مجلة جامعة فزان العلمية
Fezzan University scientific Journal
journal@fezzanu.edu.ly

Design of a Hybrid Photovoltaic-Battery-Diesel System for Green Hydrogen Production

*Ibrahim Imbayah[1]and Yasser F. Nassar[2] and Mohamed Khaleel[3] and H. J. El-Khozondar[4]and Monaem Elmnifi[5]
[1]Department of Energy Engineering, College of Renewable Energy, Tajoura, Libya
[2]Mechanical and Renewable Energy Eng. Dept., Faculty of Eng., Wadi Alshatti University, Libya
[3]Libyan Center for Sustainable Development Research, Al-Khums, Libya
[4]Department of Materials and London Centre for Nanotechnology, Imperial College, LondonSW7 2AZ, UK
[5]Department of Mechanical Engineering Technology, Belgorod State Technological University, Belgorod, Russia

Abstract

The Ubari region, located in southwestern Libya at 26°N, 12°E, has abundant solar radiation, with irradiances exceeding 2,200 kWh/m²/year and over 2,500 hours of sunshine per year. Currently, the power supply is dominated by diesel fuel. This paper presents an investigation into converting the Ubari power plant into a hybrid power system comprising 30 MW of monocrystalline photovoltaic power, 60 MWh of lithium-ion battery storage with 90% round-trip efficiency, and 5 MW of backup diesel power. Using HOMER Pro software, 602 scenarios were run to determine the optimal configuration, which consists of 30 MW photovoltaic power, 60 MWh battery storage, and 5 MW diesel backup power. Under normal operation, 100% renewable energy supply is achievable with a levelized cost of electricity of \$0.06/kWh, which is about 1/4 of the current cost of \$0.25/kWh supplied by diesel fuel alone. At 8% discount rate, over a 25-year operation, the internal rate of return is 14.5%, and the simple payback is 7 years, which indicates economic viability. The addition of a 20 MW proton exchange membrane type electrolyser will consume 4,673 MWh/year of PV power to produce 200 metric tons/year of green hydrogen, which will cost \$4-5/kg, comparable to European import targets. In addition, 15,000 tons/year of CO2 emissions will be reduced, which will satisfy Libya's Paris agreement commitment. In conclusion, this study will be technically and economically feasible locally, which will be applicable to other desert-dwelling people in North Africa and the Sahel regions.

Keywords: Renewable Energy; Photovoltaic Systems; HOMER Pro; Green Hydrogen; Desert Electrification; Libyan Desert; Hybrid Energy Systems; LCOE; Li-Ion Battery Storage

Introduction

The global electricity generation in 2024 reached approximately 30,850 TWh (30.85 PWh), with fossil fuels (coal, gas, oil) providing about 58%, renewables (hydro, wind, solar, bio, geo) around 32%, and nuclear around 10% [1]. While the global hydrogen production capacity was still dominated by fossil fuel-based methods, with total demand near 100 Mt. driven by concerns about climate change and global warming, the global installed capacity of renewable energy grew by 50% in 2024. In the end of 2024, the global installed capacities of renewables such as solar, wind, hydropower, geothermal,

---

* Research author: Email addresses ibrahim.alzayani@gmail.com – Seminar on the transition to clean energy in Fezzan: Renewable energy engineering in esert regions – Thursday, February 12, 2026

marine, biogas, etc reached about 4,448.1 GW, from them 2,200 GW for PV solar energy systems, while the global installed electrolyser capacity was projected to reach around 5 GW, and the global cumulative installed capacity of battery energy storage systems was approximately 150 GW / 363 GWh.. This growth in the RE market reflects a global shift towards renewable and sustainable energy technologies [2-4].

Collectively, these desert regions account for a third of the total land on Earth, but surprisingly, these regions are able to soak up a considerable amount of the sun's energy. The Sahara Desert alone receives about 22 PWh of the sun's energy annually, which is about one hundred times the total current demand for electricity on the entire planet [5,6]. In the last two decades, there has been a significant improvement in the manufacturing of solar panels, which has led to a decline in the cost of solar energy by over 90%. In fact, the weighted average levelized cost of energy (LCOE) of solar power has reduced from about \$0.378/kWh in 2010 to about \$0.049/kWh in 2023 [7]. Thus, the idea of using solar power in the deserts, which are far off, is not only viable but also economically viable. While the most common source of power in these regions is the diesel generator, which is used in the deserts in Africa, the Middle East, and the Australian Outback, it is a costly affair, with the cost of fuel per kWh ranging between \$0.20 and \$0.35, and also poses a threat to the environment, with the emission of CO2, NOx, and particulate matter [8]. At the same time, the cost of batteries has reduced considerably in the last decade or so, with the cost of Li-ion batteries coming down by about 89 percent between 2010 and 2023, to about \$150/kWh or less. In fact, the idea of using a hybrid system, which includes the combination of solar and batteries, is viable [9].

Furthermore, the country's geographical area is approximately 1.76 million square kilometres, with around 95% of that area being desert or semi-desert, mostly the Sahara. According to the Libyan Electricity and Renewable Energy Authority, also known as GECOL, the country's power generation is lacking, with areas such as the south, particularly the Fezzan region [10].

Building on this, the challenges in the southern parts of the country are more pronounced, with weak grid connectivity, expensive and lengthy fuel supplies, and a troubled political environment that has stalled large-scale infrastructure development for several years. Interestingly enough, these areas boast the strongest solar resource in the country, with Global Solar Atlas and Solargis sources indicating that the Global Horizontal Irradiance in these regions ranges from 2,200 to 2,500 kWh/m^2 annually [11, 12].

In the context of these regional challenges and resources, Libya ratified the Paris Agreement in 2022, with its Nationally Determined Contribution committing to the development of 3,500 MW in renewable energy by 2030, including 2,000 MW of solar PV capacity [13]. The development of this commitment has faced challenges in terms of funding, political stability, and the availability of bankable documents. Conducting an in-depth case study of the Ubari region will directly support the national ambitions in terms of proving the technical, financial, and environmental benefits in quantifiable terms.

In the past decade, there has been an increase in the number of publications on hybrid renewable energy systems (HRES) in North African desert environments. For a remote Libyan village, a PV-wind-diesel-battery system was optimised using HOMER software, resulting in a levelized cost of energy between \$0.18 and \$0.22/kWh and a renewable fraction between 65 and 80% [10]. GIS-based studies were conducted to optimise the location of solar power plants in Libya, resulting in Fezzan being the best location for solar power plants, given the high solar irradiance levels of over 6.1 kWh/m^2/day [15-19]. This is confirmed by similar studies that show that HRES systems in the Sahara region can achieve a low COE of less than \$0.10/kWh when storage energy is optimised [20- 38].

There has been increased interest in the production of green hydrogen, given the European Commission's Hydrogen Strategy of 2020, which identified North Africa as a major hydrogen import region [39-44]. A preliminary study of the potential of Libya to export hydrogen resulted in the findings that solar-based hydrogen production plants in the Fezzan basin have the potential to meet up to 5% of the hydrogen demands of Europe in the year 2035 at a cost that is comparable to the EU's hydrogen import target of \$2/kg once carbon pricing is factored [45-48].

The specific objectives of this study are: (i) to design and optimize a hybrid PV–battery–diesel system for the Ubari power plant utilizing HOMER Pro, incorporating local solar radiation data, load profiles, and component cost functions; (ii) to quantify the technical performance metrics of the optimal configuration, including renewable fraction, capacity shortage, and excess electricity; (iii) to assess the economic viability of the hybrid system through analyses of NPC, LCOE, IRR, and payback period; (iv) to estimate the potential for green hydrogen production facilitated by surplus PV generation and evaluate its cost competitiveness; and (v) to quantify the corresponding reductions in CO_2 emissions and assess their alignment with Libya's climate commitments.

Methodology

Research Framework

The Data collection and site characterisation, multi-criteria site selection analysis, HOMER Pro system optimisation and simulation, and post-processing analysis of technical performance, economic viability, and environmental impact comprise the four stages of the study's research framework. The approach uses the Net Present Cost minimisation goal function prevalent in microgrid design literature and complies with the IEC 62257 series of standards for renewable energy systems in distant and rural locations.

Solar Resource Data and Site Characterization

The solar radiation data for the Ubari site, which is located at Latitude 26.58°N, Longitude 12.00°E, has been extracted from two reliable satellite data sources to validate accuracy: Global Solar Atlas, which is produced by the World Bank and Solargis, 2024, and the NASA POWER database, which is used for cross-checking. The monthly mean hourly global horizontal irradiance data show a clear seasonal trend, where the maximum is around 7.8 kWh/m²/day, occurring between June and July, and the minimum is 4.3 kWh/m²/day, recorded between December and January, with an average value close to 6.1 kWh/m²/day, which equates to 2,227 kWh/m²/year.

Due to a lack of local measured solar irradiation data, the Solargis data, which is based on a 30-year average between 1994 and 2023, has been chosen as the reference data for HOMER Pro, which is considered reliable for data accuracy. Solargis dataset and the HOMER program are validated by many local researchers [48-61]. In addition, HOMER simulation is based on the 2007 Meteorological Year, which is similar to the Typical Meteorological Year approach. Figure 1 indicates that Ubari has excellent solar power availability, which is stable throughout the seasons, as cross-validated from multiple satellite data sources for accuracy in HOMER Pro.

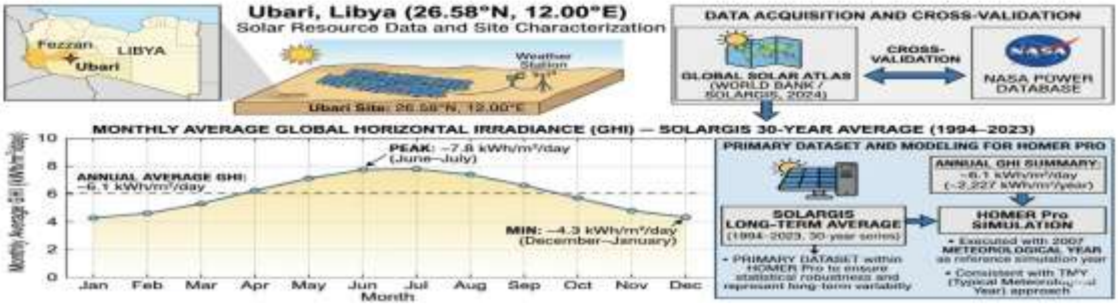


Figure 1: Seasonal Solar Irradiance and Data Cross-Validation for Ubari, Libya

Multi-Criteria Site Selection

A Multi-Criteria Decision Analysis (MCDA) was undertaken to confirm that the best option for the installation site was Ubari from the available locations in the Fezzan area of Libya. Table 1 shows the site selection matrix for the proposed site in Ubari using the MCDA method. Among the sites considered for the installation, the proposed site in Ubari had the best composite score in the MCDA method and met all the criteria. The proposed site in Ubari is near the Murzuq Aquifer, which is one of the largest fossil water reserves in Africa, and this would be useful for the production of hydrogen, which requires about 9 liters of water for the production of 1 kg of hydrogen.

Table 1. Multi-Criteria Decision Analysis (MCDA) site selection matrix for Ubari, Libya.

Criterion	Weight	Threshold / Minimum	Ubari Score
Global Horizontal Irradiance (GHI)	40%	≥ 2,200 kWh/m²/yr	2,227 kWh/m²/yr ✓
Proximity to Existing Grid Infrastructure	25%	< 50 km	Existing plant site ✓
Water Resource Availability	20%	Groundwater or coastal	Murzuq aquifer ✓
Site Topography (Slope)	15%	< 5%	< 2% (flat desert) ✓

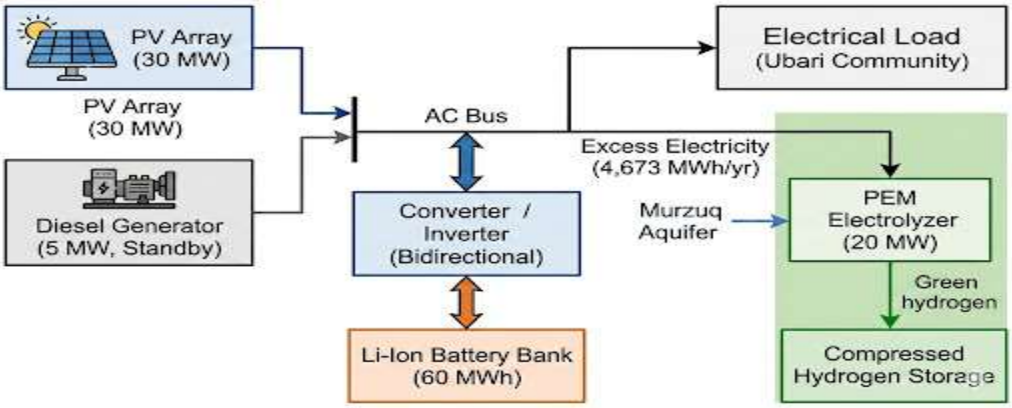
HOMER Pro Simulation Platform

HOMER Pro (version 3.x, HOMER Energy LLC) was selected as the primary software for simulating and optimising the microgrid system, given its proven track record in peer-reviewed publications, strong economic modelling capabilities, and ability to evaluate multiple system configurations simultaneously. The software runs hourly simulations for each design, checking whether the system is able to meet the electrical load each hour while satisfying all the constraints. Any design able to meet the constraints during all 8,760 hours of the year is considered a feasible design, and HOMER Pro ranks the feasible designs based on their net present cost (NPC).

In total, 602 candidate configurations were analysed, each varying three parameters: the PV array size from 0 to 12 MW in steps, the battery bank from 0 to 30 strings of 1 MWh Li-Ion modules, and the generator dispatch strategy from either Load Following or Cycle Charging. Of the total configurations analysed, 499 (or 82.9%) were found to be feasible, while the remaining 103 configurations were eliminated due to various reasons, including insufficient converter capacity (6 configurations), lack of available generation sources (36 configurations), and redundant components (11 configurations involving converters, and 50 involving extra converters). The best design is the feasible design with the overall lowest NPC [62,63].

Hybrid Microgrid System Configuration

The schematic of the concept is depicted below, illustrating how the multi-energy system works: The AC Bus is the core of the multi-energy system, connecting the main source of power, 30 MW of PV, and the storage, a 60 MWh Li-ion battery, with a bidirectional converter. The 5 MW Diesel Gen is included as a standby source, providing zero power to the grid under normal circumstances. On the other hand, the strategic value addition is



depicted in the shaded region on the right, where a 20 MW PEM Electrolyser uses the surplus power generated annually, i.e., 4,673 MWh, to produce approximately 200 tonnes of green hydrogen, using desalinated water extracted from the Murzuq Aquifer. Figure 2 is a schematic of how all the components of the optimised Ubari system interact with each other.

Figure 2: Optimized Hybrid Microgrid System Configuration for the Ubari Power Plant

Input Data and Assumptions

The main input parameters for the HOMER Pro simulation program are shown in Table 2 and Table 3, which cover the economic assumptions for the HOMER Pro program and the hydrogen cost analysis.

Table 2. HOMER Pro simulation input parameters for the Ubari hybrid system.

Parameter	Value	Unit / Reference
Simulation Timestep	60	minutes (hourly)
Annual Average GHI	6.1 (2,227/year)	kWh/m²/day
PV Panel Technology	Monocrystalline Silicon	22% efficiency
PV Capital Cost	700–800	USD/kW
Battery Chemistry	Li-Ion (Generic 1 MWh string)	HOMER library
Battery Round-Trip Efficiency	90%	—
Battery Minimum State of Charge	20% (setpoint: 80%)	—
Battery Lifetime	15	years
Diesel Generator Capacity	5,000	kW
Diesel Fuel Cost	1.20	USD/liter
Diesel Lower Heating Value	43.2	MJ/kg
Diesel Carbon Content	88%	—

Parameter	Value	Unit / Reference
Discount Rate	8%	—
Annual Inflation Rate	3%	—
Project Lifetime	25	years
PV Annual Degradation Rate	0.5%	per year
Dispatch Strategy	Load Following (LF)	HOMER default

Table 3. Economic assumptions used in HOMER Pro and hydrogen cost analysis.

Parameter	Value
Real Discount Rate	8%
Annual Inflation Rate	3%
Project Lifetime	25 years
Diesel Fuel Cost	$1.20 / liter
PV Capital Cost	$700–800 / kW
Battery Capital Cost (Li-Ion)	$300,000 / MWh string
Battery Replacement Cost	$250,000 / MWh string (yr 15)
Diesel Generator Capital Cost	$500 / kW
PEM Electrolyzer Capital Cost	$1,000 / kW
Annual PV Degradation Rate	0.5% per year

Electrolyzer and Hydrogen System Inputs

The hydrogen production system was also examined using a mass-energy balance method, although it was not developed in HOMER Pro. It was based on the excess electrical energy generated in the HOMER simulation. For the electrolyser, a 70 percent system efficiency was assumed, with a specific energy requirement of 50 kWh per kilogram of hydrogen, and a water requirement coming from a desalination unit using a reverse osmosis process with a capacity of 5,000 cubic meters per day. Hydrogen was also assumed to be stored in compressed form at 700 bar in standard Type IV containers. The capital cost of the 20 MW plant, using a cost per kilowatt of $1,000, was based on IRENA benchmarks in 2024 for large-scale systems.

Photovoltaic Power Output

Stion SN-115 – thin film PV module has been selected according to recommendations of local researches [64-66] .The instantaneous PV power at time t, as provided by the de-rated PV model in HOMER Pro, is [67-72]:

$$PPV(t) = YPV \cdot fPV \cdot (GT(t) \,/\, GSTC) \cdot [1 + \alpha P \cdot (TC(t) - TSTC)] \tag{1}$$

$$T_{cell} = T_{\infty} + 7.8 \times 10^{-2} H_t$$

where:

YPV: rated capacity of the PV system in kW at STC
fPV: derating factor for the PV system, dimensionless, including dust, wiring losses, and mismatch effects. fPV = 0.80
GT(t): solar irradiance on the surface of the PV system at time t, in kW/m²
GSTC: irradiance at STC, which is 1 kW/m²
αP: temperature coefficient of power, in %/°C. αP = -0.0047°C
TC(t): cell temperature at time t, in °C, estimated using the NOCT method
TSTC: cell temperature at STC, which is 25°C

The cell temperature, denoted by the function T_C(t), is determined using the model referred to as the Nominal Operating Cell Temperature model. In this case, the cell temperature is given by the ambient temperature, denoted by the function T_amb(t), and a term that is proportional to the solar irradiance, given by the product of (NOCT - 20) and the function G_T(t), and finally divided by 0.8. In this case, the NOCT is given as 47°C, as described in the generic flat plate module in HOMER.

Li-Ion Battery Energy Balance

The state of charge (SOC) of the battery bank at the end of each hour-long step t is determined by a set of energy balance equations, differentiated depending upon whether the batteries are being charged or discharged. Some of the key constants used in the equation are [73-81]:

Charge	$SOC(t) = SOC(t-1)\ (1 - \sigma) + [PPV(t) - Pload(t)]\ \eta\, \Delta t\ /\ Enom$	(2)
Discharge	$SOC(t) = SOC(t-1)\ (1 - \sigma) - [Pload(t) - PPV(t)]\ \Delta t\ /\ (\eta\ Enom)$	(3)

where:
SOC(t): state of charge at time t, kWh, or a fraction of E_nom
σ: hourly self-discharge rate, about 1%/day, assumed constant
Δt: step size, 1 hour
η: Battery efficiency, 0.949 (square root of round-trip efficiency, 0.90)
E_nom: nominal capacity, kWh; usable capacity, E_usable = 0.80 * E_nom (depth of discharge limit)

The operational constraint requires: SOC_min ≤ SOC(t) ≤ SOC_max, where SOC_min = 0.20 · E_nom and SOC_max = E_nom.

Diesel Generator Fuel Consumption

The fuel usage curve of the diesel generator is modeled using a piecewise nonlinear model with the following parameters [82,83]:

$$F(Pgen(t)) = a + b \cdot Pgen(t) + c \cdot [Pgen(t)]^2 \quad (L/hr) \tag{4}$$

where Intercept a = 0.0140 L/hr/kW_rated
Slope b = 0.244 L/hr/kW
Linear term c = 0

The parameters are based on the manufacturer data used in the HOMER Pro generic large genset database. Note that the parameters are given for a 5 MW, or 5,000 kW, generator. The total fuel usage is calculated by the following formula: Q_fuel = Σ over all hours F(P_gen(t)) * Δt, where the time horizon is the full 8,760 hours.

Converter

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 [84-86].

$$p_{inv}(t) = \frac{P_L^m\ (t)}{\eta_{inv}} \qquad (5)$$

Energy Balance and Dispatch Logic

The energy balance of the system at every hour with Load Following is as follows:

$$PPV(t) + Pbat,dis(t) + Pgen(t) = Pload(t) + Pbat,ch(t) + Pexcess(t) \qquad (6)$$

The picture with Load Following is that we run the generator only when the PV and battery cannot supply the load, and only run it enough to supply the main load. This minimizes fuel use as much as possible, unlike Cycle Charging, where the generator runs at full capacity to charge the battery alone. The optimization calculation of HOMER concluded that Load Following is the best method for this system.

Levelized Cost of Energy

The primary indicator used by HOMER Pro is the Levelized Cost of Energy (LCOE) [87-92]:

$$LCOE = NPC \cdot CRF(i, n) / Eserved \qquad (7)$$

$$CRF(i, n) = i \cdot (1 + i)^n / [(1 + i)^n - 1] \qquad (8)$$

In the equation, NPC is the net present cost in USD, and E_served_disc is the amount of energy delivered to the load on a yearly basis, in kWh/year, after discounting the amount. The NPC is the total amount of cost incurred in the initial phase and the subsequent phases, considering replacements:

$$NPC = CAPEX + \Sigma t = 1^n\ [(OPEX\_t + Crep,t) / (1 + i)^t] \qquad (9)$$

In the equation, CAPEX is the initial cost, OPEX_t is the cost incurred in the subsequent phases, and C_rep,t is the cost incurred after the end of the useful life of the component.

Hydrogen Production Model

The yearly amount of H_2 generated is given by the following equation, expressed in kg/year [93-97]:

$$mH_2 = (Eexcess \cdot \eta elec) / SECH_2 \qquad (9)$$

where E_excess is the annual excess electricity (kWh/year), η_elec is the PEM electrolyzer system efficiency (70%), and SEC_H_2 is the specific energy consumption of the electrolyzer (50 kWh/kg H_2). The water demand for electrolysis is: m_H_2O = 9 · m_H_2 (kg water per kg H_2), met by the 5,000 m^3/day RO desalination unit drawing from the Murzuq aquifer.

CO_2 Emissions Model

The annual CO_2 emissions reduction relative to the diesel baseline is [98-108]:

$$\Delta CO_2 = Esolar \cdot EFdiesel - Ediesel,actual \cdot EFdiesel \qquad (10)$$

In the equation, E_excess is the total amount of surplus electricity per year, expressed in kWh/year; η_elec is the system efficiency of the PEM electrolyzer, which is 70%; and SEC_H_2 is the specific energy used by the electrolyzer, which is 50 kWh per kg of H_2. Water is also required for the electrolysis process, given by m_H_2O = 9 * m_H_2 (kg of water per kg of H_2), provided by the 5,000 m^3/day desalination plant using the reverse osmosis technology and the Murzuq aquifer as the source.

Results and Analysis

Optimal System Configuration

The HOMER Pro analysis indicates that the best option overall, based on the NPC, is the fully renewable option, which consists of the PV system coupled with the Li-Ion battery bank, as this option outperforms the other 499 possible options. For the optimal solution, the system consists of a 30 MW flat plate monocrystalline PV array, a 60 MWh Li-Ion battery bank made up of 60 strings of 1 MWh each, with 80% depth of discharge, which equates to 48 MWh, and the system also consists of a 5 MW diesel generator that is kept on standby for emergency situations that affect the stability of the grid. However, the diesel generator is used 0% for the year in the optimal solution, which also confirms the

HOMER Pro results that indicate zero diesel fuel consumption and zero CO_2 emissions for the optimal solution.

In the optimal solution, the PV array uses the LF Dispatch mode, which is indicated in HOMER Pro as LF, to supply 9,237.9 MWh of power annually, whereas the system's electrical demand requirement is 4,113.0 MWh. Therefore, the losses in the battery bank, which equate to 5,124.9 MWh, consist of the charge losses, whereas 4,672.9 MWh is available for hydrogen production. In the optimal solution, the battery bank uses 2,272.4 MWh, whereas the autonomy of the battery bank is 1,703.9 hours. Table 4 indicates the technical performance results for the optimal HOMER Pro solution, which consists of the PV system, the Li-Ion battery bank, and the diesel generator.

Table 4. Technical performance metrics for the optimal HOMER Pro configuration

Performance Metric	Value	Unit
Annual Electric Production (PV)	9,237.9	MWh/year
Annual Electric Consumption (Load)	4,113.0	MWh/year
Excess Electricity (available for H_2)	4,672.9	MWh/year
Battery Annual Throughput	2,272.4	MWh/year
Battery Autonomy	1,703.9	hours
Renewable Energy Fraction	100%	—
Renewable Penetration	3,007.4%	—
Capacity Shortage	0	kWh/year
Unmet Load	≈ 0	kWh/year
Diesel Generation	0	kWh/year
Annual CO_2 Emissions	0	tonnes CO_2

Annual Energy Generation vs. Consumption (The Performance Gap)

The main optimization challenge was the balancing act between the strong, albeit intermittent, solar power and the steady local energy requirement. Figure 3 shows this in the Annual Generation Profile and Load Matching Performance (MWh/year) of the optimization results, where the performance graph from HOMER Pro shows the blue line representing the monthly average daily solar power (peaking during the summer months) and the orange line representing the steady state of the local energy requirement. The small graph at the bottom left is a bar chart confirming the results, showing the yearly energy production from the solar panels at 9,237.9 MWh/year and the energy requirement at 4,113.0 MWh/year. The wide shaded area between the lines represents the Excess Electricity available for battery charging and hydrogen production at 4,672.9 MWh/year.

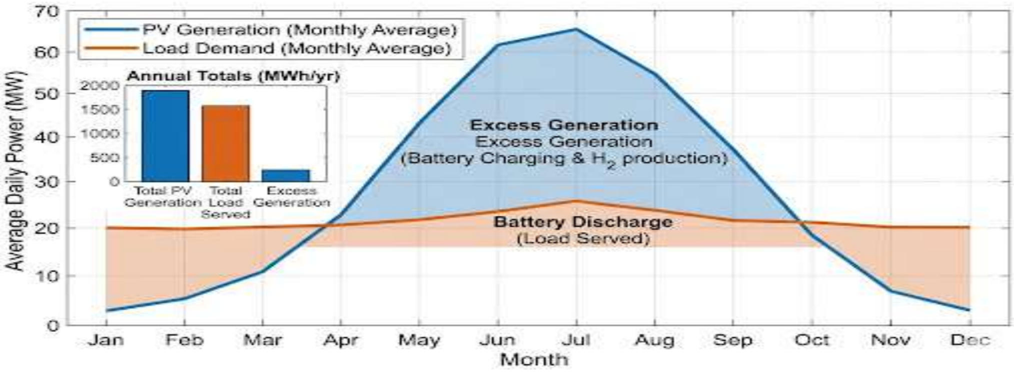


Figure 3: Annual Generation Profile and Load Matching Performance (MWh/year)

Economic Feasibility Analysis

The optimum hybrid configuration compares with the diesel-only approach. Over the 25-year period, the net present cost (NPC) of the hybrid approach is $1.118 billion. This is largely due to the capital costs of the solar array and the battery bank. On the other hand, if one were to use the diesel-only approach with a cost of $1.20 per litre, and with a yearly consumption of 12 million litres for the same power output, and include the capital costs and operation/maintenance costs of the generators, the result is an NPC of about $2.8 billion over the same period.

Figure 4 illustrates the overall costs and the levelized cost of energy (LCOE) needed for the investment decision. Here, the result for the hybrid approach is an LCOE of $0.06 per kWh (blue bar), representing a decrease of 76% compared with the $0.25 per kWh (grey bar) of the diesel-only approach.

Additionally, the NPC is also significantly lower, i.e., $1.118 billion for the hybrid approach versus $2.8 billion for the diesel-only approach. On the right-hand side, the $22 million CAPEX for the optimum approach is illustrated, with the solar array accounting for 51%, and the battery bank accounting for 41%.

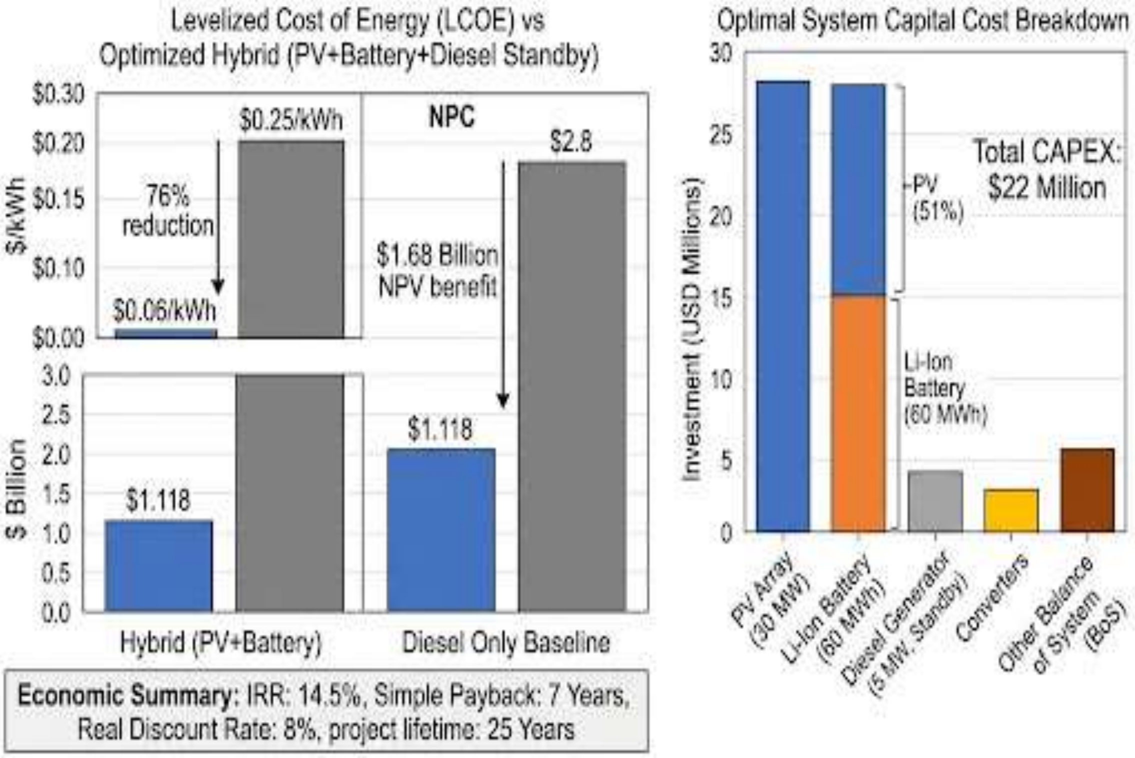


Figure 4: Hybrid System LCOE and Net Present Cost (NPC) Comparison

The levelized cost of energy for the hybrid system amounts to only $0.06/kWh, which is 76% lower than the diesel baseline. Moreover, the simple payback period of seven years, coupled with an IRR of 14.5%, indicates that the project is extremely lucrative considering that the cost of finance for infrastructure projects ranges between 8% and 12%. Table 5 shows the economic comparison between the optimal hybrid system and the diesel baseline.

Table 5. Economic comparison between the optimal hybrid system and the diesel-only baseline.

Economic Indicator	Hybrid (PV+Bat)	Diesel Baseline
CAPEX (Initial Capital Cost)	$22 M	$3.5 M
Net Present Cost (NPC, 25 yr)	$1.118 B	≈ $2.8 B
LCOE	$0.06/kWh	$0.25/kWh
Simple Payback Period	7 years	N/A
Internal Rate of Return (IRR)	14.5%	—
Annual O&M Cost	$17.5 M/yr	$38 M/yr (fuel)
Fuel Cost Savings vs. Baseline	80%	—

Hourly Performance and Dispatch Strategy

The operation of the hybrid system on an hour-by-hour level is essential in demonstrating the robustness of the system and how the fully renewable system will suffice to meet the demand. Figure 5 is an Hourly Operations and Dispatch Strategy Analysis Chart, with the time period ranging from 0 to 24 hours. It is a scientific time series that illustrates the optimal load-following strategy on a representative summer day. The main axis on the left illustrates the power in MW. At night, the battery supplies power to the load (orange line, where the SOC dips). At the onset of the day, the PV power kicks in (blue line, where the line peaks around noon) and supplies the load directly (shaded area). At around 10:00 hours, the battery is recharged (shaded area). The secondary axis on the right illustrates the Battery SOC in percent with the orange dashed line, with a clean discharge pattern between 20 and 80 percent (usual Li-ion, 1MWh string), with the diesel power remaining at 0 percent.

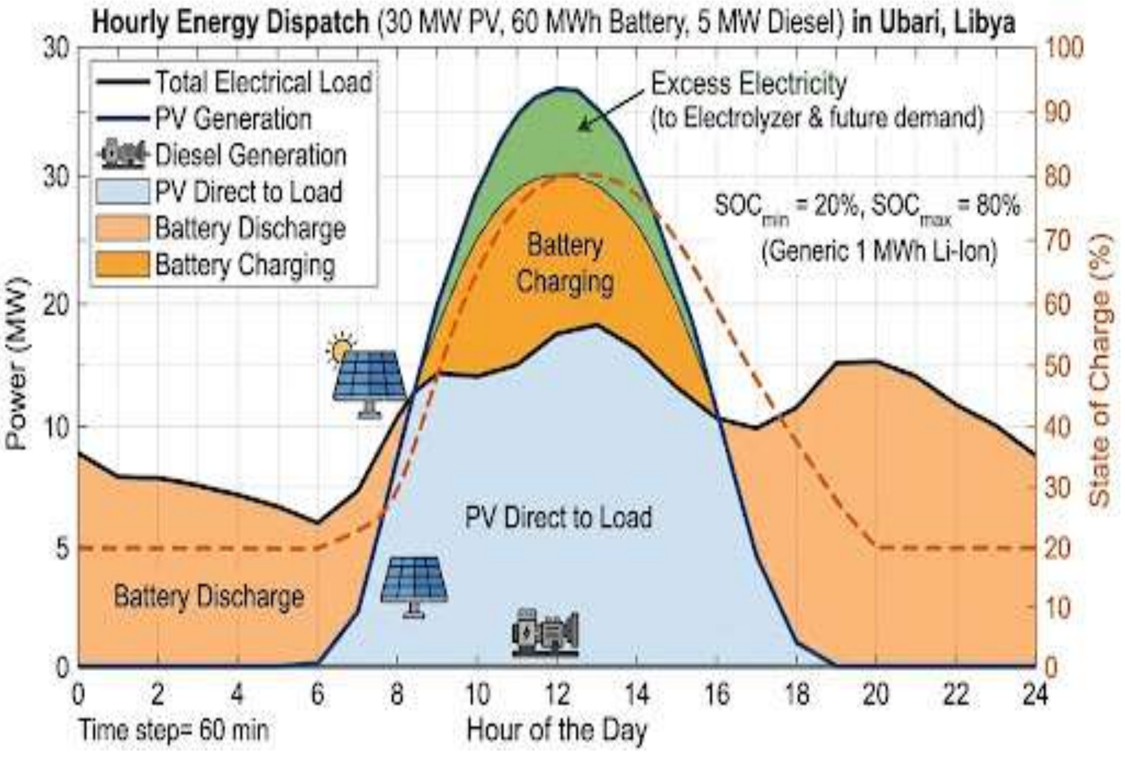


Figure 5: Hourly Operations and Dispatch Strategy Analysis (24-Hour Period)

Scenario Comparison

The assessment has verified the performance range and has confirmed that the chosen configuration is optimal; see Table 6, which presents the economic comparison between the best hybrid system and the baseline diesel-only system.

Table 6. Economic comparison between the optimal hybrid system and the diesel-only baseline.

Scenario	PV (MW)	Battery (MWh)	LCOE ($/kWh)	RE Fraction
S1: Diesel Only (Baseline)	0	0	0.25	0%
S2: PV + Diesel (no storage)	15	0	0.12	55%
S3: PV + Battery + Diesel (Optimal)	30	60	0.06	100%
S4: PV + Battery (oversized)	30	120	0.08	100%

Hydrogen Production Results

Applying the hydrogen production model presented in Section 3.6 to the yearly excess electricity of 4,672.9 MWh, the following result is obtained: Using the excess power generated per annum to power the hydrogen production system, the amount of hydrogen generated will be m_H_2 = (4,672,900 kWh * 0.70 kWh/kg / 50 kg/kWh) ≈ 65,420 kg/year, or about 65.4 tonnes/year. Increasing the power of the system to 20 MW, using a PEM system, will allow the system to handle the full design capacity of the excess energy generated in the PV array, which is 30 MW at peak sun. This will result in the production of about 200 tonnes/year of hydrogen when the seasonal operation is taken into account, considering that the system will only operate at 95%. The levelized cost of hydrogen (LCOH) is estimated at between $4.0 and $5.0 per kilogram, considering the cost of the electrolysis capital at $1.8/kg, desalination at $0.4/kg, compression and storage at $0.5/kg, and operation and maintenance at between $1.3 and $2.

Environmental Impact Assessment

Ubari plant would consume around 17,647 tonnes of diesel annually, based on 0.85 kg CO_2/kWh * 4,113 MWh + losses from the diesel generator. That equates to 15,000 tonnes of CO_2 emissions annually, along with emissions of NOx, PM, SO_2, and unburned hydrocarbons. However, in the optimal hybrid scenario, the CO_2 emissions for the plant's ROR operation would be zero, with 100% renewable energy share and no diesel consumption. The only emissions would come from the production of the PV panels and the battery, which would be around 30-45 g CO_2-eq/kWh for the monocrystalline PV. These emissions would be paid back in around 1.5 to 2 years, which is less than the 25-year lifespan of the plant.

Discussion

Significance for Libyan Desert Development

The study presents a strong case for the fact that the hybrid system in the Ubari region is more than just an upgrade in the technical tools used for the generation of power. The achievement of 100% renewable power without facing any capacity shortfall and keeping the unmet load near zero is impressive, especially since the region is remote from the Libyan grid and has historically had some of the worst power reliability metrics in the country. The cost of the power generated comes out to be $0.06 compared to the average cost of power in Europe, which comes out to be €0.25 for each kWh of power. This implies that the region could possibly support water desalination plants, manufacturing industries, and even digital infrastructure if the hybrid system is put in place in the region. The achievement of 100% renewable power is important for the Libyan government since the country spends heavily on diesel subsidies for the remote communities in the country. This expenditure comes out to be in the hundreds of millions of dollars annually. The country could possibly save this cost if the hybrid system were to be replicated across the twelve districts in the Fezzan region. This would ensure the generation of technical skills in the region as well. The study shows that the renewable system is more cost-effective even without the use of carbon pricing and green finance subsidies.

Green Hydrogen as Strategic Value Addition

The price of 4–5 US Dollars/kg of green hydrogen produced by the Ubari project is at the boundary of what is economically viable. Moreover, the price of 4–5 US Dollars/kg of green hydrogen, which is the LCOH, is aligned with the REPowerEU targets for Europe. Even without considering the possible reduction in the price of electrolysers, which is expected to drop by 50% by 2030, the price of 4–5 US Dollars/kg of green hydrogen produced by the Ubari project is still competitive. Moreover, the location of the Libyan plant, which is 1,600 km away from the coast of Sicily, is advantageous. HOMER Pro indicates that the excess electricity produced is 4,672.9 MWh/year, which is much more than the 3,500 MWh/year that would be needed for the 20 MW PEM electrolyser with 70% efficiency to produce 200 tonnes of green hydrogen. Therefore, the excess capacity is advantageous for the variability in the operation of the electrolyser, which can also cater to the possible increase in the demand for green hydrogen in the service area of the Ubari without the need for the addition of new capacity for the photovoltaic system. Moreover, the increase in the demand for green hydrogen due to urbanisation and other growth factors can also be catered to without the need for new capacity, considering the possible reduction in the cost of electricity.

Challenges and Risk Factors

There are some issues to take into account. First, the accumulation of sand and dust on the PV panels in the desert environment may reduce the power output of the PV modules by 5-30% if the panels are not regularly cleaned. This is an operational issue that the derating factor ($f_{PV} = 0.80$) does not fully address, which could even underestimate the effect of the Saharan dust storms. However, the solution for this would be the use of automated cleaning systems for the PV panels, which are commercially available and should be included in the PV system design with minimal additional cost.

Second, the extreme heat in the area, which in the summer months exceeds 45°C, will affect the PV system's performance using the temperature coefficient. This effect is already included in the HOMER model, which would be confirmed using actual cell temperatures rather than the NOCT values.

Third, the geopolitical risks in the Libyan context, which include issues of regulation, currency inconvertibility, and the possibility of the project being suspended, would affect the overall feasibility of the PV system from the perspective of the investor, which the economic model in the HOMER software does not take into account.

In the context of the battery lifespan, which is another sensitivity factor for the PV system, the lifespan of the Li-Ion battery is assumed to be 15 years, meaning one battery replacement would be necessary within the 25-year lifespan of the PV system. However, if the degradation rate of the battery in the actual environment is higher than the assumed rate, for example, due to the effect of the ambient temperature, the cost of battery replacement would be incurred earlier, affecting the overall economic viability of the PV system in the area. In the context of the desert environment in the area of Ubari, the battery enclosures would need to be designed to handle the heat.

Recommendations

The recommendations based on the simulation results are as follows:

1. Developing a Renewable Energy Free Economic Zone in Ubari, Libya, offering easier permitting, tax breaks, and grid connection to attract investment that meets Libya's 2030 renewable energy targets.
2. Signing Power Purchase Agreements and Hydrogen Offtake Agreements with European energy companies to provide bankable contracts for project finance.
3. Designing the project for scalability: starting with 10 MW PV + 20 MWh storage (Phase 1) and scaling up to 30 MW + 60 MWh, etc., as needed and finance allows.
4. Build the local workforce skills base through collaboration with Fezzan University and technical colleges, ensuring a steady supply of trained PV technicians, electrical engineers, and hydrogen system operators.
5. Conduct a detailed study of the Murzuq Aquifer from a geotechnical and environmental perspective to ensure the continued sustainability of water extraction for the proposed RO system serving the electrolysis plant.
6. Establish a real-time system for the monitoring and management of data to ensure the continued performance of the PV system, battery systems, and the electrolyzers, quickly identifying any deviations in performance.

Conclusion

This study employed a detailed HOMER Pro analysis of all possible system configurations, amounting to a total of 602 system configurations, and determined that a system consisting of a 30 MW solar PV array, 60 MWh of Li-Ion batteries, and a 5 MW diesel standby system represents the technically optimal and economically best option for the Ubari power plant, a location in southwest Libya. This optimal system design attains a goal of 100% renewable energy use without capacity gaps, a minimum LCOE of \$0.06/kWh, compared to the \$0.25/kWh LCOE of the baseline system, a NPV savings of \$1.68 billion over a 25-year period with a return on investment of 14.5% using an 8% discount rate, a reduction of CO2 emissions by 15,000 tonnes annually, which aligns with the Paris Agreement, and a production of 4,672.9 MWh/year of surplus electricity used to operate a 20 MW PEM electrolyzer, which produces approximately 200 tonnes/year of green hydrogen at a competitive LCOH of \$4-\$5/kg. The site selection process, using the MCDA method, was validated using four weighted criteria, all of which confirm that the Ubari location represents the optimal site selection. The sensitivity analysis employed to determine how changes in system derates, battery life, discount rate, and diesel costs impact system design outcomes revealed that the optimal system configuration was the best option regardless of these changes. This study provides a solid foundation upon which a scientific basis exists regarding the use of renewable energy in the desert region of North Africa

References

[1] https://ember-energy.org/latest-insights/global-electricity-review-2025/2024-in-review/

[2] Salem, M., et al. 2025. Towards Green Economy: Case of Electricity Generation Sector in Libya. Solar Energy and Sustainable Development Journal. 14 (1): 334–360.

[3] Salem, M., et al. 2025. Technical and environmental cost-benefit analysis of strategies towards a green economy in the electricity sector in Libya. Economics and Policy of Energy and the Environment. 2: 133-167.

[4] Khaleel, M., et al. 2024. Towards Hydrogen Sector Investments for Achieving Sustainable Electricity Generation. Solar Energy and Sustainable Development Journal. 13(1): 71-96.

[5] International Energy Agency, Renewables 2023: Analysis and Forecast to 2028, Paris, France, Jan. 2024.

[6] Desertec Foundation, DESERTEC Concept – Renewable Energy from Desert Regions, Desertec Foundation, 2022. https://www.desertec.org.

[7] International Renewable Energy Agency (IRENA), Renewable Power Generation Costs in 2023, Abu Dhabi, 2024.

[8] REN21 (Renewable Energy Policy Network for the 21st Century), Renewables 2024 Global Status Report, Paris, 2024.

[9] BloombergNEF, Battery Price Survey 2023, Bloomberg New Energy Finance, New York, 2023.

[10] General Electricity Company of Libya (GECOL), Annual Report: Libyan Electricity Generation and Distribution Statistics, Tripoli, 2023.

[11] World Bank/Solargis, Libya Solar Resource Assessment, Global Solar Atlas, 2024. https://globalsolaratlas.info

[12] Solargis, Solar Resource Maps for Libya: Long-Term Monthly Average GHI, 2023. https://solargis.com

[13] Government of Libya, Libya’s Nationally Determined Contribution (NDC) under the UNFCCC Paris Agreement, Ministry of Environment, Tripoli, 2022.

[14] Salam. M., et al., “Techno-economic analysis of a hybrid renewable energy system for a remote community in Libya,” Energy Reports, vol. 5, pp. 1038–1048, 2019.

[15] Bakouri, K., et al. 2023. Learning lessons from Murzuq-Libya meteorological station: Evaluation criteria and improvement recommendations. Solar Energy and Sustainable Development Journal. 12(1): 30-48.

[16] Andeef, M., et al. 2023. Transitioning to Solar Fuel Instead of Fossil Fuel in the Electricity Industry. International Journal of Electrical Engineering and Sustainability (IJEES). 1(4): 32–46.

[17] Khaleel, M., et al. 2023. Solar and Wind Atlas for Libya. International Journal of Electrical Engineering and Sustainability (IJEES). 1(3): 27-43.

[18] Fathi, N., and Salem, A. 2007. The reliability of the photovoltaic utilization in southern cities of Libya. Desalination. 209(1-3): 86-90.

[19] Alatrash, A., et al. 2024. Assessing the Viability of Solar and Wind Energy Technologies in Semi-Arid and Arid Regions: A Case Study of Libya's Climatic Conditions. Appl. Sol. Energy. 60: 149–170.

[20] Aqila, A. et al. 2025. Design of Hybrid Renewable Energy System (PV/Wind/Battery) Under Real Climatic Conditions: Case Study of Samno Village– Southern Libya. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 168–181.

[21] Aqila, A., et al. 2025. Design and analysis of a PV/wind/battery hybrid renewable energy system for residential buildings under real-time conditions. In Proceedings of the Engineering for Palestine Conference.

[22] Aqila, A., and Fathi, N. 2026. Design and analysis of a hybrid renewable energy system to cover part of the residential sector loads in Libya. Fezzan University scientific Journal. Under press.

[23] Aqila , A. H., Abubaker, A., and Nassar, Y. 2025. Design of a Hybrid Renewable Energy System to Meet Housing Thermal Loads: Performance Evaluation Under Real Conditions of a House in Samno Region, Libya. Wadi Alshatti University Journal of Pure and Applied Sciences, 3(2), 179-191.

[24] Mohammed, S. et al. 2025. Exploring Promised Sites for Establishing Hydropower Energy Storage Stations in Libya Using GIS. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 85–94.

[25] Amer, K. et al. 2025. Economic-Environmental-Energetic (3E) Analysis of Photovoltaic Solar Energy Systems: Case Study of Mechanical & Renewable Energy Engineering Departments at Wadi AlShatti University. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 51–58.

[26] Abuqila, M. et al. 2025. Estimation of the Storage Capacity of Electric Vehicle Batteries under Real Weather and Drive-mode Conditions. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 58–71.

[27] Salim, E. et al. 2025. A Brief Overview of Hybrid Renewable Energy Systems and Integration of Isolated Hybrid PV Solar System with Pumped Hydropower Storage for Brack City – Libya. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 152–167.

[28] Almhdi, E. et al. 2025. Power and Carbon Footprint Evaluation and Optimization in Transitioning Data Centres. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 221–229.

[29] Ahmed, B. et al. 2026. Optimal Design of Hybrid Renewable Energy System (PV/Wind/PHS) Under Multiple Grid Connection Constraints. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 83–93.

[30] Imbayah, I., et al. 2026. Modeling A 600 MW Floating Photovoltaic System in Al-Khums city, Libya: Performance Analysis and Implementation Using PVSyst. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 223-237.

[31] Alfathi, S., Miskeen, G., and Mremi, W. 2026. Evaluation and Prediction Performance of Solar Panel and Wind Turbine Systems Using Simulation. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 94-104.

[32] Alkhazmi, A., et al. 2026. Design and Analysis of PV Solar Street Lighting systems in Remote Areas: A Case Study. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 1-14.

[33] El-Khozondar, et al. 2025. Economic and Environmental Implications of Solar Energy Street Lighting in Urban Regions: A Case Study. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 142-151.

[34] Imbayah, I., et al. 2025. Design of a PV solar-covered parking system for the college of renewable energy Tajoura, Libya: A PVsyst-based performance analysis. University of Zawia Journal of Engineering Sciences and Technology. 3(2): 288-307.

[35] El-Khozondar, H., et al. 2025. Sustainable street lighting in Gaza: Solar energy solutions for main street. Energy 360. 4(12): 100042.

[36] Fathi, Y. et al. 2024. Design of Reliable Standalone Utility-Scale Pumped Hydroelectric Storage Powered by PV/Wind Hybrid Renewable System. Energy Conversion and Management. 322: 119173

[37] Latiwash, I. et al. 2025. Performance Analysis and Sizing Optimization of Utility-Scale PV/Battery Storage System for Urban Zones. University of Zawia Journal of Engineering Sciences and Technology. 3(2): 261–275.

[38] Alatrash, A., et al. 2025. Optimum Number of Glass Covers of Thermal Flat Plate Solar Collectors. Wadi Alshatti University Journal of Pure and Applied Sciences. 2(1): 1-10.

[39] Rekik, S., and El Alimi, S. 2024. A spatial ranking of optimal sites for solar-driven green hydrogen production using GIS and multi-criteria decision-making approach: A case of Tunisia. Energy Exploration & Exploitation 42 (6): 2150-2190.

[40] Rekik, S. 2024. Optimizing green hydrogen strategies in Tunisia: A combined SWOT-MCDM approach. Scientific African 26: e02438.

[41] M Khaleel, Z Yusupov, S Rekik. 2025. Advancing hydrogen as a key driver for decarbonized power systems. Unconventional Resources, 100278.

[42] Rekik, S., and El Alimi, S. 2024. Solar-powered hydrogen potential in Tunisia: A spatio-techno-economic analysis. 2024 IEEE International Conference on Artificial Intelligence & Green Energy.

[43] Rekik, S., Khabbouchi, I., Eladeb, A., Alshammari, B., and Kolsi, L. 2025. A spatio-techno-economic analysis for wind-powered hydrogen production in Tunisia. Alexandria Engineering Journal. 128: 833-851

[44] European Commission, A Hydrogen Strategy for a Climate-Neutral Europe, COM(2020)301 Final, Brussels, 2020.

[45] O. Tlili et al., "North Africa green hydrogen for the European market," Int. J. Hydrogen Energy, vol. 45, no. 6, pp. 3618–3628, 2020.

[46] Abduallah, A., et al. 2026. Leveraging Hydrogen for covering energy shortage in an electricity subgrid. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1: 245-254.

[47] Elnaggar, M., et al. 2026. Leveraging Wind Energy for Electricity and Hydrogen Production: A Sustainable Solution to Power Shortages and Eco-Friendly Alternative Fuel. Advanced Energy and Sustainability Research. 7(1): e202500049.

[48] Fathi, N., Hafez, A., and Alsadi, S. 2020. Multi-Factorial Comparison for 24 Distinct Transposition Models for Inclined Surface Solar Irradiance Computation in the State of Palestine: A Case Study. Front. Energy Res. 7:163.

[49] Fathi, N. 2020. Analytical-numerical computation of view factor for several arrangements of two rectangular surfaces with non-common edge. International Journal of Heat and Mass Transfer. 159: 120130.

[50] Alsadi, S., El-Khozondar, H., and Refaat, S. 2022. Determination of the Most Accurate Horizontal to Tilted Sky-Diffuse Solar Irradiation Transposition Model for the Capital Cities in MENA Region. 2022 3rd International Conference on Smart Grid and Renewable Energy (SGRE), Doha, Qatar, 1-6.

[51] Nassar, Y., Hala, J., Belhaj, S., Alsadi, S., and Abuhamoud, N. 2022. View Factors in Horizontal Plane Fixed-Mode Solar PV Fields. Front. Energy Res. 10:859075.

[52] Khaleel, M., et al. 2025. Sensitivity of global solar irradiance to transposition models: Assessing risks associated with model discrepancies. e-Prime - Advances in Electrical Engineering, Electronics and Energy. 11: 100887.

[53] Aqila, A., Fathi, Y., and Hala, J. 2025. Determining the Least Risky Solar Radiation Transposition Model for Estimating Global Inclined Solar Irradiation. Solar Energy and Sustainable Development Journal 14 ((FICTS-2024)). 1-16.

[54] Fathi, N., et al. 2022. Investigating the Applicability of Horizontal to Tilted Sky-Diffuse Solar Irradiation Transposition Models for Key Libyan Cities. 2022 IEEE 2nd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA), Sabratha, Libya, 2022, pp. 9-14.

[55] Alsadi, S., and Yasser, F. 2017. Estimation of Solar Irradiance on Solar Fields: An Analytical Approach and Experimental Results. IEEE Transactions on Sustainable Energy/. 8(4): 1601-1608, Oct. 2017,

[56] Fathi, N., et al. 2023. Regression Model for Optimum Solar Collectors' Tilt Angles in Libya. In 2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES), Gaza, Palestine, State of. 1-6.

[57] Samer, Y., and Fathi, N. 2019. A general expression for the shadow geometry for fixed mode horizontal, step-like structure and inclined solar fields. Solar Energy. 181:53-69.

[58] Alsadi, S., Nassar, Y., and Amer, K. 2016. General polynomial for optimizing the tilt angle of flat solar energy harvesters based on ASHRAE clear sky model in mid and high latitudes. Energy and Power. 6(2): 29-38.

[59] Samer, Y., and Fathi, N. 2017. A numerical simulation of a stationary solar field augmented by plane reflectors: Optimum design parameters. Smart grid and renewable energy. 8(7): 221-239.

[60] Abdulwahab, S., et al. 2023. Meeting Solar Energy Demands: Significance of Transposition Models for Solar Irradiance. International Journal of Electrical Engineering and Sustainability. 1(3): 90-105.

[61] Belhaj, S., et al. 2022. A Generic Model for Optimum Tilt Angle of Flat-Plate Solar Harvesters for Middle East and North Africa Region. Appl. Sol. Energy. 58: 800–812.

[62] El-batta, F., et al. 2023. Standalone hybrid PV/wind/diesel-electric generator system for a COVID-19 quarantine center. Environmental Progress & Sustainable Energy 42 (3): e14049

[63] Al-Maghalseh, M., et al. 2022. Design of an isolated renewable hybrid energy system: a case study. Materials for Renewable and Sustainable Energy. 11(3): 225-240.

[64] Fathi, N. et al. 2022. Mapping of PV Solar Module Technologies Across Libyan Territory. Iraqi International Conference on Communication and Information Technologies. pp. 227–232.

[65] Alsharif, A., et al. 2023. Mitigation of Dust Impact on Solar Photovoltaics Performance Considering Libyan Climate Zone: A Review. Wadi AlShatti University Journal of Pure and Applied Sciences. 1(1): 22-27.

[66] Miskeen, G., et al. 2022. Atlas of PV solar systems across Libyan territory. International Conference on Engineering & MIS (ICEMIS), Istanbul, Turkey.

[67] Awad, H., et al. 3033. Optimal design and economic feasibility of rooftop photovoltaic energy system for Assuit University, Egypt. Ain Shams Engineering Journal. 13(3): 763-774

[68] El-Khozondar, H., et al. 2024. Photovoltaic Solar Energy for Street Lighting: A Case Study at Kuwaiti Roundabout, Gaza Strip, Palestine. Power Engineering and Engineering Thermophysics. 3(2): 77–91.

[69] Ali, F., et al. 2019. Numerical Analysis and Optimization of Area Contribution of The PV Cells in the PV/T Flat-Plate Solar Air Heating Collector. Solar Energy Research Update. 6: 43-50.

[70] Fathi, N., et al. 2023. Thermoelectrical Analysis of a New Hybrid PV-Thermal Flat Plate Solar Collector. 2023 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES), Gaza, Palestine, State of, 2023, 1-5.

[71] Salem, A., and Yousif, S. 2004. The Choice of Solar Energy in the Field of Electrical Generation-Photovoltaic or Solar Thermal-For Arabic Region. World Renewable Energy Congress VIII (WREC 2004), 534.

[72] Nassar, Y. 2008. Solar energy engineering active applications. Sebha University, Sebha, Libya.

[73] Khaleel, M., et al. 2025. Battery technologies In electrical power Systems: Pioneering secure energy transitions. Journal of Power Sources. 653: 237709.

[74] Albadry, O., et al. 2025. Static Analysis of Energy Storage Systems in Electric Vehicle Case Study: Lithium-Ion Battery. In Conference: Engineering for Palestine Conference, Palestine Polytechnic University, Hebron, Palestine.

[75] Alsharif, A., et al. 2023. Power Management and Sizing Optimization for Isolated Systems Considering Solar, Battery, and Diesel Generator based on Cost and Reliability under Murzuq and Sabha Cities Weather. International conference on research of mechanical design automation and materials, 28th -29th Sep 2023, bhopal, Madhya Pradesh, India.

[76] El Halim, A., Yasser, N., El-Khozondar, H., and Bayoumi, E. 2023. Fast Charging of Lithium-ion Battery for Electric Vehicles Application. In 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES). Gaza, Palestine.

[77] Khaleel, M., et al. 2025. Battery technologies In electrical power Systems: Pioneering secure energy transitions. Journal of Power Sources. 653: 237709.

[78] Aqila, A., et al. 2025. Design and Analysis of a (PV/Wind/Battery) Hybrid Renewable Energy System for Residential buildings under real time conditions. In Conference: Engineering for Palestine Conference, Palestine Polytechnic University, Hebron, Palestine.

[79] El-Khozondar, H., et al. 2023. DC off-grid PV system to supply electricity to 50 boats at Gaza seaport. In 8th International Engineering Conference on Renewable Energy & Sustainability (ieCRES).

[80] Ahmed, A., Alsharif, a., and Yasser, N. 2023. Recent advances in energy storage technologies. International Journal of Electrical Engineering and Sustainability. 1(1): 9-17.

[81] Khaleel, M., Yusupov, Z., Fathi, N., and Hala, J. 2023. Enhancing Microgrid Performance through Hybrid Energy Storage System Integration: ANFIS and GA Approaches. International Journal of Electrical Engineering and Sustainability. 1(1): 38-48.

[82] Irhouma, M., et al. Optimum Design of an off-Grid hybrid PV/diesel/battery power system for Brack Alshatti city, Libya. Fezzan University scientific Journal. Under press.

[83] Fathi, N., Amer, K., Irhouma, M., and Ahmed, S. 2016. Economical and environmental assessment of electrical generators: A case study of southern region of Libya. International Journal of Energy Policy and Management. 1(4): 64-71.

[84] Albuzia, D., Ali, A., Mohmed, M., and Hafez, A. (2025). Reliable and Robust Optimal Interleaved Boost Converter Interfacing PhotoVoltaic Generator. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 192-201.

[85] Mremi, W., Al-Mathnani, A., and Alfathi, S. 2026. Harmonic Distortion in Three-Phase Networks Using a 24-Pulse STATCOM: Modeling, Simulation, and Performance Evaluation. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 122-130.

[86] Al-Mathnani, A., Mohammed, A., Al-Hashmi, S., and Geepalla, E. 2025. Control and Modification of 12-Pulse Static Compensator with PV Cell Using New Control Algorithm. Wadi Alshatti University Journal of Pure and Applied Sciences, 3(1): 30-34.

[87] Ben Dalla, L., Karal, Ö., EL-Sseid, M., and Alsharif, A. 2026. An IoT-Enabled, THD-Based Fault Detection and Predictive Maintenance Framework for Solar PV Systems in Harsh Climates: Integrating DFT and Machine Learning for Enhanced Performance and Resilience. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 41-55.

[88] Al-Maghalseh, M., Hammad, A., Hamdan, M., and Abdelhafez, E. 2026. Thermal Comfort of Buildings Integrated Photovoltaics (BIPV). Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 146-164.

[89] Salem, M., Elmabruk, A., Irhouma, M., and Mangir, I. 2025. Assessment of Wind Energy Potential in Western Mountain: Nalut and Yefren as case study. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(1): 35-42.

[90] Abduallah, A., Mohammed, S., and Ghatus, M. 2025. Integrating Electricity Sub-Grid with Pumped Hydropower Storage System for Grid Stability and Sustainability. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 322-332.

[91] Fathi, N., et al. 2021. Dynamic analysis and sizing optimization of a pumped hydroelectric storage-integrated hybrid PV/Wind system: A case study. Energy Conversion and Management. 229:113744.

[92] Ahmad, S., Agrira, A., and Nassar, Y. 2025. The Impact of Loss of Power Supply Probability on Design and Performance of Wind/ Pumped Hydropower Energy Storage Hybrid System. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2):52-62.

[93] Alnadhif, M., et al. 2026. Technical-Economic-Energetic-Environmental Analysis of a PV-Wind-Biomass-Hydrogen Hybrid Energy System for Urban Zones. Unpublished.

[94] Alnadhif, M., et al. 2026. Design of a Multi-Source Hybrid Renewable Energy System (Solar, Wind, Biomass, and Hydrogen) for Achieving Sustainability. Fezzan University scientific Journal. Unpublished.

[95] Latiwash, I., et al. 2026. Energy, Economic and Environmental Analysis of a Solar Photovoltaic Energy System Integrated with a Hydrogen System to Supply the Electrical Load of an Urban Area. Fezzan University scientific Journal. Unpublished.

[96] Abdulwahab, S., Nassar, Y., Salem, M., and Alnadhif, M. 2026. Design of an Off-Grid Hybrid renewable energy PV/Biomass to meet the energy requirements of the agricultural sector in Libya. Fezzan University scientific Journal. Unpublished.

[97] Mohamed, A. 2025. High-Pressure Compression, Liquefaction and Metal Hydrides for Hydrogen Storage. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 75–84.

[98] Al-Maghalseh, M. 2025. The environmental impact and societal conditions of PV power plants: a case study of Jericho gate-Palestine stat of. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 16-31.

[99] Inweer, M., and Nassar, Y. 2025. Carbon Emissions Life Cycle Assessment of Cement Industry in Libya. Wadi Alshatti University Journal of Pure and Applied Sciences. 3(2): 162-173.

[100] Inweer, M., et al. 2025. Carbon footprint life cycle assessment of cement industry in Libya. Discov. Concr. Cem. 1: 37.

[101] Mohammed, S., et al. 2023. Carbon and Energy Life Cycle Analysis of Wind Energy Industry in Libya. Solar Energy and Sustainable Development Journal. 12(1): 50-69.

[102] Mansour S., et al. 2025. Estimation of CO2 emission within Libya's electricity generation sector. Next Research. 2(3): 100567.

[103] Salem, M., and Hala, E. 2025. Estimation of CO2 Emissions from the Electric Power Industry Sector in Libya. Solar Energy and Sustainable Development Journal. 14 (1): 42–55.

[104] Almhdi, E., and Miskeen, G. 2025. Power and Carbon Footprint Evaluation and Optimization in Transitioning Data Centres. Wadi Alshatti University Journal of Pure and Applied Sciences, 3(2): 221-229.

[105] Moumani, K. 2023. Management of sustainable development in the light of Arab and international cooperation, a case study of the Arab vision of management of sustainable development. Wadi Alshatti University Journal of Pure and Applied Sciences. 1(1):1-8.

[106] El-Khozondar, H., et al. 2026. Feasibility of Concentrating Solar Power as a Solar Fuel for Electrical Power Stations: A Case Study of Ubari Gas-Power Station in Libya. Wadi Alshatti University Journal of Pure and Applied Sciences. 4(1): 56-69.

[107] Mohammed, S., et al. 2023. Carbon and Energy Life Cycle Analysis of Wind Energy Industry in Libya. Solar Energy and Sustainable Development Journal. 12(1): 50-69.

[108] Aissa, K., and Alsadi, S. 2017. Estimation of Environmental Damage Costs from CO2e Emissions in Libya and the Revenue from Carbon Tax Implementation. Low Carbon Economy. 8: 118-132