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Cost-Effective Analysis of a Hybrid PV/Fuel Cell/Battery System for Sustainable Seawater Desalination in a Tourist Resort in Ras Al-Hekma City, Egypt

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Abstract - The increasing global demand for clean water and sustainable energy solutions has driven the exploration of hybrid renewable energy systems for desalination applications. This study investigates the optimal sizing of a stand-alone hybrid energy system comprising PhotoVoltaic (PV) panels, Fuel Cells (FCs), and Battery Storage (BS) to power a Seawater Desalination (SD) plant and meet the electrical load of a tourist resort in Ras Al-Hekma City, Egypt. The resort's total electrical demand of 3.5MVA includes a Reverse Osmosis (RO) desalination plant, lighting, air conditioning, and a wastewater treatment facility. Three system configurations - PV/BS, PV/FC, and PV/FC/BS - were analyzed to determine the most cost-effective and reliable solution. The performance of each system was evaluated based on energy production, storage requirements, and economic metrics such as the Cost of Energy (COE) and Net Present Cost (NPC). Results indicate that the PV/FC/BS hybrid system offers a balanced solution with a COE of 0.081$/kWh, combining the reliability of fuel cells with the sustainability of solar energy and battery storage. This research highlights the potential of hybrid renewable energy systems to address water scarcity and energy challenges in remote coastal regions while contributing to Egypt's renewable energy goals.

Keywords: Hybrid renewable energy system; Seawater desalination; Cost of Energy (COE); Ras Al-Hekma City.

1 Introduction

As the global population expands at an accelerating rate, the demand for clean and safe water continues to grow. Numerous nations are already experiencing significant water shortages, and these issues are projected to worsen in the coming years. Consequently, the development of sustainable techniques to supply clean water for drinking, irrigation, agriculture, and domestic purposes is imperative. Electrodialysis is a process that utilizes electrical energy and ion-selective membranes to remove charged particles from water. It serves as an effective method for both desalination and the treatment of wastewater. Enhancing the sustainability of this process can be achieved by integrating it with renewable energy sources such as solar and wind. Among the technologies developed for this purpose, photo-electrodialysis, and photovoltaic-assisted electrodialysis are widely adopted for harnessing solar power in electrodialysis systems. However, these systems rely on environmental factors like solar availability and wind consistency, which fluctuate with time and location. Electrodialysis is especially suitable for treating brackish water, rather than seawater, due to its comparatively lower energy consumption. The energy required to desalinate brackish water—typically in the range of 1,000 to 5,000 ppm—varies between 0.4 and 4kWh per cubic meter. This review outlines the core principles of electrodialysis and examines its combination with renewable energy sources, including photo-electrodialysis, photovoltaic-assisted systems, reversible electrodialysis, and wind-driven electrodialysis. It also addresses freshwater output, energy

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efficiency, and the economic feasibility of such hybrid systems [1].

The sharp rise in population and rapid industrial growth have significantly reduced the availability of freshwater. As a result, desalination has become an essential strategy to combat the global water scarcity crisis. However, several barriers—such as the production of highly saline waste, substantial capital investment, and considerable energy consumption, which is largely met by fossil fuels—hinder the broader implementation of desalination technologies. Additionally, desalination plants fueled by non-renewable energy sources contribute to environmental degradation through Greenhouse Gas (GHG) emissions. In contrast, renewable energy sources are not only abundant and clean but also present a viable solution for powering desalination facilities. This interconnection between water and energy—often referred to as the water-energy nexus—is vital for achieving sustainability. Therefore, incorporating Renewable Energy Systems (RES) into desalination processes has become increasingly important. The aim of this review is to explore and evaluate various desalination technologies, including both thermal and membrane-based systems, alongside renewable energy types such as solar, wind, hydropower, geothermal, and biomass. It also considers socio-economic influences, environmental challenges, current limitations, and prospective research opportunities within both the desalination and renewable energy sectors [2].

Employing renewable energy within the water-energy nexus framework offers a powerful means of addressing climate change. As global concerns about GHG emissions and rising energy consumption intensify, many governments have introduced policies that promote the use of renewables. These clean technologies can be directly applied to desalination systems, whether membrane-based approaches like Reverse Osmosis (RO) and Membrane Distillation (MD), or thermal methods such as Multi-Stage Flash (MSF) and Multi-Effect Distillation (MED). While fossil-fuel-based desalination methods tend to have higher production capacities, renewable-powered alternatives typically consume less energy per unit of water produced, presenting a compelling case for wider adoption. Beyond direct applications, renewable energy also facilitates innovative processes such as generating biofuels from algae cultivated in wastewater; offering the added benefit of nutrient removal; and harvesting energy from salinity gradients using pressure-retarded osmosis or reverse electrodialysis. This paper reviews these evolving technologies, assessing their performance and applicability. It highlights the potential of integrating renewable energy into water treatment and outlines future directions to optimize energy systems for broader implementation in water-related infrastructure [3].

The main objective of this paper is to design and evaluate the optimal configuration of a hybrid renewable energy system; comprising PV panels, Fuel Cells (FCs), and Battery Storage (BS); to power both a seawater desalination plant and a tourist resort in Ras Al-Hekma City, Egypt. The study addresses the growing need for sustainable water and energy solutions in remote coastal regions by exploring three system scenarios: PV/BS, PV/FC, and PV/FC/BS. Using simulation and cost analysis tools, the research identifies the most cost-effective, reliable, and environmentally sustainable option to meet the 3.5MVA electrical demand of the resort. Ultimately, the paper aims to contribute to Egypt's renewable energy goals and demonstrate the feasibility of integrating clean energy technologies into water treatment infrastructure.

2 Location and Significance of Ras El-Hekma City

Ras El-Hekma City is a strategically located coastal city on Egypt's northwestern Mediterranean coast, near Alexandria, spanning approximately 230km². It lies within a region of notable sites, including El-Dabaa, El Alamein, and Marsa Matruh, and experiences a typical Mediterranean climate with mild, wet winters and warm, dry summers [4-6]. The area is historically significant, named after King Farouk's former recreational palace, and is now being developed into an integrated urban hub to boost tourism and real estate investment. Ras El-Hekma City is geographically located at a of 31.2°N and 27.85°E, **Fig. 1**. **Figure 2** shows the solar atlas of Egypt where one of the sun-belt countries is endowed with high-intensity direct solar radiation. Sunshine duration throughout the year ranges from 9 to 11h/day with few cloudy days [7].

The monthly averages of daily solar radiation for the study site were obtained from NASA's Surface Meteorology and Solar Energy database [8,9]. This dataset was utilized by HOMER® software to determine both the clearness index and the hourly solar radiation values, as illustrated in **Fig. 3** and **Fig. 4. Figure 3** shows the variation of solar radiation intensity during the year for one day for all months in the year at Ras El-Hekma City, Egypt. **Figure 4** presents the maximum recorded solar radiation was 7.52 kWh/m²/day in June, with the lowest value observed in December at 2.91kWh/m²/day. The annual average solar radiation was calculated to be 5.51kWh/m²/day. These values indicate that the location benefits from substantial sunlight throughout the year.

Fig. 1 Location of Ras Al-Hekma City, Egypt; (https://www.google.com/maps) [7]

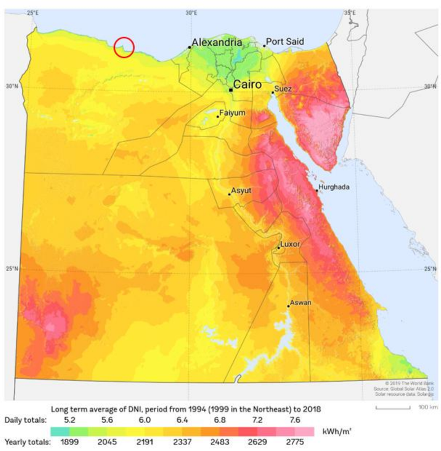


Fig. 2 Direct normal irradiation, Egypt; https://globalsolaratlas.info/download/egypt

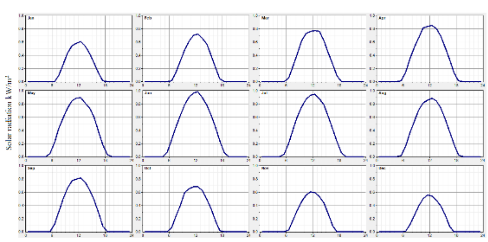


Fig. 3 Variation of solar radiation intensity during the year at Ras El-Hekma City, Egypt

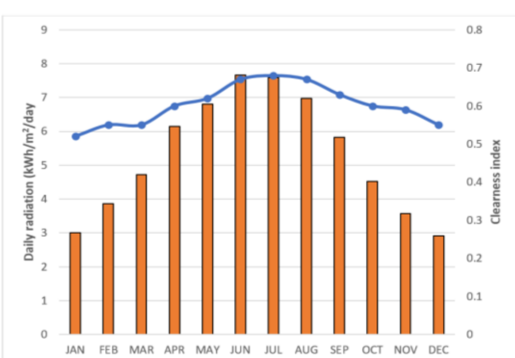


Fig. 4 Average daily solar radiation and clearance index during each month at Ras El-Hekma City, Egypt

3 Types of Load Demand in Ras El-Hekma City

The energy demand corresponds to an industrial electrical load serving a tourist resort located in Ras El-Hekma City. The electricity requirements support the following systems:

(1) Seawater Desalination (SD) Plant: This facility treats seawater to produce potable water for approximately 2,500 individuals, including staff and guests. The standard treatment system includes pre-treatment stages, RO desalination, automatic membrane flushing, and a Clean-In-Place (CIP) system for periodic membrane cleaning. The power demand is 0.25MW. Additional treatment steps can be incorporated based on water quality needs as presented in **Figure 5**.

(2) Lighting and Air Conditioning: To accommodate 1,000 guest rooms and associated services, the resort requires a dedicated power station with a capacity of 3MVA to meet the lighting and HVAC (heating, ventilation, and air conditioning) needs.

(3) Wastewater Treatment and Reuse: A Membrane BioReactor (MBR) plant processes wastewater to achieve Class A+ effluent standards, making it suitable for high-risk reuse applications. Standard procedures include initial screening, biological treatment, ultrafiltration, and sterilization. Further advanced treatments—such as nutrient removal—may be applied. This system also supports irrigation and recycled water applications for golf courses and other landscaping needs. Additional infrastructure includes desalination systems for irrigation water, filtration units for recycled water, and media filters for removing suspended solids from wastewater intended for vehicle cleaning operations. The power demand is 0.25MW.

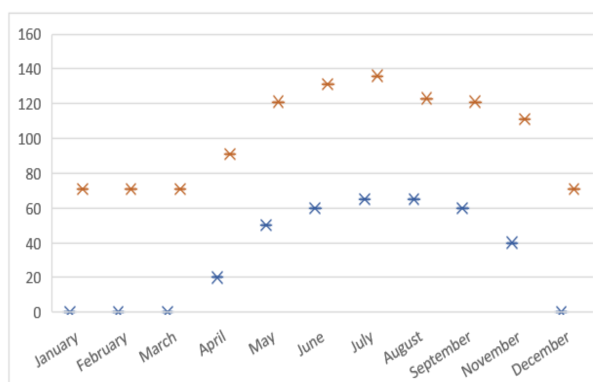


Fig. 5 The seasonal profile of the first load demand of SD plant

The combined electrical demand for these operations is 3.5 MVA. An additional 10% capacity is considered in the power station design to accommodate potential future increases in energy consumption.

Figure 6 displays a schematic overview of the primary components of the proposed SD system. The RO units were selected due to their efficiency and ability to treat highly saline water - up to 40,000 mg/L - sourced from the Mediterranean Sea, providing high-quality freshwater output. The treatment process begins with pre-filtration using backwashing and cartridge filters, by standard water treatment procedures. Specifications for the RO system is detailed in **Table 1**.

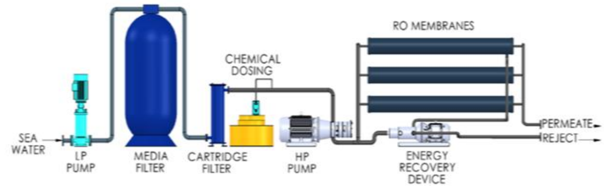


Fig. 6 Schematic diagram of the main components of the proposed RO SD plant

Table 1 Standard specifications of proposed RO SD plants

Parameter	Units	SWRO-50	SWRO-100	SWRO-150	SWRO-250	SWRO-500	SWRO-1000
Permeate Flow Rate	m³/day	50	100	150	250	500	1000
Permeate Recovery Rate	%	40 (typical)					
Permeate TDS	mg/L	<500 (typical)					
Raw Water TDS	mg/L	<40,000					
Raw Water TSS	mg/L	<30					
Raw Water Temperature	°C	15 ~ 35					
Ambient Design Temperature	°C	5 ~ 45 (-15 ~ 50 for insulated containerized system)					
Feed Water Inlet Pressure	kPa	>15 (flooded suction)					
Permeate Discharge Pressure	kPa	~40 (higher discharge pressures available on request)					
Brine Discharge Pressure	kPa	~40 (higher discharge pressures available on request)					
Power Supply	--	AC 380~450 V, 3 Phase, 50/60 Hz					
Power Consumption (Standard)	kW	20	25	35.5	52.5	105	190
Power Consumption (High Efficiency)	kW	--	--	26	--	43	71
No. Containers (Optional)	--	--	1 x 20’	1 x 20’	1 x 20’	1 x 40’	2 x 40’

4 Hybrid Renewable Energy Sources

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 [9]. In 2015, the United Nations introduced the 2030 Agenda, which includes 17 Sustainable Development Goals (SDGs) [10]. 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 [11].

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 [12]. 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 [13].

Egypt's significance in the global energy landscape stems largely from its strategic geographic features [14]. 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 [15]. 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, **Fig. 7,** indicates a consistent pattern of dependence on fossil fuels for energy production [16].

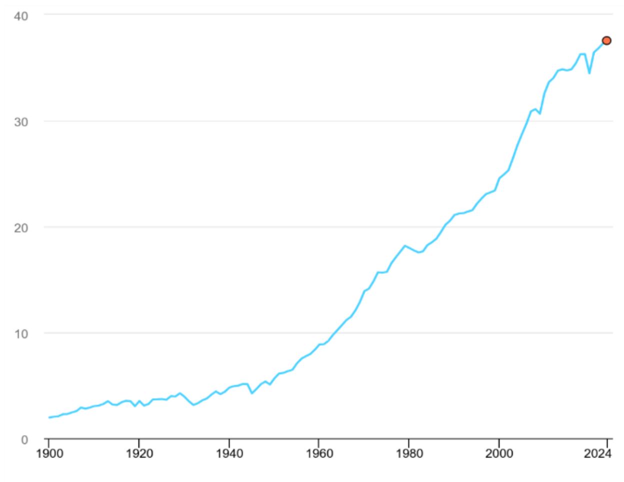


Fig. 7 Electricity production from conventional energy sources and CO_2 emissions from gaseous fuel consumption (Mt) over the years from 1900 to 2024 [16]

4.1 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 156,300GWh [15]. Of this total, 66% was supplied by natural gas, 7% by hydropower, and only 8% by renewable sources [15]. 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 [17].

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 545MW in Zafarana. The Zafarana wind farm, completed in 2015 with a \$6.8 billion investment, expanded its capacity to 340MW by 2017 and 600MW by 2018. A national strategy was introduced to expand wind power capacity to 7.2GW by 2020. By that year, wind energy accounted 1.44% of the country's total electricity production, making it the third-largest renewable energy source [18]. 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.

4.2 Renewable energy for desalination and remote areas

With the rising global awareness around environmental protection and emission reduction, shifting toward 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 raising concerns 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 [19].

4.3 Hybrid systems and micro 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 micro grids come into play. A microgrid enhances the traditional power infrastructure through technologies that allow two-way communication and electricity flow, distributed energy generation, automated control systems, and predictive analytics [20-22].

Microgrids facilitate dynamic interaction between energy providers and consumers, allowing electricity usage to be optimized based on real-time conditions, costs, and environmental concerns. These results in a more secure, efficient, and reliable energy system [23, 24].

4.4 Installed renewable energy capacity in Egypt

As of 2021, Egypt's installed renewable energy capacity reached approximately 19.2GW. To meet future energy goals, the government has outlined plans to scale this capacity significantly - targeting 50.5GW by the 2029/2030 period and ultimately reaching 62.6GW 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 2**, which illustrates the projected growth in renewable energy installations over the coming years [25].

Table 2 Egypt's renewable energy capacity in GW [26]

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

4.5 PV Cells

In recent years, countries around the world have increasingly adopted renewable energy sources for electricity generation, and the energy sector itself has shifted focus toward sustainable options. Among various green energy sources—such as wind, biomass, hydro, and solar—solar energy has seen rapid growth due to the global decline in non-renewable resources. Solar energy, available abundantly throughout the year, is clean, quiet, and environmentally friendly. Consequently, a growing number of industries large and small—as well as residential users, are turning to PV solar cells for electricity generation.

Much of the academic research in this area has concentrated on the modeling of PV cells, particularly using the one-diode equivalent circuit model. This article explores the Single-Diode Solar Cell (SDSC) and the more advanced Double-Diode Solar Cell (DDSC) models using MATLAB/Simulink under varying operating conditions. The performance of both models is evaluated under different temperatures, solar irradiance levels, and shunt resistance values. The study enables a clear understanding of the voltage-current (V-I) and power-voltage (P-V) characteristics of solar cells. Comparative simulation results between the SDSC and DDSC models are presented, and the impact of partial shading on performance is also discussed [26].

Globally, energy production still heavily depends on fossil fuels like coal and petroleum. However, due to rising demand from expanding industrial activities and increased household appliance usage, fossil fuel supplies are dwindling. Traditional fossil-fueled power plants not only have high costs-including capital, operational, and maintenance expenses-but also result in significant environmental damage, such as CO_2 emissions, air and water pollution, and acid rain. As a result, building new fossil-fuel based power stations involve considerable investment and land requirements [26].

Solar radiation, produced by nuclear fusion at the sun's core, reaches Earth in quantities sufficient to meet global energy demands many times over. Because of its minimal environmental impact—zero carbon emissions and low maintenance—solar energy is being increasingly favored by governments, industries, and organizations as a sustainable power generation method [26].

Egypt, in particular, benefits from a high level of solar radiation. According to the country's solar atlas, Egypt receives an average of 3,050 hours of sunshine annually. The direct normal irradiance ranges from 1,970 to 3,200 kWh/m² per year, while overall solar irradiance lies between 2,000 and 3,200kWh/m². These favorable conditions make Egypt an ideal location for a broad spectrum of solar technologies, including PV systems and Concentrated Solar Power (CSP) plants [27].

As per the Global Solar Atlas, Egypt's solar energy potential is estimated at around 74 billion MWh annually [28], a figure far exceeding the country's current electricity output [29–31]. In response to this potential, the Ministry of Electricity and Renewable Energy has initiated multiple projects to harness solar power. These initiatives include both completed and ongoing solar developments utilizing various solar technologies, as summarized in **Table 3**.

Table 3 Solar power projects in Egypt

Installed Capacity 1747 MW	Bemba	1456 MW
	Net Metering	100 MW
	Decentralized System	32 MW
	Siwa Solar Plant	10 MW
	Kurymat	140 MW
Project Under Construction 226 MW	Private Sector	200 MW
	Kom Ombo	26 MW
Project Under Development 1070MW	West Nile	600 MW
	Hurghada	20 MW
	Kom Ombo	50 MW
	Zafarana	100 MW
	Private Sector	200 MW
	West Nile	100 MW

Net metering is a policy that allows property owners to install PV solar systems on their buildings to cover part or all their electricity needs. Any surplus energy generated by these systems can be fed back into the national power grid, and consumers are permitted to draw from this excess later after the solar panels have been installed [32]. This setup requires a grid-connected solar system and the use of a bi-directional electricity meter. This specialized meter records both the energy consumed from the grid and the additional energy generated by the solar system and exported back to the Egyptian Electricity Transmission Company [33].

4.6 Battery storage

Solar and wind energy systems are inherently dependent on environmental conditions such as sunlight and wind speed, both of which fluctuate throughout the day and across seasons. This variability presents a major challenge to ensuring consistent and reliable power delivery to consumers. Battery energy storage systems play a crucial role in mitigating this issue by storing surplus electricity generated during favorable conditions and supplying it during periods of low generation, such as nighttime or poor weather.

In this study, lithium-ion batteries have been selected for analysis due to their superior performance and availability in local markets, offering advantages over traditional lead–acid batteries [34].

Batteries serve as a fundamental component of standalone microgrids, ensuring uninterrupted power by covering the energy deficit when renewable generation falls short [35]. The battery's State of Charge (SOC) at any given time (t) can be calculated using an energy balance approach, which considers the interaction between energy generated by wind and solar systems and the power consumed by the load, as defined by the following equations [36]:

Charging mode:

$$E_B(t+1) = E_B(t)(1-\sigma) + surpluspower * \eta_{BC} \quad (1)$$

Discharging mode:

$$E_B(t+1) = E_B(t)(1-\sigma) - deficit\,(power/\eta_{BD}) \quad (2)$$

Here, E_B represents the energy stored in the battery. The parameters η_{BC} and η_{BD} denote the battery's charging and discharging efficiencies, respectively. For this study, these efficiencies are assumed to be 90% for charging and 85% for discharging [37]. The symbol σ refers to the battery's self-discharge rate, which indicates the loss of stored energy over time. For most battery types, this rate is typically around 0.2% per day [38].

4.7 Fuel cell and hydrogen storage tank

A FC is an electrochemical device that efficiently converts hydrogen gas into electricity, heat, and water with no harmful emissions. It operates by reacting hydrogen with oxygen from the air, resulting in clean electricity generation, with water as the only by-product. This makes fuel cells a sustainable and environmentally friendly energy solution suitable for a wide range of applications, including stationary power systems, mobile electronics, and transport.

To maintain a continuous hydrogen supply for the fuel cell, a hydrogen storage tank is used. These tanks typically store hydrogen gas at high pressures—ranging from 5,000 to 10,000 psi—ensuring high energy density and extended operational periods between refueling sessions. The storage tank plays a vital role in the fuel cell system, enabling uninterrupted operation without the need for frequent hydrogen replenishment [39].

In hybrid energy systems, particularly those involving PV and wind energy sources, fuel cells serve as a reliable backup when renewable sources are unable to meet energy demands. A key component in this setup is the Proton Exchange Membrane (PEM) electrolyzer, which uses electricity to produce hydrogen during periods of low energy consumption. The electrolyzer facilitates water electrolysis, separating water into oxygen and protons at the anode, while hydrogen is formed at the cathode. Though the capital cost of electrolyzers is relatively high, their operational and replacement costs are significantly lower.

Hydrogen storage system sizing is based on the surplus energy from PV and wind sources and the minimum energy load required. In this configuration, the electrolyzer can generate up to 23kg of hydrogen per hour using excess energy. The hydrogen storage tank is designed to hold up to 100kg of hydrogen, the maximum safe level expected throughout the year. Gas compression at high pressure is employed to reduce storage volume—a 125-liter tank can store 5kg of hydrogen under these conditions. This compression technology is widely used by automotive manufacturers, allowing hydrogen-powered vehicles to travel 500–600 km per refueling cycle [40–41].

In this system, hydrogen is compressed and stored using Model H15T4X20021 tanks, each capable of compressing 10 kg of hydrogen to 345 bars. The complete setup consists of ten compressors and ten hydrogen tanks, along with an additional tank for surplus hydrogen. Altogether, the system can store 100kg of hydrogen at a constant pressure of 345 bar, with the tanks interconnected via pipelines to maintain consistent storage and distribution pressure [42]. **Table 4** provides a summary of the reviewed studies and system configurations.

5 Results and Discussion

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 PV, FC, and BS systems are studied. Three different scenarios; PV/BS, PV/FC, and PV/FC/BS involve 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 COE, **Fig. 8.**

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-Hikmah City is approximately 5.5 kWh/m²/day and the average annual solar irradiance: is ~2,000kWh/m²/year as shown in **Fig. 4**.

Table 4 Summary of the reviewed studies and system configurations

Author, year, and reference	Location	Hybrid Energy Sources	COE ($/kWh)	NPC ($)	Method
Krishan and Suhag 2019 [43]	India	Wind/PV/Battery	0.288	228,353	HOMER and MATLAB
Das *et al.* 2019 [44]	India	PV/Battery/ Pumped Hydro/Biogas	--	0.813 million	Water cycle algorithm and moth-flame optimization
Elkadeem *et al*. 2019 [45]	Sudan	Wind/PV/DG/Battery	0.387	24.16 million	HOMER
Ramesh and Saini, 2020 [46]	India	Wind/PV/DG/Battery	0.027	1,55,977	HOMER
Kasaeian *et al.* 2020 [47]	Iran	PV/Wind/Battery	0.44	23,148.84	HOMER
Ayodele et al. 2021 [48]	Nigeria	Wind/PV/Hydrogen Storage	2.34	206,323	HOMER
Makhija *et al.* 2021 [49]	India	PV/Battery	0.0598	185,431	System Adviser Model
Ali *et al.* 2021 [50]	Pakistan	Wind/Hydro/Battery	0.068	--	HOMER
		PV/ Hydro/Wind/Battery	0.077	--	HOMER
Li *et al.* 2021 [51]	China	Wind/PV/Battery	0.069	28,041	HOMER
Almutairi 2021 [52]	Iran	PV/Wind/DG/Battery	1.058	284,724	HOMER
Thirunavukkarasu , 2021 [53]	India	PV/Wind/DG/Battery	0.266	138,197	HOMER
N. Ganjei, 2022 [54]	Iran	PV/DG/Battery	0.371	3224	HOMER
F. Ishraque, 2020 [55]	Bangladesh	PV/Wind/DG	0.125	6191	HOMER
R. Ranjan, 2020 [56]	India	PV/Wind/ DG/Battery	0.144	--	HOMER
Venkatachala, 2021 [57]	India	PV/Wind/DG/Battery	0.1266	28.944.800	HOMER
M. Kharrich, 2021[58]	Morocco	PV/Wind/Battery/DG	0.0917	74327	HOMER
Khosravani, A Safae, 2023 [59]	USA	PV/DG/Battery	0.302	--	HOMER Pro Microgrid
Mahmoud, 2022 [60]	Egypt	PV/Wind/ Battery/DG	0.21582	6323657.28	MATLAB simulation
Makhija *et al.* 2021 [61]	India	PV/Battery	0.0598	185,431	Simulated using SAM software
Ali *et al.* 2021 [62]	Pakistan	Wind/Hydro/Battery	0.068	6,322,356	HOMER Pro

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%. The system lifetime is 25 years for PV and 10 years for both battery systems and FCs.

5.1 First scenario: Cost-effective analysis of hybrid PV/Batteries system

Assume the system operates for 8 hours/day, the required energy (E) output is:

$$E = 3.5 \times 8 = 28\, MWh/day \quad (3)$$

Assume system losses of 20% (due to inefficiencies, dust, temperature, etc.); the required energy from PV is:

$E_{PV} = 28/((1-0.2)) = 35MWh/day$ (4)

The PV capacity required to generate 75.6 MWh/day is:

$PV_{Capacity} = E_{PV}/(Irradiance \times \mu) = 35000/5.5 \times 0.75 = 8485kW \approx 8.5MW$ (5)

If each PV panel has a capacity of 400 W, the number of panels (N_{Panels}) required is:

$N_{Panels} = (8500 \times 10^3)/400 = 21250\ Panels$ (6)

Assume the battery system (BS) needs to store energy for 4 hours of operation, typical for peak shaving or backup, the energy storage ($E_{storage}$) required is:

$E_{storage} = 3.5 \times 4 = 14MVA$ (7)

Assume Depth of Discharge (DoD) of battery storage is 80%, battery capacity (Bcapacity) is calculated as:

$B_{capacity} = \frac{14}{0.8} = 17.5MWh$ (8)

Using Lithium-ion batteries (common for large-scale systems), the cost of Lithium-ion batteries is about 200$/kWh.

The inverter capacity should be rated at least 3.5 MVA to handle the peak load and potential overloads.

The PV system cost is 0.8 $/W (including installation);

$Total\ PV\ cost = 8.5 \times 0.8 = \$6.8\ million$ (9)

The cost of a Battery System (BS) is 200 $/kWh;

$Total\ BS\ cost = 17.5 \times 200 = \$3.5\ million$ (10)

Balance of System (BoS) costs include the cost of inverters, mounting structures, wiring, etc. are about 20% of PV and battery costs.

$BoS\ cost = 0.2 \times (6.8 + 3.5) = \$2.06\ million$ (11)

Total System Costs (TSC) are calculated:

$TSC = PV\ cost + BS\ cost + BoS\ cost$

$= 6.8 + 3.5 + 2.06 = \$12.36\ million$ (12)

To calculate the COE; annual energy production (E_{annual}) is calculated as:

$E_{annual} = 35 \times 365 = 12775MWh/day$ (13)

Assume the system lifetime is 25 years, and assume discount rate = 5%; the Capital Recovery Factor (CRF) is calculated as:

$CRF = r(1-r)^n/(r(1-r)^n - 1) = 0.05(1-0.05)^{25}/(0.05(1-0.05)^{25} - 1) \approx 0.07095$ (14)

Where; r = discount rate, n = lifetime.

Levelized COE is calculated as:

$COE = (TSC \times CRF)/E_{annual} = 0.076\ \$/kWh$ (15)

5.2 Second scenario: Cost-effective analysis of hybrid PV/Fuel Cell System

The system needs to supply 3.5MVA, assuming a Power Factor (PF) of 0.9, the power requirement (P) is calculated as:

$P = 3.5 \times 0.9 = 3.15\ MW$ (16)

If the system operates continuously for t = 24 hours, the daily energy requirement (EPV) is:

$E_{PV} = P \times t = 3.15 \times 24 = 75.6MWh/day$ (17)

Sizing the PV Array; solar irradiance is 5.5 kWh/m²/day; assume an overall system efficiency μ of 80% (including inverter losses, wiring losses, etc.).

The PV capacity required to generate 75.6MWh/day is:

$PV_{Capacity} = \frac{E_{PV}}{Irradiance \times \mu} = \frac{75.6}{5.5 \times 0.8} = 17.18\ MW$ (18)

If each panel has a capacity of 400W, the number of panels (N_{panels}) required is calculated as:

$N_{panels} = \frac{17.18 \times 10^6}{400} = 42955\ Panels$ (19)

Sizing the fuel cell system; the FC system will act as a backup or supplementary power source during periods of low solar generation (e.g., nighttime or cloudy days).

Assume the fuel cell system covers 30% of the daily energy requirement (E_{FC}):

$E_{FC} = 75.6 \times 0.3 = 22.68MWh/day$ (20)

To supply this energy over 24 hours, the required fuel cell capacity ($FC_{capacity}$) is calculated as:

$FC_{capacity} = \frac{22.68}{24} = 0.945MW \approx 1MW$ (21)

Assuming a fuel cell efficiency of 50%, the energy content of hydrogen is 33.3 kWh/kg. The daily hydrogen consumption (H_C) is:

$H_C = \frac{22.68}{33.3 \times 0.5} = 1362\ kg/day$ (22)

Cost analysis: assume the cost of PV panels is 0.80 $/W (including the cost of inverters, mounting, wiring, *etc*), the cost of PV (PV_{cost}) is calculated as:

$PV_{cost} = 16.3 \times 10^6 \times 0.8 = \$13.04\ million$ (23)

Fuel cell system costs; 1,000 $/kW for fuel cell systems, fuel cell cost (FC_{cost}):

$FC_{cost} = (10^3 kW) \times (1000\ \$/kW) = \$1\ million$ (24)

Assume 500 $/kg for hydrogen storage (HS_{cost});

$HS_{cost} = 1.362 \times 500 = \$0.681\ million\ (daily\ cost)$ (25)

The total hydrogen cost (HS_{cost}) for a 10-year lifetime is:

$Tolal\ HS_{cost}\ (for\ 10 - year\ lifetme) = 0.681 \times 365 \times 10 = \$2.48\ billion$ (26)

Total fuel cell system cost:

$Total\ FC_{cost} = \$1\ million + \$2.48\ billion = \$2.481\ billion$ (27)

$Total\ System\ Cost = \$13.04\ million\ (PV) + \$2.48\ billion\ (Fuell\ Cell) = \$2.494\ billion$ (28)

COE calculation; the total energy produced over 25 years:

$$Annual\ Energy = 75.6\ MWh/day \times 365 = 27{,}594\ MWh/year \quad (29)$$

$$Total\ Energy = 27{,}594\ MWh/year \times 25\ years = 689{,}850\ MWh \quad (30)$$

$$Total\ System\ Cost \text{ is } \$2.\ 494\ billion \quad (31)$$

$$COE = \frac{Total\ System\ Cost}{Total\ Energy\ Produced} = 0.089\$\ /kWh \quad (32)$$

5.3 Third scenario: Cost-effective analysis of hybrid PV/FC/BS System

To calculate the COE for a PV, fuel cell, and battery storage system, the following steps are considered:

Capital Expenditure CapEx; Upfront costs of the PV array, fuel cell system, battery storage, inverters, balance of system, and installation.

Operational Expenditure (OpEx); annual costs for maintenance, fuel (for the fuel cell), replacements, and other operational expenses. Total energy produced by the system over its lifetime, 25 years for PV, 10 years for both batteries and fuel cells. The rate used to discount future costs and energy production to their present value (typically reflects the cost of capital or desired return on investment), is 5% (0.05).

COE formula is calculated as:

$$COE = \frac{Total\ System\ Lifetime\ Costs}{Total\ Lifetime\ Energy\ Produced} \quad (33)$$

Where:

$$Total\ Lifetime\ Costs = CapEx + Present\ Value\ of\ OpEx$$

$$Total\ Lifetime\ Energy\ Production = Annual\ Energy\ Production \times System\ Lifetime \quad (34)$$

Use the Present Value of Annuity formula:

$$PV_{OpEx} = Annual_{OpEx} \times \left(\frac{1-(1+n)^{-n}}{r}\right) \quad (35)$$

Where: r discount rate (=0.05); n is system lifetime (=25 years).

$$PV_{OpEx} = \$22620750 \times ((1-(1+25)^{-25})/0.05) = \$\ 318.7 \times 10^6 \quad (36)$$

$$Total\ Lifetime\ Costs = CapEx + PV_{OpEx} = 39{,}567{,}500 + 318{,}700{,}000 = \$\ 358{,}267{,}500 \quad (37)$$

$$Annual\ Energy\ Production = 75.6\ MWh/day \times 365\ days = 27{,}594\ MWh/year \quad (38)$$

$$Lifetime\ Energy\ Production = 27{,}594\ MWh/year \times 25\ years = 689{,}850\ MWh \quad (39)$$

$$COE = \frac{Total\ System\ Lifetime\ Costs}{Total\ Lifetime\ Energy\ Produced} = \frac{358276500}{68985\ MWh} = 0.081\ \$/kWh \quad (40)$$

To compare the performance and economics of three HRES; PV/BS, PV/FC, and PV/FC/BS; delivering 3.5MVA in Ras-Al-Hekma City, Egypt, the evaluation of each configuration in HOMER Pro style is focusing on: sizing of components, COE, renewable penetration, fuel dependency, and system lifetime economics.

Table 5 and **Table 6**, compare the design and cost performance of three HRES configurations; PV/BS, PV/FC, and PV/FC/BS; to supply a 3.5MVA load in Ras Al-Hekma City, Egypt.

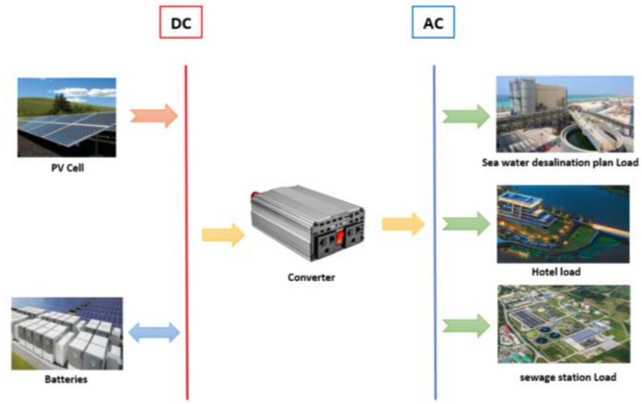
Table 5 outlines the key components, sizing, and capital costs of three HRES scenarios,
along with associated operational and replacement costs. PV/BS System; this configuration introduces fuel costs and system complexity, but reduces dependency on costly battery systems. PV/FC/BS System; this system balances the benefits of both storage types and offers resilience and reliability, albeit with slightly higher complexity and maintenance.

Table 6 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.
(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.

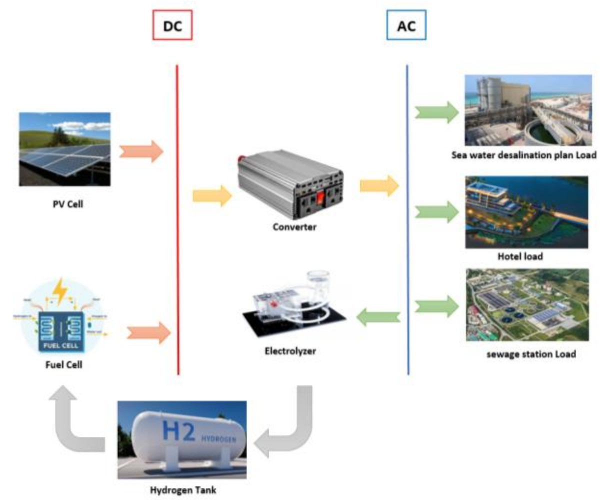
PV/BS is ideal where simplicity and fuel independence are prioritized, but long-term battery costs are a drawback. PV/FC offers greater dispatchability and reliability, but introduces high fuel-related costs and system complexity. PV/FC/BS provides a compromise between cost, reliability, and energy flexibility,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

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

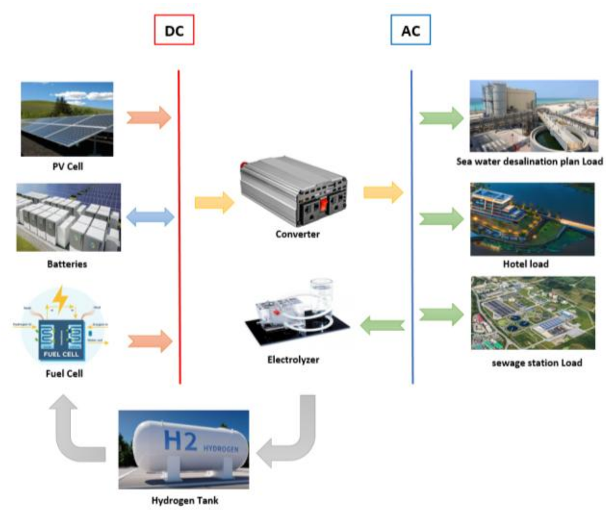
Hybrid renewable energy system of PV/BS is lowest COE and simplicity which is ideal for remote or off-grid areas with good sun. Hybrid renewable energy system of PV/FC/BS is High reliability with moderate cost which is good balance with backup and better resilience. Hybrid renewable energy system of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



(A) 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

Fig. 8 Three different scenarios of hybrid energy sources; (A) PV/BS, (B) PV/FC, and (C) PV/FC/BS with off-grid

Table 5 Sizing and costs of HRES; PV/BS, PV/FC, and PV/FC/BS delivering 3.5MVA in Ras Al-Hekma City

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
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
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

Table 6 COE, HRES; PV/BS, PV/FC, and PV/FC/BS delivering 3.5MVA in Ras Al-Hekma City, Egypt

Metric	Unit	Value		
		PV/BS	PV/FC	PV/FC/BS
CapEx	$M	21.6	23.9	23.45
O&M + Repl.	$/year	360000	400000	450000
COE	$/kWh	0.076	0.089	0.081

6 Conclusion

This study demonstrates the feasibility of using a hybrid renewable energy system to power a tourist resort and desalination plant in Ras Al-Hekma City, Egypt. Three configurations - PV/BS, PV/FC, and PV/FC/BS - were evaluated, with the PV/FC/BS system emerging as the most viable option due to its balanced performance, reliability, and cost-effectiveness. The integration of PV panels, fuel cells, and battery storage ensures continuous energy supply despite the intermittent nature of solar radiation, while also reducing dependence on fossil fuels and minimizing environmental impact.

The PV/BS system emerged as the most cost-effective option, with a 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 findings underscore the importance of hybrid systems in addressing the water-energy nexus, particularly in remote areas with high solar potential. Future work could explore advanced energy management strategies, alternative storage technologies, and the inclusion of additional renewable sources like wind energy to further optimize system performance. This research contributes to the growing body of knowledge on sustainable desalination and renewable energy integration, supporting global efforts toward cleaner production and climate change mitigation.

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