

Techno-Economic Assessment of Renewable Energy-Based Microgrids: A Case Study for Building in El Gouna, Egypt

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ARTICLE INFO

Article history:

Received 13 January 2025

Revised 13 March 2025

Accepted 22 August 2025

Available online 17 October 2025

Handling Editor: Prof. Dr. Mohamed Talaat Moustafa

Keywords:

Microgrid
Wind-PV Hybrid systems
Renewable energy
Wind Turbine
Solar Energy
PV system

ABSTRACT

The increasing global demand for clean and reliable electricity has positioned microgrids as a key solution for integrating renewable energy into modern power systems. This paper presents a comprehensive review of microgrid technologies, focusing on the integration of solar and wind energy as sustainable alternatives to conventional fossil fuel-based power generation. Microgrids enhance system resilience, improve power quality, and enable local energy management while supporting the global transition toward decarbonization and energy decentralization. The study outlines the operational modes of microgrids—grid-connected, islanded, and hybrid and evaluates the technical and economic viability of each. Special emphasis is given to the performance characteristics, sizing methodology, and cost analysis of wind turbines and photovoltaic systems. A modeling framework is developed to simulate four renewable-based scenarios in El Gouna, Egypt, comparing 100% wind, 100% PV (on-grid and off-grid), and a hybrid wind–PV configuration. Results show that while wind-dominant systems offer high reliability, hybrid solutions provide the most cost-effective performance, with reduced dependency on a single energy source. The findings highlight the role of integrated renewable energy microgrids in enhancing energy security, reducing emissions, and ensuring a sustainable energy future.

1. Introduction

Microgrids are essential for enhancing energy resilience, enabling local control, and integrating renewable energy sources into a more sustainable and reliable power system. A microgrid is an electricity distribution system that includes local loads and distributed energy resources (DERS), which can operate in a coordinated manner either while connected to the main utility grid or in islanded mode. Various renewable energy sources, such as photovoltaic (PV) modules, small wind turbines, and mini-hydro systems, are commonly used as power generators within microgrids. This allows microgrids to improve grid efficiency, reduce dependence on centralized systems, and contribute to resolving energy crises [1, 2]. One of the core advantages of microgrids is their ability to operate independently during main grid failures, provided that local generation and storage can meet demand. Their growing popularity is driven by the higher utilization of renewables, increased reliability and flexibility, improved power quality, and lower capital and operational costs. Globally, electricity systems are undergoing a transition toward decentralization, decarbonization, and democratization — trends that align closely with microgrid development. In this context, microgrids serve as a critical enabler of bottom-up energy innovation and distributed, carbon-free energy solutions the general components of microgrid are illustrated in Fig. 1. [1, 3-5].

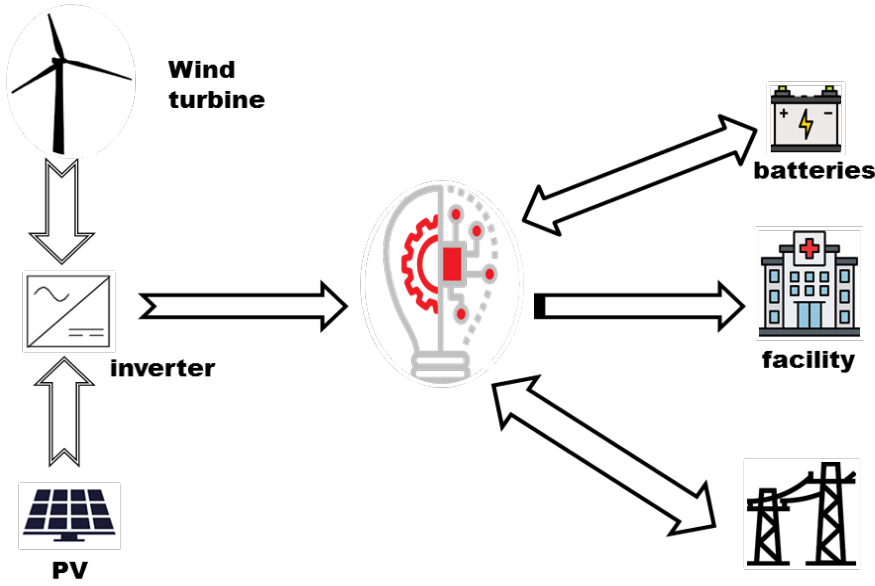


Figure 1. Microgrid components

A microgrid operates by interconnecting distributed energy sources such as generators, solar panels, and energy storage systems—with nearby consumers including homes, communities, businesses, and industrial facilities. This localized energy network provides numerous advantages over conventional centralized systems. One of the primary benefits is the potential for electricity cost reduction, as microgrids can draw power from the main grid only when it is economically favorable, while relying on local generation and storage to maximize self-consumption [6]. In addition to cost efficiency, microgrids can contribute to grid stability and generate income by offering ancillary services to the national grid where market regulations allow. Furthermore, they play a critical role in achieving sustainability goals by enabling the integration of renewable energy sources and reducing greenhouse gas emissions. Perhaps most importantly, microgrids enhance energy resilience and safety by enabling autonomous operation during main grid outages. This ensures uninterrupted power supply to critical loads, even during widespread blackouts, making microgrids a robust solution for both urban and remote applications [6].

1.1 Microgrid Connection Modes

Microgrids are generally classified into three main types based on their mode of operation and connectivity with the main utility grid: grid-connected, islanded (off-grid), and hybrid microgrids [7, 8]. The grid-connected microgrid operates in parallel with the main power grid, allowing the exchange of power between the local distributed energy resources and the utility network. This type provides increased reliability, better power quality, and enhanced energy efficiency. It is commonly used in urban or industrial areas where a stable grid is already available, and it helps reduce peak loads and support grid stability. When the grid fails, this type can sometimes switch to islanded mode temporarily, depending on the system configuration [9, 10]. On the other hand, the islanded (off-grid) microgrid functions independently from the utility grid and relies entirely on local energy generation sources such as solar panels, wind turbines, diesel generators, and energy storage systems (like batteries). These microgrids are ideal for remote or rural areas with limited or no access to the central grid, providing a sustainable and autonomous power solution [8]. The third type, the hybrid microgrid, combines features of both grid-connected and islanded systems [11]. It can operate with or without the main grid and switch seamlessly between modes. This hybrid functionality offers enhanced flexibility, resilience, and energy security, particularly valuable in regions prone to outages or with intermittent renewable generation [12]. The comparison of Microgrid connection modes is demonstrated in the following Table 1.

TABLE 1

The comparison of Microgrid connection modes

Feature	Grid-Connected	Islanded (Off-Grid)	Hybrid
Connectivity	Connected to the main utility grid	Completely isolated from the utility grid	Can operate both grid-connected and islanded
Typical Application	Urban/industrial areas	Remote or rural areas	Areas requiring high reliability and flexibility
Power Sources	Solar, wind, grid power, batteries	Solar, wind, diesel generators, batteries	Mix of grid and local generation
Energy Storage	Optional but recommended (to handle grid outages)	Essential (must support full local demand)	Critical for both modes
Reliability	Moderate (depends on grid stability)	High (fully self-reliant if well designed)	Very high (can switch based on condition)
Control System Complexity	Moderate (grid handles frequency/voltage mostly)	High (local system manages all control)	Very high (needs seamless transition mechanisms)
Cost	Lower upfront (leverages existing grid)	Higher upfront (requires complete infrastructure)	Highest (complex control + dual-mode equipment)
Main Challenge	Grid dependency, synchronization issues	Supply-demand balance, high CAPEX	Complex coordination between modes
Example	Community solar projects in cities	Microgrids in African or remote islands	University campuses or military bases
References	[13], [8], [6]	[13], [6]	[8],[6], [14]

The remainder of this paper is organized as follows: Section 2 provides a comprehensive overview of microgrid architecture, operational modes, and the integration of renewable energy sources such as wind and photovoltaic (PV) systems. Section 3 discusses the fundamental working principles, classifications, and components of wind and solar technologies, including system sizing methodologies and efficiency considerations. Section 4 presents different photovoltaic technologies and their comparative performance in terms of cost, lifespan, and efficiency. Section 5 outlines the modeling assumptions and scenario design used to simulate various renewable energy configurations for the El Gouna region. Section 6 discusses the results of the simulation, comparing technical and economic performance across wind-only, solar-only, off-grid PV, and hybrid systems. Finally, Section 7 concludes the paper with key findings, practical implications, and recommendations for future work in the deployment of cost-effective and resilient renewable energy microgrids.

2. Renewable Energy

2.1. Wind Energy

Power has been extracted from the wind over hundreds of years with historic designs, known as windmills, constructed from wood, cloth and stone for the purpose of pumping water or grinding corn. Historic designs typically large, heavy and inefficient were replaced in the 19th century by fossil fuel engines and the implementation of a nationally distributed power network. A greater understanding of aerodynamics and advances in materials, particularly polymers, has led to the return of wind energy extraction in the latter half of the 20th century. Wind power devices are now used to produce electricity and are commonly termed Wind Turbine. We need to understand the principle of wind turbines. It turns wind energy into electricity using the aerodynamic force from the rotor blades, which work like an airplane wing or helicopter rotor blade. When wind flows across the blade, the air pressure on one side of the blade decreases. The difference in air pressure across the two sides of the blade creates both lift and drag. The force of the lift is stronger than the drag and this causes the rotor to spin [15, 16]. The rotor connects to the generator, either directly (if it's a direct drive turbine) or through a shaft and a series of gears (a gearbox) that speed up the rotation and allow for a physically smaller generator. This translation of aerodynamic force to rotation of a generator creates electricity.

The primary components that control a wind turbine are Pitch Control System: The pitch control adjusts the angle of the turbine blades the yaw control system ensures that the turbine blades are always aligned with the wind direction

to capture maximum energy. Power Control and Generator Regulation Wind turbines have generators that convert mechanical energy from the rotating blades into electrical power. The power output is dependent on wind speed, and a pitch controller and generator controller are used to ensure that the power output remains within the turbine's rated capacity. The orientation of the shaft and rotational axis determines the first classification of the wind turbine. A turbine with a shaft mounted horizontally parallel to the ground is known as a horizontal axis wind turbine or (HAWT). Shown at Fig. 2 A vertical axis wind turbine (VAWT) has its shaft normal to the ground. Shown at Fig. 3 [15, 17-19].

Horizontal Axis Wind Turbines (HAWTS) are the most commonly deployed type, especially at the utility scale. They are designed with a horizontal rotor shaft and aerodynamically shaped blades that face directly into the wind. These turbines are usually mounted on tall towers—sometimes the height of multi-story buildings—and feature a nacelle at the top that houses key components such as the generator and gearbox, protecting them from environmental stress. To maximize efficiency, HAWTS use a wind vane and yaw system to maintain optimal alignment with the wind direction, ensuring that the rotor plane maintains a 180-degree angle to the wind. These turbines are known for their high efficiency, cost-effectiveness compared to other models, and reliability in large-scale applications. Their high and consistent rotational speed also enhances profitability. Moreover, many HAWTS are equipped with mechanisms that allow the blades to tilt during storms to prevent damage. However, they come with challenges such as the logistical difficulty of transporting and installing tall towers and long blades. Additionally, they require a yaw control system to reorient the rotor, and their size can cause interference with radar systems, although signal filtering techniques can mitigate this issue.

On the other hand, Vertical Axis Wind Turbines (VAWTS) feature a rotor shaft that is perpendicular to the ground, with blades that rotate around a vertical axis. These turbines are typically smaller and are often used in residential or low-power applications. Although VAWTS is less common than HAWTS, it offer some unique advantages as explained in Table 2. They can maintain functionality in turbulent wind conditions and at lower wind speeds, which makes them suitable for urban environments. Furthermore, they are generally simpler to install and maintain, as they do not require complex orientation mechanisms. Despite these benefits, VAWTS tend to have lower efficiency compared to their horizontal counterparts. They often require an external push to start rotating and are prone to higher vibration and mechanical stress, leading to increased maintenance requirements and operational costs.

In summary, while HAWTS dominate large-scale energy generation due to their efficiency and capacity, VAWTS provide practical alternatives for small-scale, localized applications where wind conditions are variable, and ease of installation is prioritized.

TABLE 2

Comparison of Horizontal vs. Vertical Axis Wind Turbines [20, 21]			
Aspect	Horizontal Axis Wind Turbine (HAWT)	Vertical Axis Wind Turbine (VAWT)	Remarks
Definition	Most common type; large-scale turbines with horizontal blades facing the wind. Requires yaw system to align with wind direction.	Less common; blades rotate around a vertical axis. Suitable for residential use.	HAWTs are used in utility-scale projects; VAWTs are niche and location-specific.
Advantages	• High efficiency • Cost-effective • High capacity and reliability • Blades can tilt during storms • Consistent rotational speed	• Works well in turbulent/low wind • Easier to install and maintain	HAWTs perform better overall; VAWTs are more practical in dense or urban settings.
Disadvantages	• Difficult transportation/installation • Needs yaw control • May interfere with radar systems	• Low efficiency • Requires initial push • High vibration • High maintenance costs	HAWTs are more efficient; VAWTs face technical limitations despite easier setup.

Sizing a wind turbine requires several key assumptions and calculations to determine the appropriate turbine capacity to meet energy demand. First, the annual energy load to be supplied must be estimated; for example, if the energy demand is 730 kW, the annual load is calculated as the product of this demand and the total hours in a year (8760 hours), resulting in approximately 6,394,800 kWh per year. Next, the local wind speed at the installation site must be known—in this case, 9 m/s at the Red Sea. Air density, typically around 1.225 kg/m³, and the capacity factor, often assumed to be 0.3 for wind turbines, are also essential parameters. The overall efficiency of the turbine (η_t) is calculated as the product of the power coefficient (C_p), generator efficiency (η_{gen}), and gearbox efficiency (η_{gear}), which can be approximately 0.4 [22].

The power available in the wind is given by the equation

$$P_w = \frac{1}{2} \rho A v^3 \quad (1)$$

where P_w is the power extracted from the wind, ρ is the air density, A is the swept area of the turbine, and v is the wind velocity. The mechanical power transmitted by the turbine (P_m) is then

$$P_m = \eta_t \times P_w \quad (2)$$

The swept area A is calculated from the rotor diameter D using $A = \pi D^2/4$. Finally, capital cost estimation can be derived by multiplying the cost per kW by the installed power capacity. These steps provide a structured approach to determine the required size and cost of a wind turbine installation [23]. The equivalent circuit of wind turbine is shown in Fig. 2.

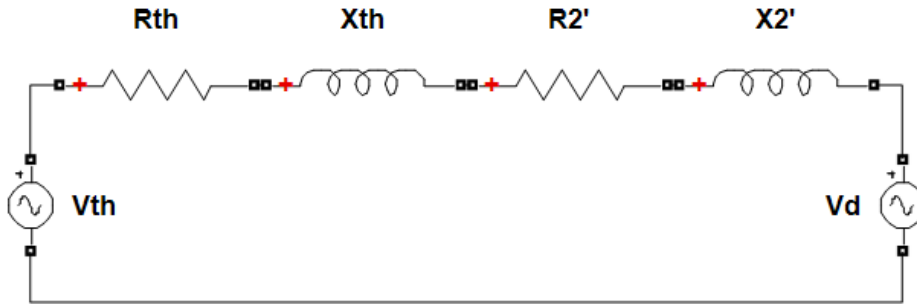


Figure 2: the equivalent circuit of wind turbine induction generator

$$R_{eq} = R_{th} + R'_2, \quad X_{eq} = X_{th} + X'_2 \quad (3)$$

$$V_d = -R_d I'_{a2} = -\frac{R'_2}{s} (1-s) I'_{a2} \quad (4)$$

$$I'_{a2} = \frac{V_d - V_{th}}{R_{eq} + jX_{eq}} \quad (5)$$

2.2. Solar energy

Solar energy is produced through the direct conversion of sunlight into electricity. Sunlight consists of photons, which are discrete packets of light energy. When photons from sunlight strike a solar panel, they are absorbed by the panel's photovoltaic (PV) cells. These PV cells then convert the absorbed light energy into direct current (DC) electricity via the photovoltaic effect. This DC electricity is subsequently routed to an inverter, which transforms it into alternating current (AC) electricity, suitable for powering homes and businesses or feeding into the electrical grid. For optimal exposure to solar irradiation, panels are typically mounted on rooftops or ground-based structures. They can be

deployed in diverse settings, ranging from individual residential and small business installations to large-scale commercial solar farms requiring significant land area. In every configuration, each solar panel or array is connected to either an electrical grid or a battery storage system, allowing for the storage of excess energy for periods when sunlight is unavailable. While all renewable energy sectors have expanded, the solar energy sector has exhibited particularly rapid growth. Over the past decade, solar energy has achieved an average annual growth rate of 33%, establishing it as the world's fastest-growing source of electricity, a trend projected to continue [24].

The rapid growth in solar energy adoption is attributable to several key factors. Primarily, the consistent decrease in solar panel manufacturing costs has made solar energy a progressively more economically viable investment for both consumers and businesses. Secondly, supportive government incentives and policies, including tax credits and renewable energy mandates, have significantly enhanced solar energy's appeal as an electricity source. Lastly, evolving consumer preferences, driven by environmental awareness, have led many to prioritize clean, renewable energy alternatives like solar over more carbon-intensive sources. Within the solar energy landscape, photovoltaic (PV) technology stands out as the most prevalent, cost-effective, and easily deployable option. Photovoltaic (PV) devices directly convert sunlight into electrical energy. The fundamental unit of this conversion is a single PV cell, typically a small component generating approximately 1 to 2 watts of power [25]. These photovoltaic (PV) cells are typically fabricated from various semiconductor materials and are remarkably thin, often less than the thickness of four human hairs. To ensure durability and withstand outdoor conditions for many years, individual cells are encapsulated between protective layers, commonly glass and plastics. To increase electrical output, PV cells are interconnected in series or parallel to form larger units called modules or panels. These modules can function independently, or multiple modules can be connected to create arrays. One or more arrays are then integrated into the electrical grid as part of a complete PV system [26]. This inherent modular structure allows PV systems to be scaled effectively, meeting a wide range of electrical power demands, from small-scale applications to large utility projects. Regarding the diverse technologies available, silicon remains the dominant base material for solar cells, largely due to its abundance as one of the most common elements on Earth. Several distinct technological approaches can be identified for silicon-based solar cells [27]. Table 3 illustrates the differences between the technologies of PV.

TABLE 3

Different types of photovoltaic technologies

Type	Efficiency Range	Cost	Lifespan	Advantages	Disadvantages
Monocrystalline Silicon (Mono-Si) [28]	20–24%	High	25–30 years	- High efficiency, - long lifespan, - space-efficient	- High cost - more material waste
Polycrystalline Silicon (Poly-Si) [29]	15–18%	Moderate	20–25 years	- Lower cost - Simpler production	- Lower efficiency, - less aesthetic appearance
Thin-Film (CdTe, CIGS, a-Si) [30]	10–13% (CdTe), 13–16% (CIGS)	Low–Moderate	10–20 years	- Lightweight, - flexible, - Low-cost materials,	- Shorter lifespan, - Degradation faster, - Lower efficiency
Perovskite Solar Cells [31]	20–25% (lab)	Low (lab), TBD (mass)	<10 years (current)	- Lightweight - high efficiency potential	- Stability, - Toxicity (lead), - scalability challenges
Organic Photovoltaics (OPV) [32]	8–12%	Low	5–10 years	- Lightweight, - Semi-transparent, - flexible, - Low-cost	- Low efficiency and - Stability - Short lifespan

3. Components of a Photovoltaic (PV) System

Effective operation of a photovoltaic (PV) system necessitates careful matching of its module output to the electrical load, a critical factor for ensuring system effectiveness, maximizing efficiency, and minimizing overall costs. A complete PV system comprises several interconnected components, each playing a vital role in converting solar energy into usable electricity and delivering it to the desired application.

3.1. Solar Modules

The primary energy conversion units in most PV systems are solar modules, predominantly fabricated from silicon crystalline technology. These modules are assemblies of multiple individual solar cells, typically wired in series (positive to negative) and encapsulated within a robust aluminum frame. Each silicon solar cell intrinsically generates approximately 0.5 volts. Consequently, a standard 36-cell module is rated to produce 18 volts, while larger modules commonly integrate 60 or 72 cells. The current output (amperage) of a module is directly proportional to the active area of its constituent cells; larger cells yield higher amperage.

3.2. Scaling Power Output

To achieve higher power outputs, multiple PV modules are electrically interconnected to form a solar array. Modules are typically wired in series to sum their voltages (e.g., connecting the negative terminal of one module to the positive terminal of another). For PV systems with multiple series strings of modules, a combiner box is employed. This enclosure houses the positive and negative leads from each string, connecting the positive leads to individual fuses and the negative leads to a common negative bus bar. This setup defines the "source circuit." The primary function of the combiner box is to consolidate multiple series strings into a single, higher-current parallel circuit, thereby enabling efficient current collection. For instance, an array comprising three strings of 10 modules, each producing 30 volts, wired in series, would yield 300 volts per string at 4 amps. Once these strings are combined within the box, the output circuit would deliver 300 volts at 12 amps (3 strings $\times$ 4 amps/string).

3.3. Charge Controllers

For PV systems incorporating battery storage, a charge controller is an essential component that regulates the flow of electrical energy from the PV modules to the battery bank. Its primary role is to prevent battery overcharging, thereby extending battery lifespan and ensuring safe operation. Charge controllers vary in their current regulation capacity and may offer additional functionalities, such as managing direct current (DC) loads or optimizing energy delivery to a load based on battery state-of-charge. During daylight hours, the PV array supplies power to both the controller and the battery, with the controller continuously monitoring the battery's energy level to maintain full charge. At night, when the array is inactive, the controller facilitates the discharge of the battery to energize the connected loads as required.

3.4. Energy Storage

When solar energy is stored for later use, particularly during periods without sunlight, a battery bank is employed. For residential PV applications, lead-acid batteries are the most commonly utilized due to their cost-effectiveness and proven performance. Users should select deep-cycle batteries, which are specifically designed for repeated deep discharges typical in renewable energy systems, unlike automotive starting batteries. Two primary types of lead-acid batteries exist: flooded lead-acid (FLA) and sealed absorbed glass mat (AGM). Battery nominal voltages can vary (e.g., 2V, 6V, 12V), as can their individual amp-hour capacities, which dictate the amount of energy they can store. For example, a 12-volt battery might have a capacity of 35 amp-hours, while another at the same voltage could offer 58 amp-hours, with physical dimensions varying accordingly.

3.5. Inverters – DC to AC Conversion

The electrical energy produced by a PV array or stored in a battery bank is in the form of direct current (DC). While DC loads (e.g., lights, fans, pumps, motors, and specialized equipment) can be directly powered, most residential and commercial appliances operate on alternating current (AC). An inverter is therefore an indispensable component, converting DC electricity into AC electricity. Inverters are available in a wide range of power ratings to accommodate various load sizes. Small inverters can, for instance, convert 12-volt DC from a vehicle's battery to 120-volt AC for powering a laptop. Larger units are designed to supply AC power to entire buildings or grids.

For safety and maintenance, an AC disconnect switch is mandated by electrical codes (e.g., the National Electrical Code - NEC) on the AC side of the inverter. This switch allows for the safe isolation of the inverter from the AC circuit, essential for troubleshooting or performing system maintenance. For grid-connected PV systems, local utility regulations often require this component. Furthermore, comprehensive system metering is crucial for monitoring performance. In stand-alone or off-grid PV systems, a battery meter measures the energy flow into and out of the battery bank, providing critical insights into charging and discharging cycles, battery health, and potential system issues (e.g., incomplete charging, battery degradation, or imminent shutdown). Modern PV systems also leverage web-based tools and mobile applications for remote monitoring, enabling users to track system activity via a cell phone or tablet from any location [27, 33-35].

4. Modeling Scenarios and Assumptions

To evaluate the optimal cost-effective microgrid configuration for meeting local energy demands in El Gouna, Red Sea, a series of system scenarios were developed and modeled. The total annual energy demand was estimated at approximately 6.4 GWh/year, based on a calculated load profile and operational assumptions. The region's average wind speed was taken as 9 m/s, and solar irradiation levels are considered high, making it ideal for both wind and photovoltaic (PV) applications. Four scenarios were proposed:

- a 100% wind energy system connected to the grid,
- a 100% PV system connected to the grid,
- a 100% PV system operating off-grid with a backup system, and
- a hybrid system combining wind and PV resources.

These scenarios were developed to compare energy output, system efficiency, component sizing, cost implications, and reliability under real-world environmental and technical constraints. Each scenario was designed using a standardized set of assumptions. The wind turbine efficiency was considered to be 40%, with an overall turbine efficiency factor including generator and gear losses. PV modules were assumed to have efficiencies ranging between 75% and 76.5%, with module power ratings between 600–610 W. For wind-based systems, the air density was taken as 1.225 kg/m³, and the capacity factor was set to 0.3. In the off-grid PV scenario, additional considerations were given to energy storage and backup capacity, though these are not explicitly detailed in the cost model. The hybrid scenario utilized a combination of both technologies to simulate shared load contribution and diversification of supply sources. These configurations form the basis for a technical and economic comparison, which is discussed in the following section.

5. Results and Discussion

The first scenario, which utilizes three 250 kW wind turbines, provides the highest annual energy output (6,438,600 kWh). The system operates with an efficiency of 40% and has an expected lifespan of 20–30 years. However, it entails a high capital cost of \$2,499,000 and a payback period of around 9 years. This model is suitable for coastal regions with strong and stable wind resources, such as El Gouna. The second scenario relies entirely on solar energy through 1,196 PV modules, each rated at 610 W. This system achieves the highest efficiency (76.53%) among all scenarios and has a moderate lifespan of 20–25 years. Being connected to the grid, it benefits from energy export and backup

without requiring local storage. Although the cost is not specified, this option is expected to be more affordable than large-scale wind deployment. In the third scenario, an off-grid PV system with 6,136 modules rated at 600 W each is proposed. This configuration maintains a comparable annual energy output while operating independently of the grid, using local backup solutions for storage and reliability. Despite its practicality in remote or unconnected areas, this scenario involves significant land use and higher system complexity, with a slightly lower efficiency of 75.1% and a lifespan of 20–25 years.

The fourth scenario presents a hybrid model, integrating one 250 kW wind turbine with 787 PV modules (610 W each). This configuration provides the same energy output as the PV-only models but at a significantly reduced cost of \$262,800, making it the most cost-effective among the evaluated options. The system efficiency is relatively lower (30%), potentially due to assumed derating factors or integration losses, but the lifespan of 25 years offers a reliable mid-term solution. This hybrid approach leverages both solar and wind resources to enhance availability, reduce reliance on a single energy source, and improve overall system resilience. Overall, the hybrid model stands out as the most economical solution for El Gouna, especially where budget constraints and resource diversity are considered. Meanwhile, the fully off-grid PV scenario offers energy independence at the expense of space and system complexity, and the wind-only model, while robust, requires a high initial investment. These results are summarized in Table 4.

TABLE 4
Comparison between the different renewable energy resources

According to	Scenario1 (100% wind)	Scenario2 (100% PV) ON grid	Scenario3 (100% PV) OFF grid with backup	Scenario3 (35% wind – 65% PV)
Annual energy in kWh	6438600	6394800	6394800	6394800
Number of Turbine/modules	3 Turbines	1196 PV module	6136 PV module	1 turbine – 792 module
Unit power rating wind/PV	250kw	610w	600w	250kw – 610 w
Lifetime (years)	20 – 30	20 – 25	20 – 25	25
Efficiency	40 %	76.53 %	75.1 %	58.2 %
Cost	750000\$	116730\$	4060740\$	262800\$
payback	3 years	1 year	14 years	5 years
Location	EL Gouna Red Sea			

6. Conclusion

This study highlights the critical role of microgrids as a reliable and sustainable framework for integrating renewable energy resources into modern power systems. Through a comparative analysis of various microgrid configurations including 100% wind, 100% photovoltaic (PV), off-grid PV with backup, and hybrid systems it is evident that renewable-based microgrids can effectively meet regional energy demands while reducing dependence on fossil fuels. The modelling results for El Gouna, Egypt, demonstrate that hybrid systems combining wind and solar energy offer the most cost-effective and resilient solution, balancing reliability, efficiency, and financial viability. Furthermore, the integration of advanced control mechanisms and appropriate system sizing significantly improves the performance and adaptability of microgrids under variable environmental conditions. As global energy systems continue to shift toward decentralization and decarbonization, microgrids will play a pivotal role in enhancing energy access, promoting grid stability, and supporting national and international sustainability targets.

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