



Design, Modeling, and Simulation of an Off-Grid Hybrid Energy System Integrating Solar Photovoltaics, Diesel Generators, and Batteries for Brack Al-Shatti Area, Libya

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Abstract:

The hybrid system was designed to fully meet the electricity needs of the Brack Al-Shatti area, assuming independent operation from the electrical grid. This study provides a technical evaluation of a hybrid system comprising photovoltaic (PV) panels, batteries (BT), and diesel generators (DG), developed to meet an annual electricity demand of approximately **590 GWh**. The analysis examines the impact of different PV capacities (ranging from 0 to 1000 MW) and corresponding battery sizes on diesel fuel consumption, CO₂ emissions, and the levelized cost of energy (LCOE). Diesel consumption decreases significantly as PV capacity increases, from approximately 123 million kg per year at zero PV capacity to zero at 1000 MW. At the same time, battery capacities increase from initial values to 3747 MWh, supporting the storage of excess solar energy and meeting nighttime load requirements, thereby reducing dependence on diesel fuel. The average annual energy cost (LCOE) reflects a balance between technical and economic performance, reaching a minimum of approximately US\$0.231077/kWh for PV capacities between 200 and 300 MW and battery capacities between 115 and 433 MWh. This configuration maintains operational stability while effectively reducing diesel consumption.

Keywords: batteries; diesel generators; CO₂ emissions; levelized cost of energy (LCOE); photovoltaic (PV)

Introduction

Driven by concerns about climate change, global warming, and oil depletion, the global installed capacity of renewable energy grew by 50% in 2024. By the end of 2024, the total global installed renewable energy capacity—including solar, wind, hydropower, geothermal, marine, and biogas—reached approximately 4,448.1 GW, of which about 2,200 GW was attributed to solar photovoltaic (PV) systems. This growth in the renewable energy (RE) market reflects a global shift toward sustainable and clean energy technologies [1–3].

Libya has sought to keep pace with this global transition. As one of the largest producers of oil and natural gas, and a signatory to the Paris Agreement, the country has undertaken measures to transition toward renewable energy through its 25-year strategy, which aims to increase the contribution of renewable and environmentally friendly energy sources to more than 50% of the national electricity generation mix. In light of concerns regarding the depletion of global fossil fuel reserves, solar energy and other alternative sources represent viable solutions in Libya [4–6] and are considered appropriate options for addressing energy scarcity.

Owing to recent advancements in energy technologies, developments in electrical storage systems, and reductions in component costs, solar and wind energy have emerged as widely adopted solutions for supplying electrical loads in remote and off-grid areas [6]. However, the intermittent and variable nature of these energy sources introduces complexity into energy systems, leading to technological, environmental, social, and economic challenges. It is also essential to consider the impact of thermal loads on concentrated photovoltaic (CPV) cells [7]. Electricity can be generated through various configurations, including grid-connected, off-grid, or hybrid systems [8–34]. Hybrid systems are generally regarded as the most efficient option; however, they are associated with higher costs due to the integration of specialized electrical converters.

The ongoing energy crisis in the country has prompted researchers to explore various forms of alternative energy sources and system components to ensure the provision of clean and sustainable power [35]. Numerous studies have investigated autonomous hybrid energy systems as a means to meet load demand and improve quality of life in remote and isolated regions worldwide [36–49]. One such study employed a metaheuristic technique, Multi-Objective Particle Swarm Optimization (MOPSO), to optimize microgrid systems comprising photovoltaic (PV) panels, batteries (BT), and wind turbines (WT) [50]. Another study examined an off-grid configuration incorporating PV, WT, and batteries to supply electricity to five residential loads [51–53]. Additional research has focused on analyzing the deployment of renewable energy sources (RESs) within the country [54]. In [55], various hybrid configurations were assessed for powering an isolated region in Iran using a stand-alone energy system. Moreover, several studies have explored the application of RESs in Libya, taking advantage of their local potential and environmental benefits [56–69].

Microgrids have emerged as a promising and effective solution for remote areas, offering reliable, efficient, and clean energy generation [70–72]. These systems can integrate a variety of renewable energy sources, such as solar, wind, and hydropower, alongside diesel generators. In addition, energy storage technologies can be utilized to store surplus electricity. This combination makes microgrids particularly suitable for regions lacking access to the main utility grid or experiencing frequent power outages due to natural events such as storms [73,74].

The use of photovoltaic (PV) systems has become increasingly widespread in hospitals, residential buildings, and public facilities in Libya. However, the high cost of solar systems remains a significant challenge [75]. To address this issue, optimization techniques such as the Crow Search Algorithm and Particle Swarm Optimization (PSO) have been employed for sizing hybrid renewable energy systems (RES) in Libya [76]. Solar panels are generally categorized into three main types: monocrystalline, polycrystalline, and thin-film technologies [77]. The efficiency of each type varies, producing different energy outputs depending on location and environmental conditions. Monocrystalline and polycrystalline panels are considered the most suitable for the study area, depending on seasonal variations and local climatic factors such as temperature and solar irradiance [78].

Microgrids, as classified in [79], operate in two primary modes: grid-connected and off-grid [80]. The grid-connected mode is used when the end user is connected to the utility grid, whereas the off-grid mode applies when the user is fully isolated. Mini-grid and off-grid systems based on renewable energy sources (RESs) have also been explored [81]. Furthermore, the optimal sizing of hybrid systems, including PV, wind turbines (WT), and batteries (BT), has been widely investigated [82]. For example, a study on

PV–battery systems in Morocco highlights global efforts to address energy and environmental challenges [83].

A study conducted for rural areas considered the integration of renewable energy sources (RESs), such as photovoltaic (PV), wind turbines (WT), and biomass, along with battery storage. The study utilized the Artificial Bee Colony (ABC) algorithm to optimize system sizing and validated the results using HOMER and Particle Swarm Optimization (PSO) [84]. Given the high solar irradiance in the study area, the work in [85] explored various integrated systems. Additionally, the current state of the national electrical supply system is documented in [86], indicating that the national electricity company is the sole electricity provider. Domestic electricity consumption patterns, including the use of various household appliances, are detailed in [87].

This study aims to develop an optimization model for determining the optimal sizing of a hybrid energy system based on photovoltaic (PV) solar panels and battery storage, with a diesel generator serving as a backup source during cloudy conditions or battery depletion. Appropriate objective functions and constraints were applied to balance cost and performance, ensuring that the energy demands of Brack Al-Shatti, Libya, are met. The selected objective functions include the Levelized Cost of Energy (LCOE) and Payback Time (PBTM), while the constraint ensures a zero Loss of Power Supply Probability (LPSP), reflecting continuous power supply reliability. The System Advisor Model (SAM) was employed to estimate the actual productivity of the PV system based on real-time climatic data provided by the Renewable Energy Laboratory at Wadi Alshatti University for the year 2023. It is noteworthy that the proposed system does not rely solely on solar energy but incorporates backup sources, such as diesel generators, to ensure energy availability under unfavorable conditions.

Renewable energy, derived from naturally occurring sources such as solar radiation, precipitation, tidal movements, wind, and geothermal heat, is characterized by its renewability and sustainability [88]. It represents a practical alternative to conventional fossil fuels and is often referred to as “alternative energy.” These energy flows exist naturally in the environment and can be harnessed to meet human needs, with the sun, gravitational forces, and Earth's rotation serving as primary drivers. Importantly, the growth in global energy demand is closely linked to increases in per capita Gross National Product (GNP). Projections suggest that continued reliance on fossil fuels may lead to insufficient energy supply in the future.

Renewable energy sources (RESs) offer several advantages over conventional systems. These include immediate access to electricity without the need for extensive grid expansion, reduced vulnerability to oil price fluctuations, and lower fuel transportation costs. Additionally, RESs contribute to improved healthcare services, rural development, economic efficiency, and local job creation. Their integration also plays a crucial role in addressing global challenges such as climate change and poverty by promoting the efficient use of locally available resources [89].

Urban populations connected to conventional power grids are increasingly adopting renewable energy sources due to concerns over fossil fuel depletion and environmental impacts. These clean energy sources, often referred to as “green energy,” include solar, wind, geothermal, and other sustainable alternatives.

Advancements in photovoltaic technology have significantly expanded the global potential for solar energy generation. Improved economic feasibility has supported the deployment of PV systems in both large-scale projects and small standalone applications serving residential, public, and commercial sectors.

The concept of hybrid renewable energy systems emerged in the mid-1980s and gained momentum in the early 1990s due to the need for enhanced grid stability and reliability. This growth was driven by the integration of large shares of wind energy into small autonomous grids. As global energy demand continues to rise alongside environmental concerns, renewable energy systems remain central to sustainable development strategies [90,91].

Conventional photovoltaic systems exhibit inherent variability in output due to short-term fluctuations in weather conditions [92]. To enhance efficiency and optimize energy utilization, integration with other renewable or conventional energy sources has become increasingly important. However, such integration introduces challenges related to intermittency, low energy density, and stochastic behavior.

Recent advancements in control systems, processing technologies, and energy management have enabled the reliable operation of hybrid systems combining PV with diesel backup. A comparative study between batteries and fuel cells as backup solutions identified fuel cells as a more favorable option for PV systems under certain conditions [93].

Solar energy, encompassing both light and heat from the sun, is harnessed through a wide range of technologies, including solar heating, photovoltaic systems, solar thermal energy, solar architecture, molten salt systems, and artificial photosynthesis. The underlying principle is the photovoltaic effect, where incident light provides sufficient energy to release electrons, generating a voltage that drives current through an electrical circuit.

In addition to core PV system operations, auxiliary features such as battery backup and uninterruptible power supply (UPS) capabilities enhance system reliability by maintaining critical loads during outages [94–97].

Several studies have explored the application of hybrid energy systems in various contexts. For instance, [98] proposed an off-grid hybrid system to power a COVID-19 quarantine facility in Gaza. In [99], an optimization approach was presented for a PV/wind system integrated with pumped hydro storage in Brack, Libya. In [100], a rooftop PV system was evaluated for Assiut University, focusing on economic and technical feasibility. In [101], a hybrid system comprising PV, wind, and biomass was proposed with a significant investment cost.

A wide range of energy technologies—including PV systems, wind turbines, hydropower, diesel generators, microturbines, and fuel cells—contribute to the modern energy landscape [102–107]. Energy storage technologies such as battery banks and hydrogen systems play a crucial role in system performance. The primary contribution of this study lies in presenting an integrated framework for the design, modeling, and simulation of an off-grid hybrid energy system combining renewable and conventional sources to meet the energy demands of the Wadi Al-Shatti region in southern Libya.

Study area and seasonal changes

Brack Al-Shatti is located in the southeastern part of Libya and serves as a significant urban hub within the Wadi Al-Shatti region. The city is situated approximately 700 kilometers south of the capital, Tripoli, and 60 kilometers north of Sabha, as illustrated in the map of Libya in Figure 1. Brack Al-Shatti has a population of 43,100, ranking it as a mid-sized city among southern Libyan cities, according to the Libyan census of 2004. The city is geographically located at an altitude of 349 meters above sea level, with coordinates of 27°53'33"N and 14°28'33"E.

The area is characterized by an arid climate, with relatively high temperatures in summer, moderate winters, and minimal precipitation. These climatic and environmental conditions are essential factors in the design and operation of renewable energy systems, particularly with regard to the efficiency of solar panels and energy storage systems. Climatic records and solar radiation data indicate that the area is highly suitable for solar energy projects, making it a strategically favorable location for the implementation of off-grid hybrid energy systems.

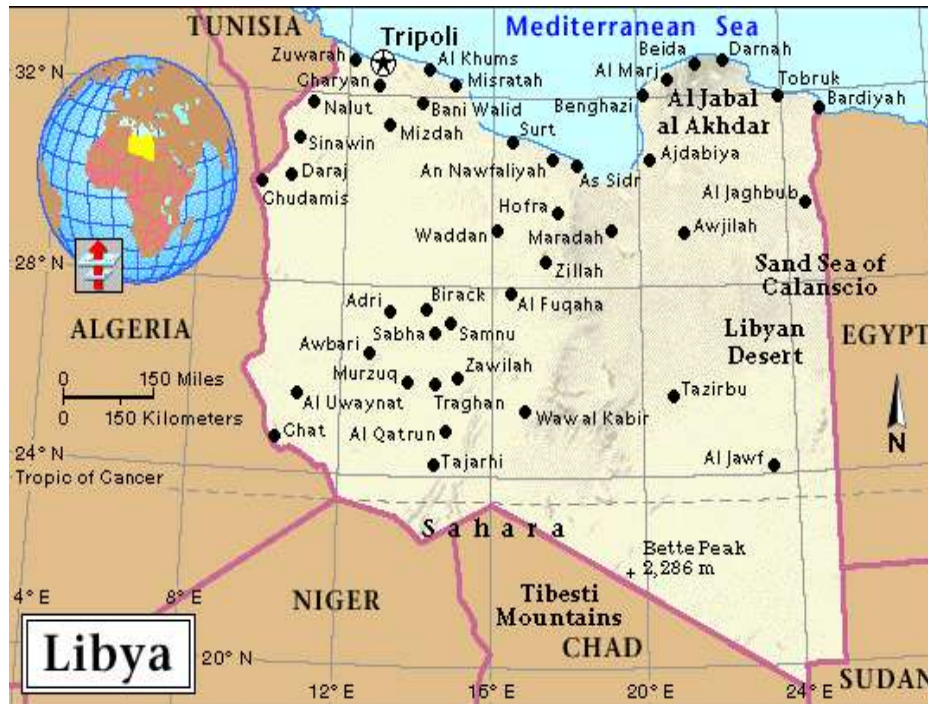


Figure 1: Map of the site under consideration [108]

Methodology for Renewable Energy Systems with Energy Storage

As illustrated in Figure 2, this study aims to simulate an integrated off-grid hybrid energy system in order to determine its optimal configuration. The hybrid system consists of photovoltaic (PV) generation, battery storage, and a diesel generator. The simulation process begins with the collection of climatic data, hourly electrical load demand, and the technical, economic, and environmental parameters of the system.

The impact of different photovoltaic capacities was analyzed, ranging from 0 to 1000 MW in increments of 100 MW. An hourly simulation was conducted over an entire year (8,760 hours) for each scenario, starting with the initial state of charge (SOC) of the batteries, PV output, and diesel generator fuel consumption. To maintain operational constraints and prevent potential load deficits, the stability of the batteries was evaluated. In the event of any modification in system parameters, the simulation was rerun.

After accounting for all costs, including capital expenditures, replacement and maintenance costs, and fuel consumption across all scenarios, the levelized cost of energy (LCOE) was calculated. Finally, the optimal configuration was identified based on the minimum LCOE that satisfies all operational constraints, resulting in a reliable, cost-effective, and environmentally sustainable system suitable for large-scale off-grid applications.

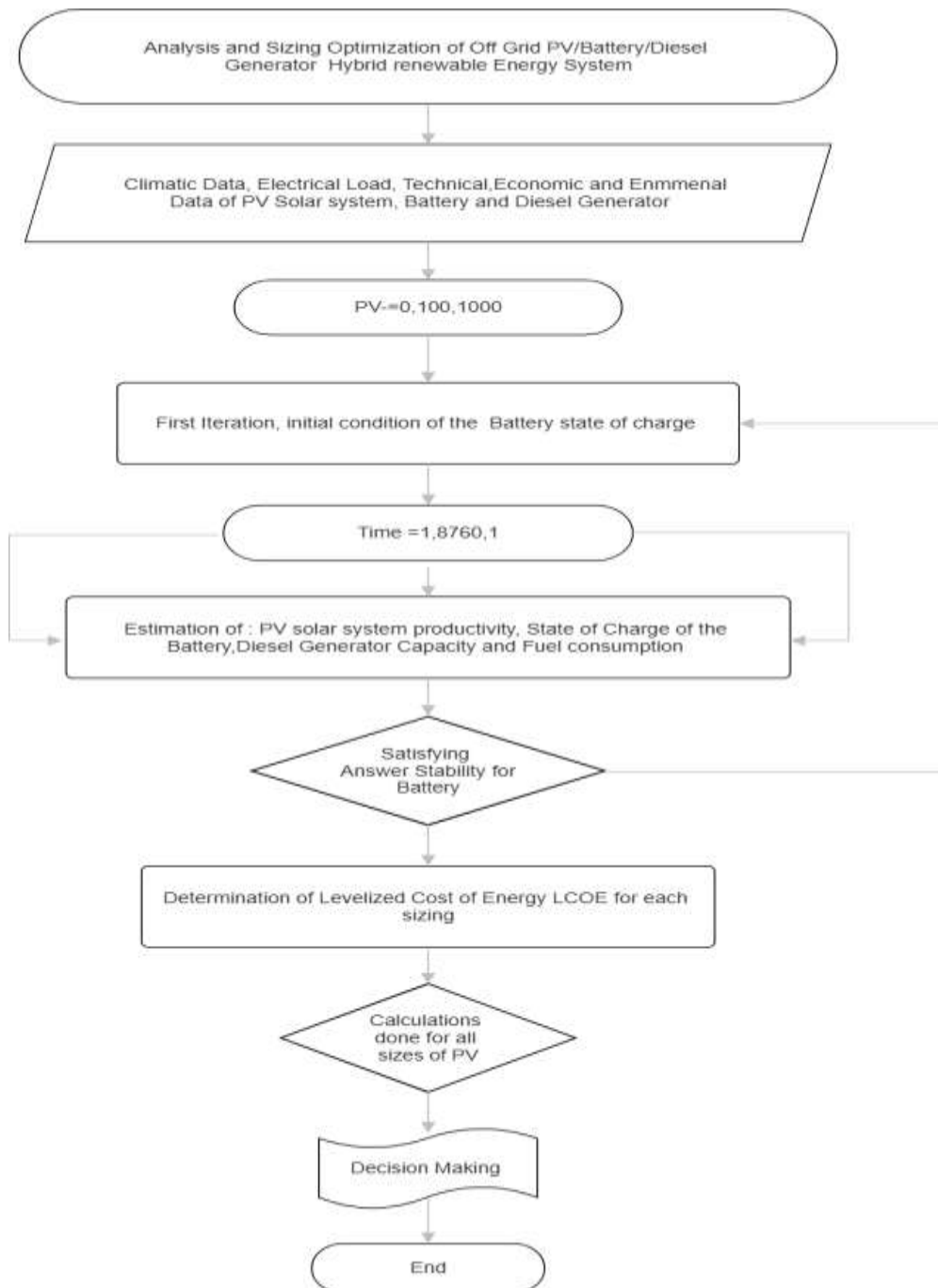


Figure 2: The following approach is illustrated in the flowchart

Collected Data

The average hourly Global Horizontal Irradiance (GHI) data for the study site in 2023 are presented in Figure 3. The data were obtained from the meteorological station located

at the Solar Energy Laboratory, Faculty of Engineering, Wadi Al-Shatti University, Brack City.

On the other hand, temperature is a key climatic parameter, as it directly affects the efficiency of photovoltaic (PV) modules and consequently influences electrical demand. Figure 4 shows that the average temperature in Brack City is approximately 22°C, ranging from 5°C to 40°C. The data were subsequently analyzed using Microsoft Excel.

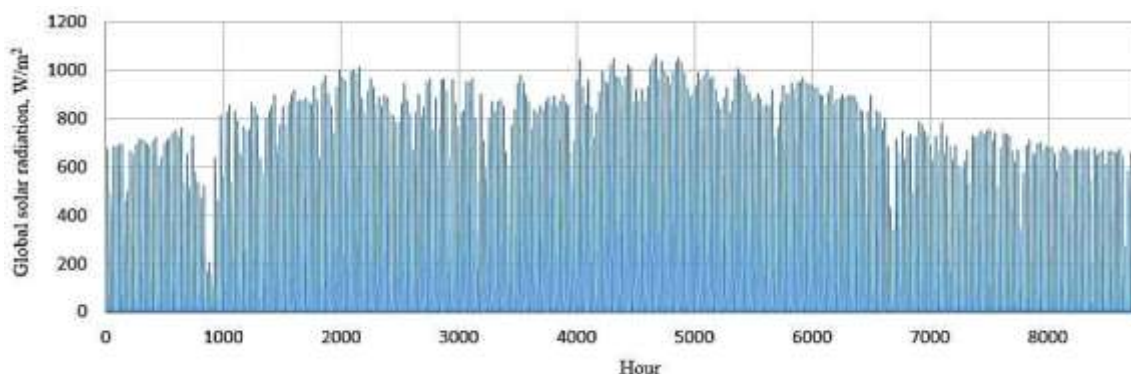


Figure.3: Hourly global horizontal solar radiation (GHI)

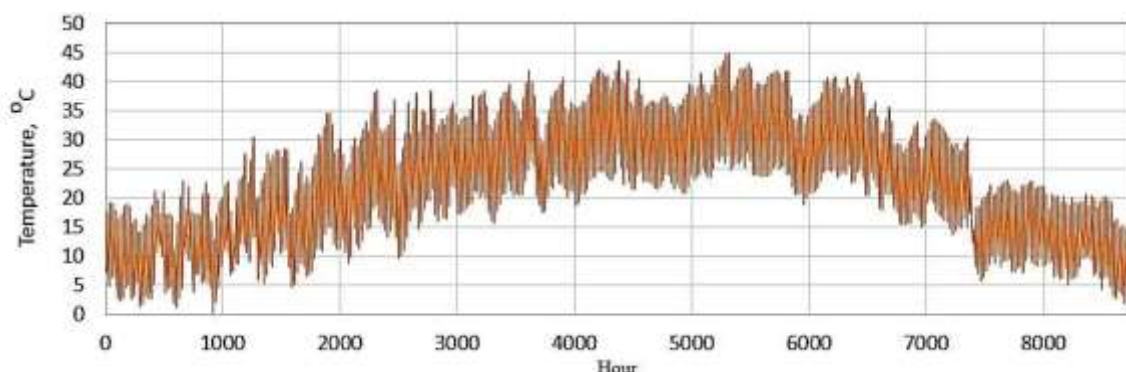


Figure 4: Hourly Variation in Ambient Air Temperature for the case study

Modeling of a Hybrid Energy System

The proposed energy system consists of a renewable energy source (PV), battery energy storage, a diesel generator (DG), and inverters, all integrated with residential demand as an AC load, as shown in Figure 5.

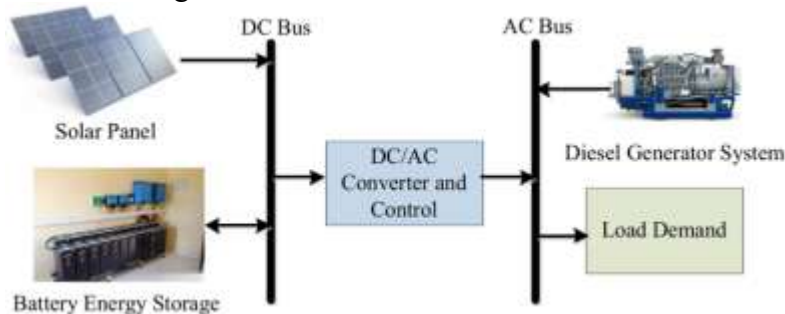


Figure 5: Schematic of the Proposed Hybrid Energy System

This hybrid system operates independently of the public grid and is designed to meet the capacity requirements of the selected study area, ensuring uninterrupted power supply, which represents a model for addressing contemporary energy challenges [109]. Table 2 presents the detailed specifications of the system components.

Table 2. System input parameters

Components	Parameters	Value	Units
Photovoltaic	Photovoltaic module Stion SN-115		
		11.40	%
		41.0	
		3.0	Amp
		125	W
		-0.004	%/°C
		-0.360	volt/°C
		0.007	Amp/°C
	Capital Cost;	870	\$/kW
	O&M Cost,	21	\$/kW/year
	Lifespan;	30	year
		0.052	kg
	Battery	Lifespan	10
Nominal voltage		12	V
Hourly self-discharge rate		0.007	%/hour
Capital cost		400000	\$/MW
O&M Cost		81000	\$/MW
Maximum DOD		70	%
Max SoC		100	%
Min SoC		20	%
Inverter	Lifespan	15	Years
	Efficiency	95	%
	Capital Cost	2800	\$
Diesel generator	Capital Cost	5000000	\$/MW
	Lifespan	25	years

	O&M Cost	200000	\$/MW
	Fuel cost	1.32	\$/kg

A hybrid energy system integrates multiple renewable energy sources and is generally more cost-effective and reliable than single-source energy systems.

In this study, the system components include photovoltaic (PV) panels, battery storage (BT), and diesel generators (DG), all designed for an off-grid configuration. To ensure efficient and safe utilization of energy storage as a flexible asset capable of performing multiple grid functions, the implementation of Energy Management Systems (EMS) and optimization strategies is essential [110–112].

The photovoltaic (PV)

The actual output power of the photovoltaic (PV) panel under real operating and climatic conditions is given by [113,114]:

$$P_{PV} = P_{STC} [1 + \beta_P (T_{cell} - T_{STC})] \frac{H_t}{H_{STC}} \quad (1)$$

Where: T_{cell} are the cell's surface temperature at Standard Test Condition, is the power temperature coefficient. The challenge that researchers will face is to find an empirical equation to determine the cell surface temperature [113,114].

$$T_{cell} = T_{\infty} + 7.8 * 10^{-2} H_t \quad (2)$$

Although all climatic data were obtained from the SolarGis platform, the incident solar radiation on the PV surface was recalculated. This is because SolarGis applies the Moneer model [115], whereas local studies indicate that the Liu and Jordan model is more suitable for southern regions [116–120].

$$P_{PV} = P_{STC} [1 + \beta_P (T_{cell} - T_{STC})] \frac{H_t}{H_{STC}}$$

Energy storage system

It is the responsible device for steadying power balance and absorbing transients within the range of maximum and minimum of SoC of the battery. Depends on the charge and discharge cycles of the battery which compute the lifespan of energy storage [121]. The battery is considered in the system to deal with the intermittent nature of Renewable Sources (RS). The utilized battery in the system is Lithium-iron phosphate (LiFePO₄) and its datasheet of the battery is reported in [121]. The capacity of the battery can be computed by Equation (3), while the charge and the discharge amount of the battery can be calculated by Equation (4) and (5), respectively [121].

$$C_{BT} = \frac{AD * E_L}{\eta_{BT} * DOD * \eta_{inv}} \quad (3)$$

where the E_L refers to the average load demand, the AD represents autonomy days, DOD refers to the depth of discharge, η_{inv} refers to the inverter efficiency, and η_b is battery efficiency. The two operations for charging and discharging to show the battery status as SoC as presented in Equation (4) have been taken into consideration for charging and discharging as presented in Equation (4) and Equation (5), respectively.

$$SoC_{Min} \leq SoC_t \leq SoC_{Max} \quad (4)$$

$$SoC = SoC(t-1) * (1 - \sigma) + \left((p_{pv}(t)) - \frac{P_L(t)}{\eta_{inv}} \right) * \eta_{BT} \quad (5)$$

$$SoC = SoC(t-1) * (1 - \sigma) + \left(\frac{P_L(t)}{\eta_{inv}} - (p_{pv}(t)) \right) * \eta_{BT} \quad (6)$$

Equations represents the battery status in charging mode considering the *sigma* that refers to the self-discharging rate of the battery bank.

Converters

When a system has both AC and DC components, power converters such as DC/AC and AC/DC are necessary. While the considered load is AC, solar PV panels and batteries produce DC output. The converter size is determined by combining peak load demand with inverter efficiency, while the inverter rating is determined using Equation [122-124].

$$p_{inv}(t) = \frac{P_t^m(t)}{\eta_{inv}} \quad (7)$$

Diesel Generator

The DG will work when the energy on the battery is depleted (minimum of DoD accomplished). The modeling mathematical equations can be calculated by Equation (8) with the help of Equation (9) and Equation (10), respectively.

$$FC_{(t)} = A_G * P_{DG} + B_G * P_r^{DG} \quad (8)$$

$$FUELC = (S_f \sum FC_{(t)}) * CPV \quad (9)$$

$$CPV = \frac{r_i(1+r_i)^n}{(1+r_i)^n - 1} \quad (10)$$

where the in Equation (8) refers to the fuel consumption that measured in (Liter/kW), is the coefficient of FC that equals 0.24, is the generated power from the DG, is the constant valve or coco efficient of FC equals 0.084, and refers to the rated power, respectively. Additionally, the cost of fuel ($FUELC$) is mathematically formulated in Equation (9), the denoted as the current price of diesel fuel per liter represents the modeled of fuel consumption, denoted as the cumulative present value which mathematically can be expressed in Equation (10).

Optimization process

Objective functions

This study aims to determine the optimal configuration of a hybrid energy system composed of photovoltaic panels (PV), battery storage, and a diesel generator for Brack City, Libya, with the objective of minimizing both the Levelized Cost of Energy (LCOE) Accordingly, the objective function (OF) is formulated to evaluate system performance based on economic feasibility and return on investment. [125]

$$OF = w_1(LCOE) + w_2(PBTM) \quad (11)$$

The LCOE of the hybrid system is calculated using the following equation

$$LCOE = \left[\frac{r(1+r)^{nPV} C_{PV} + \frac{r(1+r)^{nBT}}{(1+r)^{nBT} - 1} C_{BT} + \frac{r(1+r)^{nDG}}{(1+r)^{nDG} - 1} C_{DG} + (O\&M_{PV} + O\&M_{BT} + O\&M_{DG}) + C_{FUEL} * Fuel\ mass - NCO_2}{EL} \right] \quad (12)$$

Where C_{PV} , C_{BT} and C_{DG} are the capital costs of the PV, Batteries and Diesel Generator system; are PV, Batteries and Diesel Generator operation & maintenance costs respectively. states for the discount rate (2.5%). and are the PV, Batteries and Diesel Generator system lifespans. is the net cost of CO₂ [126]

$$NCO_2 = \phi \left[(EF_{CO_2} * Load) - (mass_{fuel} * EF_{CO_2}) \right] \quad (13)$$

Where the CO₂ price in Libya and equal 70\$/ton CO₂ [127-130] and is Emission Factor of CO₂ and equal 2.78 kg CO₂/kg diesel [131-133]. TB, the total benefits of the hybrid system over the project lifespan [134] is given by,

$$TB = \left\{ \frac{(1+r)^n - 1}{r(1+r)^n} \right\} I_S \quad (14)$$

The average annual benefits are given by [134]

$$TB_{av} = \frac{TB}{n} \quad (15)$$

The average annual benefit gives indication on the economic feasibility of the project. Another economic indicator is the Payback Time Money, PBTM depends on the project total cost, C_s , and average annual benefit. PBTM is given by,

$$PBTM = \frac{C_s}{nTB_{av}} \quad (16)$$

Where initial capital investment cost, replacement cost in year t , operation and maintenance cost in year t , fuel cost for the generated in year t , total energy generated by the system in year t (in kwh), discount rate, project lifetime (in year)

Results and Discussion

Energy Contribution and System Performance

The investigated hybrid power system integrates photovoltaic (PV) generation, battery storage, and a diesel generator to ensure continuous electrical demand supply throughout the year. The results on a temporal scale indicate that solar power output is highly sensitive to variations in solar irradiation. During peak solar hours, the PV system generates sufficient electrical power to supply the direct load and simultaneously recharge the batteries, as shown in Figure 6.

Battery Operating Dynamics

The state-of-charge (SOC) profile of the battery demonstrates stable performance throughout the year (8,760 hours). This stability corresponds to a relatively high charging level, ranging from 2,600 to 3,600 MWh for most of the year. This indicates that the system provides adequate storage capacity to accommodate daily load fluctuations and continuous solar energy surplus, enabling regular battery recharging throughout most of the operational period.

Furthermore, no repeated deep-discharge cycles were observed, which contributes to prolonging battery lifetime. However, a significant deep-discharge event is observed during the initial operation phase (approximately hours 900–1000). This is attributed to reduced solar irradiation, insufficient initial battery capacity, or delayed activation of the diesel generator as a backup source. Such conditions may accelerate battery degradation if they recur.

After a stabilization period, the SOC remains within a narrow operating range, indicating effective charge–discharge management, a good balance between load demand and solar generation, and the supportive role of the diesel generator in preventing the SOC from reaching critical minimum levels. Minor fluctuations are observed during mid-year periods; however, these variations are not operationally critical and are directly associated with changes in solar irradiation and load demand. Overall, the battery system demonstrates high operational efficiency, indicating that the hybrid system is well managed. Nevertheless, further detailed analysis is required to investigate the initial deep-discharge behavior to prevent possible recurrence, as shown in Figure 7.

Generator Contribution

To ensure uninterrupted power supply, the diesel generator operates during periods of low solar irradiance and/or when the demand exceeds the combined capacity of the PV and battery system. Its role is essential for system reliability; however, it is associated with environmental impacts due to carbon emissions and increased operational costs related to diesel fuel consumption.

Levelized Cost of Energy (LCOE)

The variation in the Levelized Cost of Energy (LCOE) is illustrated in Figure 8 as a function of the installed photovoltaic (PV) capacity for the proposed hybrid system. Initially, the system relies entirely on the diesel generator, as no PV capacity is installed (PV = 0 MW), and the LCOE is approximately 0.32327 USD/kWh. The LCOE decreases to about 0.25240 USD/kWh when 100 MW of PV capacity is integrated.

The minimum LCOE value of 0.23077 USD/kWh is achieved at a PV capacity of 200 MW, indicating the most economically optimal configuration. This result corresponds to a capital payback period of approximately 12.32 years, which reflects a favorable investment scenario.

However, the LCOE increases slightly to 0.28444 USD/kWh at 300 MW and further rises to 0.37661 USD/kWh at 500 MW. Higher PV capacities of 600, 700, and 800 MW result in a pronounced increase in LCOE, reaching 0.55081, 0.62535, and 0.69905 USD/kWh, respectively. This increase is associated with extended payback periods exceeding 36 to 44 years.

Although a slight decrease in LCOE is observed at 1000 MW (approximately 0.68966 USD/kWh), the payback period remains relatively long at 40.28 years. These results indicate that high PV capacities are not economically optimal. Instead, moderate capacities, particularly around 200 MW, provide the lowest cost of electricity generation. In summary, the analysis shows that the minimum LCOE of 0.23077 USD/kWh is obtained at 200 MW PV capacity with a payback period of 12.32 years. While CO₂ emissions decrease with increasing PV capacity, both LCOE and payback period increase correspondingly. Therefore, the optimal configuration is achieved at moderate PV penetration levels, ensuring a balanced trade-off between economic feasibility and environmental performance.

Operational and Environmental Impacts of a Hybrid Power System

The results shown in Figure 10 for the analysis of the hybrid PV–battery–diesel system indicate that increasing photovoltaic (PV) capacity leads to a significant and measurable improvement in both operational performance and environmental impact. Initially, there is no PV penetration, and the system relies entirely on the diesel generator for electricity generation, resulting in high fuel consumption and elevated CO₂ emissions, reaching approximately 4.83×10^5 tCO₂/year. This condition represents the baseline scenario for evaluating system performance improvements.

When PV capacity is increased to 100–200 MW, diesel generation decreases, leading to reductions in both fuel consumption and CO₂ emissions. However, the system still partially depends on the diesel generator due to insufficient PV contribution during periods of low solar irradiance.

At PV capacities ranging from 300 to 500 MW, a significant transition occurs, where the combined operation of PV generation and battery storage demonstrates high efficiency. At 300 MW, emissions are approximately 2.80×10^5 tCO₂/year; however, at 500 MW, they decrease to about 3.4×10^4 tCO₂/year, representing nearly a tenfold reduction compared to the baseline scenario.

This range represents a critical operational zone in which renewable energy consistently exceeds demand during daytime periods, enabling effective battery charging and limiting diesel operation to only a few hours per year. The sharp reduction in emissions corresponds to a substantial decrease in annual fuel consumption, from 71,000 t at 300 MW to 8,600 t at 500 MW, confirming a clear transition toward renewable energy reliance.

Beyond 600 MW, the system approaches a near-zero emission regime. At PV capacities between 800 and 1000 MW, diesel generators become practically redundant due to the large storage capacity (up to 4000 MWh) and high solar energy availability, which together satisfy almost the entire load demand. As a result, CO₂ emissions approach zero, with full elimination achieved at 900–1000 MW.

Assuming a carbon price of 70 USD/tCO₂ in Libya, the economic value of emission reduction increases significantly, reaching more than 33 million USD annually when diesel consumption is fully eliminated. This indicates that, in addition to environmental benefits, high-penetration photovoltaic systems can deliver substantial long-term economic value.

Overall, the results confirm that increasing PV capacity fundamentally changes system behavior: fuel consumption decreases, emissions are significantly reduced, and the system transitions from diesel-dominated operation to nearly fully renewable operation. These findings highlight the technical, environmental, and strategic advantages of high solar penetration hybrid systems, particularly in regions such as southern Libya with abundant solar resources.

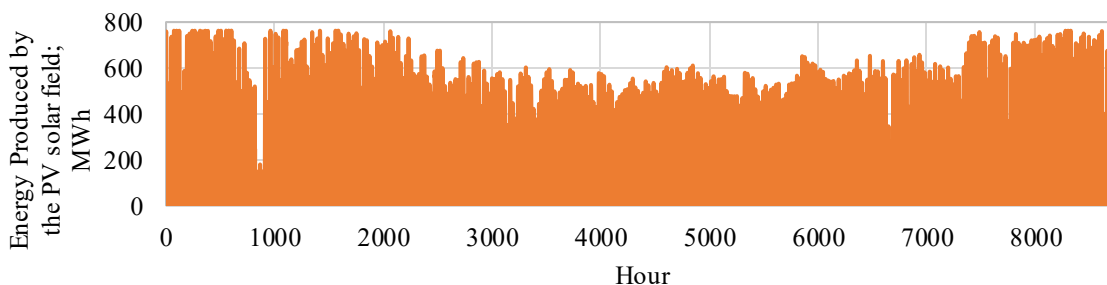


Figure 6: Energy Produced by the PV solar field; MWh

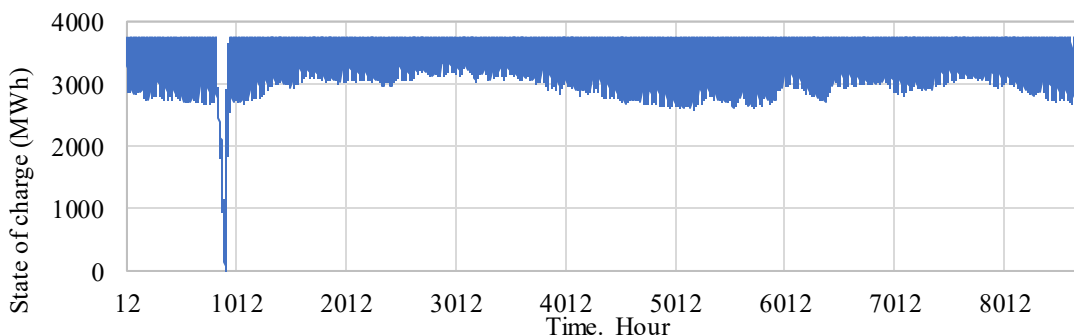


Figure 7: illustrate the state battery of charge S

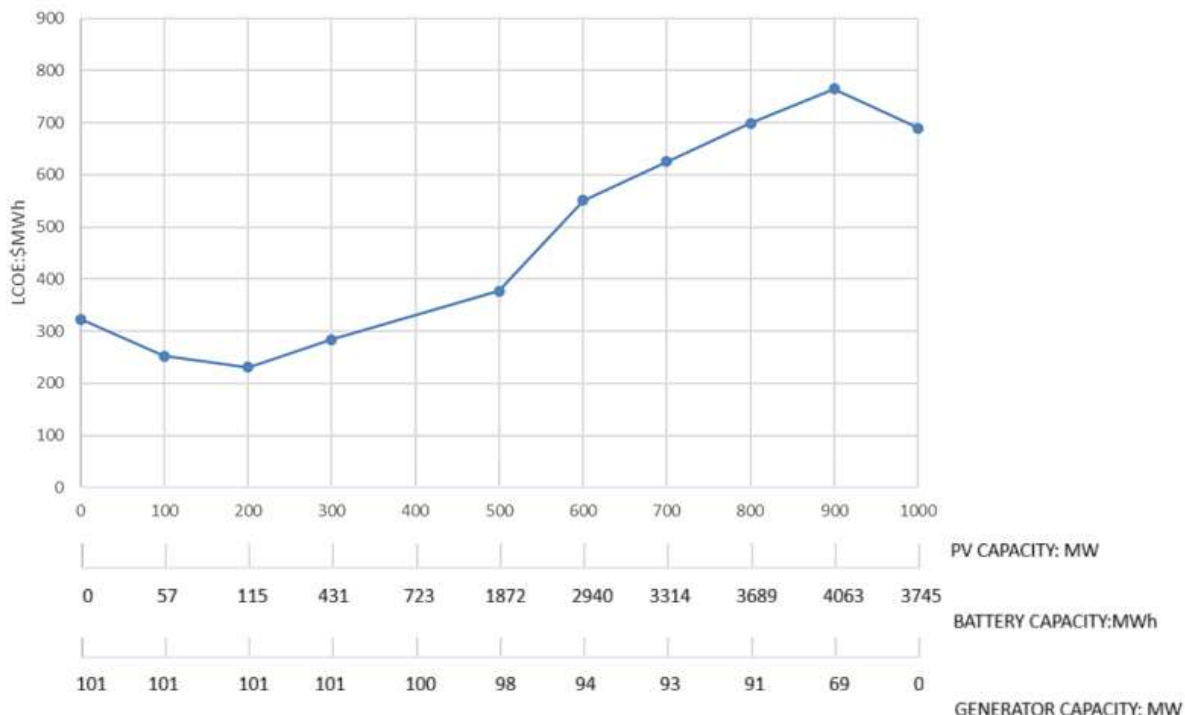


Figure (8): illustrates the variation of the Levelized Cost of Energy (LCOE)

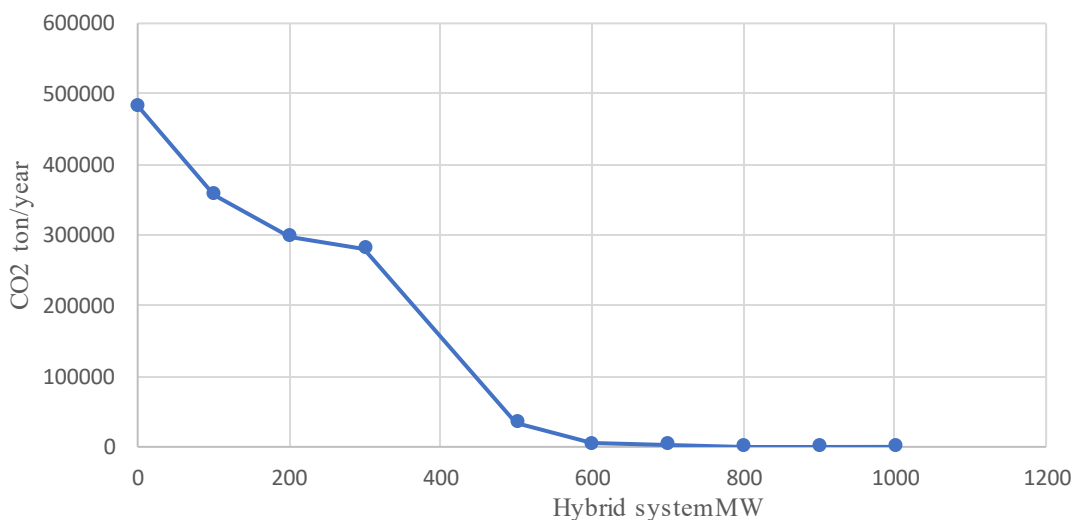


Figure 9: illustrated the CO2 of the system emissions

Conclusion

The off-grid hybrid photovoltaic (PV)–battery–diesel system for the Brack Al-Shatti area is capable of meeting an annual electricity demand of 590 GWh. Full decarbonization is achieved at PV capacities between 800 and 1000 MW, combined with battery storage capacities of approximately 3,000–3,700 MWh, leading to a substantial reduction in both CO₂ emissions and diesel fuel consumption. The results indicate that hybrid renewable energy systems are technically feasible and can provide a reliable and sustainable power supply in remote arid regions. A balanced configuration of 200–300 MW PV capacity

and 115–431 MWh battery storage minimizes diesel dependence while maintaining system stability and operational reliability.

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