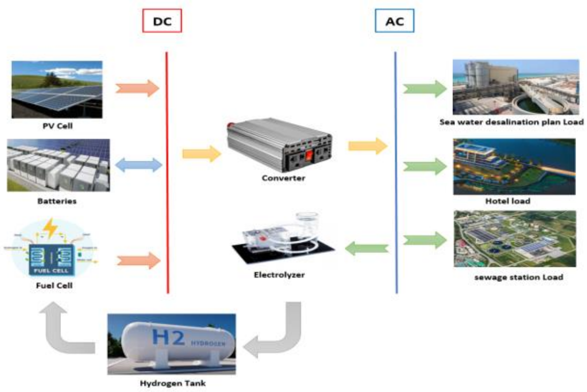
Sizing a hybrid renewable energy source to produce 3.5 MVA to supply a tourist resort load at the Egyptian Ras Al-Hekma City. Sizing of hybrid renewable energy sources with photovoltaic (PV), fuel cell (FC), and battery storage (BS) systems are studied. Three different scenarios; PV/BS, PV/FC and PV/FC/BS involves determining the energy requirements, sizing the PV array, sizing the BS system, and sizing the FC with off-grid are studied with the calculation of cost of energy (COE), Figure (2).



(A) First scenario: PV/BS hybrid energy system, with off-grid.



(B) Second scenario: PV/FC hybrid energy system with off-grid.



(C) Third scenario: PV/FC/BS hybrid energy system with off-grid.

Figure 2: Hybrid energy sources of three different scenarios with off-grid; (A) PV/BS, (B) PV/FC and (C) PV/FC/BS

Solar irradiance in Ras Al-Hekma City has an average solar irradiance of 5 ~ 6 kWh/m²/day. The average solar irradiance in Ras Al-Hekmah City is approximately 5.5 kWh/m²/day and average annual solar irradiance: ~2,000 kWh/m²/year as shown in Figure (3-4). Average ambient temperatures range from 20°C to 35°C, which affects PV panel efficiency. The overall system efficiency (µ) is about 75% due to system losses (inverter efficiency, wiring losses, etc.). FC efficiency is assumed to be 50%. System lifetime is assumed of 25 years for PV, 10 years for both BS system and FCs.

Table (2) which compare the design and cost performance of three hybrid renewable energy system (HRES) configurations; PV/BS, PV/FC, and PV/FC/BS; to supply a 3.5 MVA load in Ras Al-Hekma City, Egypt.

Table (2) outlines the key components, sizing, and capital costs of three HRES scenarios, along with associated operational and replacement costs. PV/BS System; this configuration introduces fuel costs and system complexity, but reduces dependency on costly battery systems. PV/FC/BS System; this system balances the benefits of both storage types and offers resilience and reliability, albeit with slightly higher complexity and maintenance.

Table (2), Cost of Energy (COE) Analysis, Capital Expenditure (CapEx) Comparison; PV/BS: $21.6M (lowest), PV/FC: $23.9M (highest), and PV/FC/BS: $23.45M. Though PV/BS has the lowest initial cost, its long-term economics are impacted by high battery replacement costs. O&M and Replacement Costs; PV/BS: 360k $/year, PV/FC: 400k $/year, and PV/FC/BS: 450k $/year. The hybrid PV/FC/BS system has the highest ongoing costs due to maintenance of both storage and hydrogen systems, while PV/BS remains the lowest due to simpler maintenance despite future battery replacements

Cost of Energy (COE); PV/BS: 0.076 $/kWh – Lowest COE, thanks to lower CapEx and no fuel costs. PV/FC: 0.089 $/kWh – Highest COE due to expensive fuel cells and hydrogen infrastructure. PV/FC/BS: 0.081 $/kWh – Balanced COE due to diversified energy sources and system optimization.

PV/BS is ideal where simplicity and fuel independence are prioritized, but long-term battery costs are a drawback. PV/FC offers greater dispatchability and reliability, but introduces high fuel-related costs and system complexity. PV/FC/BS provides a compromise between cost, reliability, and energy flexibility, making it a robust solution for critical or mixed load profiles.

Table 2: Sizing and costs of hybrid renewable energy systems (HRES); PV/BS, PV/FC, and PV/FC/BS delivering 3.5 MVA in Ras Al-Hekma City, Egypt.

Component	**Size**	**Cost ($)**
	PV/BS system	
PV	7.33 MW	$6.6M
BS	31.4 MWh	$12.56M
Inverter	8 MW	$2.4M
Total	—	$21.56M
O&M	—	$360k/year
Replacements (batt)	—	$17M over life
COE	$/kWh	0.079
	PV/FC system	
PV	7.5 MWp	$6.75M
FC	3.5 MW	$9.0M (@ $2600/kW)
Electrolyzer	2.5 MW	$3.75M
H_2 Storage	2000 kg	$2.0M
Inverter	8 MW	$2.4M
Total	—	$23.9M
O&M + Repl.	—	$400000 /yr
COE	$/kWh	0.089
	PV/FC/BS	
PV	6.5 MW	$5.85M
BS	15 MWh	$6M
FC	2.0 MW	$5.2M
Electrolyzer	2 MW	$3M
H_2 Storage	1000 kg	$1.0M
Inverter	8 MW	$2.4M
Total	—	$23.45M
O&M + Repl.	—	~$450k/year
COE	**$/kWh**	**0.081**

BS supply immediate short-term needs while FC covers extended demand when PV is unavailable.

Hybrid renewable energy system of PV/BS is lowest COE and simplicity which is ideal for remote or off-grid areas with good sun. Hybrid renewable energy system of PV/FC/BS is High reliability with moderate cost which is good balance with backup and better resilience. Hybrid renewable energy system of PV/FC is green H_2 pilot project is the best where hydrogen infrastructure or surplus solar is available.

A.1. Sensitivity analysis

Tables (3) and (4) listed the compare sensitivity analysis results for three Hybrid Renewable Energy Systems (HRES) in Ras Al-Hekma City, Egypt, delivering 3.5 MVA (~3.15 MW average), an evaluation to measure how key parameters affect the Cost of Energy (COE) and system design for the following configurations:

Table 3: Sensitivity Parameters.

Parameter	Unit	Values Tested
Solar Irradiance (GHI)	kWh/m²/day	5.5, 5.8, 6.2
BS Cost	$/kWh	200, 300, 400
FC Cost	$/kW	2000, 2600, 3200
Electrolyzer Cost	$/kW	1000, 1500, 2000
H_2 Fuel Cost	$/kg	4, 6, 8 (for external supply)
Discount Rate	%	5%, 7%, 10%

Table 4: Summary of results from HOMER Pro (Simulated Sensitivity Output).

Parameter Change		COE Base ($/kWh)		
		PV/ BS	PV/FC	PV/FC/ BS
Base Case	**–**	**0.076**	**0.089**	**0.081**
Higher Solar (6.2 kWh/m²/day)	+ Solar yield	0.068	0.082	0.074
Lower Solar (5.5 kWh/m²/day)	– Solar yield	0.082	0.095	0.086
BS Cost (↓ to $200/kWh)	– CAPEX	0.066	–	0.074
BS Cost (↑ to $400/kWh)	+ CAPEX	0.084	–	0.089
FC Cost (↓ to $2000/kW)	– FC cost	–	0.079	0.074
FC Cost (↑ to $3200/kW)	+ FC cost	–	0.098	0.087
H_2 Fuel Price (↑ to $8/kg)	+ FC OPEX	–	0.101	0.091
Discount Rate (↓ to 5%)	– Project discounting	0.068	0.081	0.073
Discount Rate (↑ to 10%)	+ LCOE	0.084	0.097	0.089

In case PV/BS hybrid system; Most stable COE across all conditions, sensitive to BS cost and solar radiation, best under high solar and low BS prices, and Least complex to operate.

In case of PV/FC hybrid system; most sensitive to FC and hydrogen prices, better performance with low FC cost and high solar, without hydrogen production, H_2 cost becomes dominant, and requires O&M expertise and H_2 handling.

In case of PV/FC/BS hybrid system; balanced performance, moderately sensitive to both FC and BS prices, more resilient in varying solar or load conditions, and best tradeoff between reliability and COE. Table (5) listed the final COE Sensitivity Ranking (Best to Worst).

Table 5: Final COE Sensitivity Ranking (Best to Worst).

Rank	Case	COE Range ($/kWh)
1	PV/BS	0.066 – 0.084
2	PV/FC/BS	0.073 – 0.091
3	PV/FC	0.079 – 0.101

The sensitivity graphs, Figures (3) and (4), showing how the Cost of Energy (COE) varies with each key parameter for the three HRES configurations:

Solar Irradiance: Higher sunlight improves COE for all systems. BS Cost: Strong impact on PV/BS and PV/FC/BS. FC Cost: Significantly affects FC-based systems. Hydrogen Fuel Cost: Directly impacts operating costs for FC systems. Discount Rate: Affects all configurations; lower rates reduce COE.

Figure (5) Load Growth (%); COE increases with higher load growth due to the need for larger systems. PV/BS and PV/FC/BS handle growth more cost-effectively than PV/FC alone. Battery Cycle Life (cycles); Longer BS life leads to lower COE by reducing replacement frequency. Systems with BS (especially PV/BS) benefit significantly.

B. Wind-based HRES configurations:

Wind speed data can be obtained from NASA POWER, Global Wind Atlas [19], or HOMER database [20]. Average wind speed for Ras Al-Hekma City Egypt is ~6.5 m/s at 50 -

100 m. Choosing commercial turbines suitable for the region under study from Table (6).

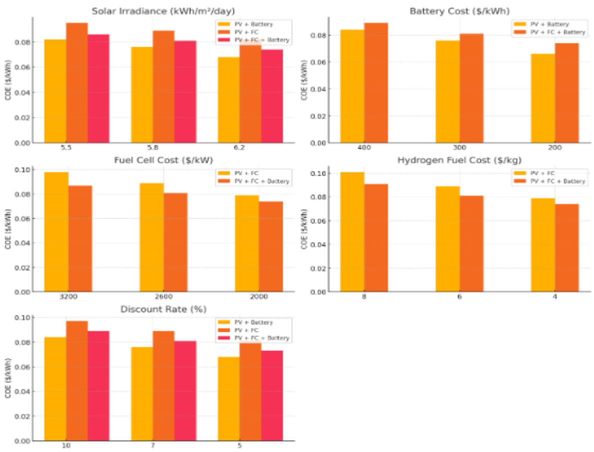


Figure 3: Separate sensitivity graphs showing how the Cost of Energy (COE) varies with each key parameter for the three HRES configurations, solar irradiance, BS cost, FC cost, hydrogen fuel cost, and DISCOUNT rate.

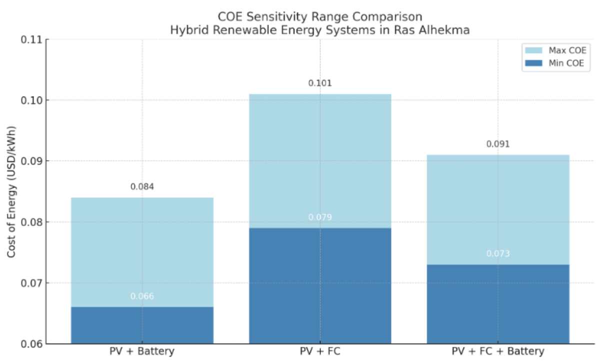


Figure 4: Comparison graph showing the Cost of Energy (COE) sensitivity range for each hybrid system configuration; PV/BS; PV/FC; and PV/FC/BS.

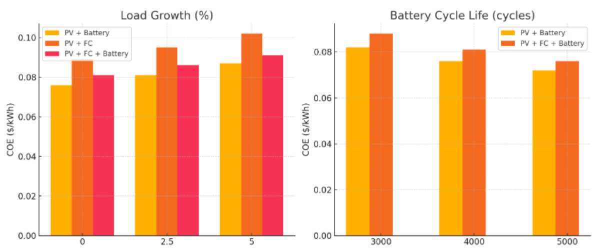
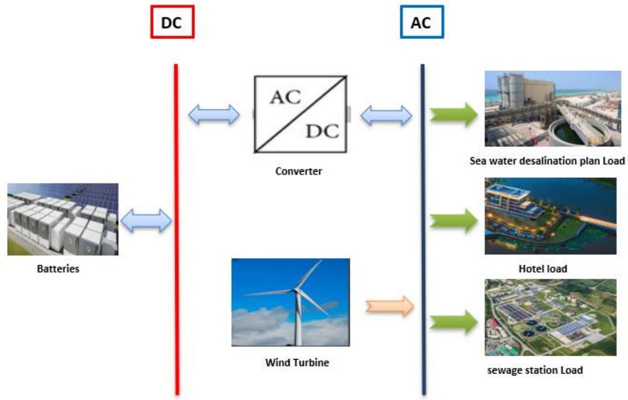


Figure 5: Additional sensitivity analysis graphs for: Load Growth (%); and Battery Cycle Life (cycles) for each hybrid system configuration; PV/BS; PV/FC; and PV/FC/BS.

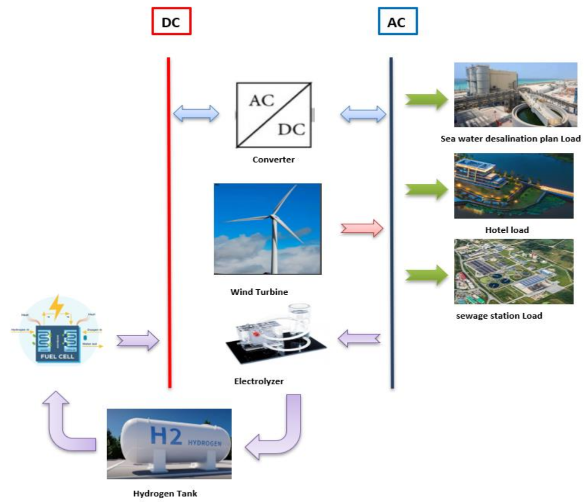
Table 6: Commercial turbines suitable for Ras Al-Hekma City, Egypt.

Model	Rated Power	Wind speed (m/s)			Cost $
		Cut-in	Rated	Cut-out Speeds	
Vestas V90	2.0 MW	4	12	25	$3 million
GE 1.5sle	1.5 MW	3.5	12	20	$2 million

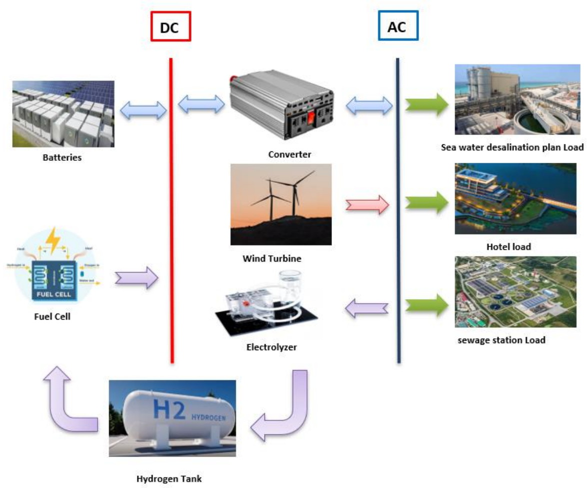
Figure (6) shows a hybrid energy sources of three different scenarios with off-grid; (A) Wind/BS, (B) Wind /FC and (C) Wind /FC/BS.



(A) First scenario: Wind/BS hybrid energy system with off-grid.



(B) Second scenario: Wind/FC hybrid energy system with off-grid.



(C) Third scenario: Wind/FC/BS hybrid energy system with off-grid.

Figure 6: Hybrid energy sources of three different scenarios with off-grid; (A) Wind/BS, (B) Wind/FC and (C) Wind/FC/BS.

Table (7) provides a comprehensive summary of the technical and economic parameters used to size a hybrid wind and battery storage (BS) system intended to supply 3.5 MVA (equivalent to 3.15 MW at a 0.9 power factor) to Ras Al-Hekma City, Egypt. The system is designed to meet a daily energy demand of 75.6 MWh, ensuring energy reliability and security in a region where conventional grid expansion may be limited or costly.

The wind component of the system comprises five 2 MW turbines, providing a total installed capacity of 10 MW. With a wind capacity factor of 35%, the turbines are expected to generate approximately 30.8 MWh per day, which is supplemented by the battery storage system. The chosen battery storage capacity is 26.25 MWh, allowing for six hours of backup at the peak load. The battery is designed with an 80% depth of discharge (DoD) and 90% efficiency, ensuring adequate energy availability while maintaining battery health and longevity.

From a cost perspective, the system's capital expenditure (CAPEX) is estimated at $27.5 million, which includes wind turbine costs (at $3 million per 2 MW unit) and battery storage at $300/kWh. Operating and maintenance (O&M) expenses over a 20-year project lifetime are estimated at $9.6 million. With a discount rate of 8%, these figures yield a total lifetime energy production of 551,880 MWh and result in a levelized Cost of Energy (COE) of $0.067/kWh.

This COE is considered competitive, especially in comparison to diesel-based generation or conventional grid extension in remote areas. The hybrid system not only supports energy sustainability and carbon emissions reduction but also enhances energy independence for the region. Moreover, the relatively low COE indicates that such a hybrid system could be a viable model for similar coastal or remote regions in Egypt and other developing countries where wind potential is high.

In summary, the proposed hybrid wind/BS system demonstrates technical feasibility and economic attractiveness for decentralized power generation in Ras Al-Hekma City, aligning with broader goals of renewable energy adoption and grid resilience in Egypt's energy strategy.

Table 7: Summary of input parameter for sizing a hybrid Wind/BS system to produce 3.5 MVA for Ras Al-Hekma City, Egypt, and the Cost of Energy (COE).

Parameter	Value
Peak Load	3.5 MVA (3.15 MW @ PF 0.9)
Daily Energy Need	75.6 MWh
Wind Turbine Capacity	10 MW (5 × 2 MW turbines)
Wind capacity factor	35%
BS backup hours	6
BS DoD	80%
BS Storage	26.25 MWh
BS efficiency	90%
BS cost	$300/kWh
Wind turbine cost	$3M per 2 MW
O&M (annual)	$480,000
Discount Rate %	8
Total CAPEX	$ 27.5 million
OPEX (20 years)	$ 9.6 million
Total Lifetime Energy	$ 551,880 MWh
Cost of Energy (COE)	$0.067/kWh

Table (8) outlines the sizing results and cost analysis of a hybrid Wind/Fuel Cell (FC) energy system designed to supply a continuous load of 3.5 MVA (3.15 MW at 0.9 power factor) for Ras Al-Hekma City, Egypt. This hybrid configuration is evaluated as an alternative to traditional generation or pure renewable systems, aiming to leverage wind energy as a primary source and hydrogen-based fuel cells for firming and backup.

The wind power system comprises five 2 MW turbines, totaling 10 MW of installed capacity. With a capacity factor of 35%, this setup yields approximately 30,660 MWh of energy annually. To address the intermittency of wind, a 3 MW fuel cell system is integrated, operating at a 10% utilization rate and 50% efficiency, contributing an additional 2,759 MWh per year. This combination results in a total annual energy output of 33,419 MWh, and a cumulative lifetime energy production of 668,380 MWh over the 20-year project duration.

Table (8) listed the economic evaluation reveals a total CAPEX of $33.8 million, which includes: $15 million for the wind turbines; $12 million for the FC system at $4,000/kW; $1.134 million for hydrogen storage (1,134 kg at $1,000/kg), and $5.6 million for balance-of-plant components (estimated at 20% of equipment costs).

Also, Table (4-10) listed The OPEX over 20 years is estimated at $20 million, consisting primarily of maintenance costs—$400,000 per year for wind (at 40 $/kW) and $600,000 per year for the FC system (at $200/kW). When both CAPEX and OPEX are combined, the total project cost amounts to $53.8 million.

Based on the projected energy output and total costs, the Cost of Energy (COE) is calculated at $0.080/kWh. While this is slightly higher than the $0.067/kWh from the wind/BS system in Table (4-10), the inclusion of a fuel cell provides greater flexibility and dispatchability, especially in low-wind periods or peak demand situations. Furthermore, the use of hydrogen—despite its high cost at $5/kg—offers a clean and scalable energy carrier that supports long-duration storage without degradation, unlike conventional batteries.

In summary, the Wind/FC hybrid system presents a technically viable solution for decentralized power generation in Ras Al-Hekma City, with the added benefit of enhanced reliability through hydrogen-based energy storage. Although the COE is moderately higher, the trade-off may be justified by improved resilience and long-term sustainability, particularly in scenarios where battery storage is either insufficient or economically constrained. This configuration also aligns with global trends favoring hydrogen as a cornerstone for future energy systems.

Table 8: Sizing results of a Wind / FC hybrid system for generate a 3.5 MVA load in Ras Al-Hekma City, Egypt, and calculate the Cost of Energy (COE).

Input data			
Load (MW)	3.15		
Wind Capacity (MW)	10		
FC Capacity (MW)	3		
Wind Capacity Factor	0.35		
FC Utilization	10%		
FC Efficiency	50%		
Hydrogen Energy Density	33.33 kWh/kg		
Hydrogen Cost ($/kg)	5		
Project Lifetime (years)	20		
Discount Rate	8%		
Energy			
Wind Energy (Annual)	30,660 MWh		
FC Energy (Annual)	2,759 MWh		
Total Annual Energy	33,419 MWh		
Lifetime Energy (20 yrs)	668,380 MWh		
Costs			
Component	Unit Cost	Size / Qty	Total Cost $
Wind Turbines	$3M	5 × 2 MW	$15,000,000
FC System	$4,000/kW	3,000 kW	$12,000,000
Hydrogen Storage	$1,000/kg	1,134 kg	$1,134,000
Balance of Plant	20% of above	–	$5.6 million
Total CAPEX	–	–	$33.8 million
Annual Wind O&M	$40/kW	10 MW	$400,000
Annual FC O&M	$200/kW	3 MW	$600,000
OPEX (20 yrs)	–	–	$20 million
Total Cost	–	–	**$53.8 million**
COE			**$0.080 / kWh**

Table (9) presents the technical and economic sizing of a Wind/Fuel Cell/Battery Storage (Wind/FC/BS) hybrid system tailored to supply a continuous 3.5 MVA (3.15 MW) load to Ras Al-Hekma City, Egypt. This system integrates three key technologies; wind turbines, hydrogen-based fuel cells (FCs), and battery storage (BS); to enhance reliability, flexibility, and renewable energy utilization.

The system includes 10 MW of wind capacity, operating at a 35% capacity factor, delivering an estimated 30,660 MWh/year, a 3 MW fuel cell, with 50% efficiency, contributing 1,580 MWh/year, a 17.5 MWh battery system with 80% depth of discharge, covering short-term fluctuations and quick ramp-up demands, and hydrogen storage capacity of 9,100 kg, providing extended backup capability.

The combined system delivers a total annual energy output of 32,240 MWh, amounting to 644,800 MWh over a 20-year lifetime. This output is slightly lower than the Wind/FC system and higher than Wind/BS, reflecting the balance between short-term (BS) and long-term (FC) support mechanisms.

The system's total capital expenditure (CAPEX) is $47.35 million, distributed across: Wind turbines: $15 million; FC system: $12 million; Battery storage: $5.25 million; Hydrogen storage: $9.1 million; Balance of plant: $6 million.

Operational costs over 20 years are estimated at $21.6 million, bringing the total project cost to $69 million. This results in a COE of $0.107/kWh, the highest among the three systems evaluated.

Table (10) provides a side-by-side comparison of the three hybrid renewable energy systems (HRES).

Table 9: Sizing results of a Wind / FC / BS Hybrid System for generate a 3.5 MVA load in Ras Al-Hekma City, Egypt, and calculate the Cost of Energy (COE).

Input data	
Load (MW)	**3.15 (3.15 MW, 0.9 pf)**
Wind Capacity (MW)	10
FC Capacity (MW)	3
BS Capacity (MWh)	17.5
Wind Capacity Factor	0.35
FC Efficiency	0.5
BS Depth of Discharge	0.8
Hydrogen Energy Density	33.33 kWh/kg
Hydrogen Storage	9,100 kg
Project Lifetime	20 years
Discount Rate	8%
Costs	
Component	Total Cost (USD)
Wind Turbines	$15,000,000
FC System	$12,000,000
BS Storage	$5,250,000
Hydrogen Storage	$9,100,000
Balance of Plant	$6,000,000
Total CAPEX	$47.35M
O&M (Wind)	$400,000/year
O&M (FC)	$600,000/year
O&M (BS)	$78,750/year
Total O&M (20yrs)	$21.6M
Total cost	**$69 M**
Energy Output	
Metric	Value
Annual Wind Energy (MWh)	30,660
Annual FC Energy	1,580
Total Annual Energy	32,240
Lifetime Energy (20 years)	644,800
COE	**$0.107 /kWh**

Table 10: Cost of Energy (COE) hybrid renewable energy systems (HRES); Wind/BS, Wind /FC, and Wind/FC/BS delivering 3.5 MVA in Ras-Al-Hekma City, Egypt.

Metric	**Unit**	**Value**		
		Wind/BS	**Wind/FC**	**Wind/FC/BS**
CapEx	$M	27.5	33.8	47.35
O&M + Repl.	$/year	9.6	20	21.6
COE	$/kWh	0.067	0.080	0.107

B.1. Sensitivity analysis

A sensitivity analysis trends for the three wind-based HRES configurations supplying 3.5 MVA in Ras Al-Hekma, Egypt:

i. Wind Speed (m/s): Range from 5.5 m/s to 6.5 m/s

As wind speed increases, COE decreases for all systems. Higher wind speeds generate more energy, reducing reliance on storage or backup. Most affected: All systems benefit, but Wind + FC sees the most relative improvement due to better FC utilization, Table (11).

ii. BS Cost: Range from 400 $/kWh to 200 $/kWh

Lower BS cost; lower COE for BS-based systems. Batteries become more economically viable, reducing the need for over-sizing generation or hydrogen storage. Most affected: Wind / BS system, where storage is a primary energy buffer, Table (11).

iii. FC Cost: Range: from 3200 $/kW to 1600 $/kW

As FC costs decrease, COE drops for systems using FCs. Reduced capital cost makes hydrogen-based backup more competitive. Most affected: Wind / FC, where FC is the main backup, Table (11).

iv. Discount Rate: Range from 10% to 6%

Lower discount rates reduce COE across all configurations. Affects the present value of long-term capital investments like wind turbines and batteries. Most affected: All systems, especially those with high capital investment like Wind / FC, Table (11).

Wind speed is the dominant technical factor affecting COE. FC cost and BS cost are major economic levers depending on system architecture. Discount rate universally impacts all configurations but doesn't change the relative ranking. Wind / BS consistently shows the lowest COE under most scenarios, while Wind / FC / BS offers a good trade-off between resilience and cost, Table (11).

Table 11: Sensitivity analysis for the three wind-based HRES configurations supplying 3.5 MVA in Ras Al-Hekma, Egypt.

Configuration	COE ($/kWh)	
	Wind Speed (m/s)	
	5.5 m/s	6.5 m/s
Wind/BS	0.091	0.074
Wind/FC	0.105	0.082
Wind/FC/BS	0.096	0.077
	BS Cost ($/kWh)	
	400 $/kWh	200 $/kWh
Wind/BS	0.091	0.074
Wind/FC/BS	0.096	0.077
	FC Cost	
	3200 $/kW	1600 $/kW
Wind/FC	0.105	0.082
Wind/FC/BS	0.096	0.077
	Discount Rate (%)	
	10%	6%
Wind/BS	0.085	0.078
Wind/FC	0.096	0.088
Wind / FC / BS	0.089	0.081

Wind/BS System: Lowest COE at $0.067/kWh. Benefits from a high wind capacity factor (35%) and direct-to- BS design. Simplest configuration, minimal O&M, and no fuel cost. Ideal for areas with consistent wind availability like this site under study. Sensitive primarily to BS cost and wind speed

Wind/FC System: COE at $0.080/kWh. Uses hydrogen storage and FC as backup during low-wind periods. Capital-intensive due to expensive FC and hydrogen storage infrastructure. More complex O&M and fuel-dependent. Suited for regions with hydrogen infrastructure or policy support.

Wind/FC/BS System: Highest COE at $0.107/kWh. Offers the most resilient and flexible system, combining short-term BS storage and long-term FC backup. Useful for critical applications requiring high availability. Most sensitive to hydrogen and FC costs, as well as BS prices. Wind + BS is the most cost-effective and simplest configuration in high-wind areas like Ras Al-Hekma.

Wind/FC/BS is the most resilient, suited for mission-critical applications despite higher cost. Wind/FC configuration is viable where hydrogen is available or policy supports green H_2. Wind speed and component costs (especially FC and BS) are the most sensitive variables affecting system COE. Discount rate plays a secondary but strategically important role through financing mechanisms.

Use Wind / BS system where cost is the primary driver, and wind availability is high and reliable. Consider Wind / FC / BS for installations requiring higher resilience, especially in remote or off-grid critical facilities. Invest in technology partnerships or incentives to reduce hydrogen and FC costs, enabling broader viability of Wind / FC-based HRES.

IV. Conclusions

This study investigated the design and performance of hybrid renewable energy systems (HRES) for a tourist resort in Ras Al-Hekma City, Egypt, with a peak load of 3.5 MVA. Two primary configurations; PV-based, and wind-based, HRES; were analyzed to determine their technical feasibility, economic viability, and environmental benefits. The key findings are summarized below:

The PV/BS system emerged as the most cost-effective option, with a Cost of Energy (COE) of 0.076 $/kWh. It demonstrated simplicity and reliability, making it ideal for regions with high solar irradiance. The PV/FC system, while offering high reliability, incurred significantly higher costs (0.089 $/kWh) due to the expense of hydrogen fuel cells and hydrogen production. The PV/FC/BS system provided a balanced solution with moderate COE (0.081 $/kWh) and enhanced resilience, suitable for critical applications requiring uninterrupted power.

The Wind/BS system achieved the lowest COE (0.067 $/kWh) among wind-based configurations, benefiting from high wind speeds and efficient battery storage. The Wind/FC system (0.080 $/kWh) and Wind/FC/BS system (0.107 $/kWh) offered greater reliability but were less economically viable due to higher capital and operational costs associated with fuel cells and hydrogen storage.

Solar irradiance and wind speed were the most influential parameters affecting COE across all configurations. Battery and fuel cell costs significantly impacted the economics of systems incorporating these technologies. Lower discount rates improved the financial viability of high-capital systems, such as those involving fuel cells.

All HRES configurations demonstrated 100% renewable energy penetration, aligning with global sustainability goals. The systems reduced reliance on fossil fuels, minimized greenhouse gas emissions, and enhanced energy independence for remote areas.

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