



Hybrid Electricity Generation System for The Gali Zakho Tunnel in Iraq: A Comparative Study of Different Configurations Using Homer Pro

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ARTICLE INFO

Article Type:

Research Article

Received: 2025.11.24

Accepted in revised form: 2026.02.22

Keywords:

Renewable energy;
Photovoltaic (PV);
Hybrid systems;
Off-grid applications;
CO₂ reduction;
HOMER Pro

ABSTRACT

This paper explores the feasibility of a renewable hybrid power plant for the Gali-Zakho highway tunnel in the north of Iraq. HOMER Pro was used to simulate, optimize, and evaluate the off-grid technical, economic, and environmental performances of seven hybrid system configurations. These investigations revealed that Case A (PV–Diesel–Battery) was the optimal configuration, not only due to having the lowest Net Present Cost (\$ 6.68 M) but also because it has a Cost of Energy of \$0.065/kWh, with an IRR of 18%, an ROI of 14%, and a simple payback period of 5.2 years for a 25-year project lifetime. The system generated about 9,440,000 kWh a year with PV panels accounting for 97.4% of the total, leading to a system renewable fraction of 94.8%; the diesel generator accounted for the remaining 2.6% by acting as a backup power source. The top-performing configuration reduced CO₂ emissions by nearly 3.7 million kg per year versus generators that ran on diesel alone, and still delivered reliable power. These results validate the applicability of PV-biased hybrid systems for tunnel infrastructure and identify their potential contribution to sustainable energy development in northern Iraq.

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Cite this article: Saeed, A. Ibrahim, Yousif, K. Mansoor and Abdulrazzaq, M. Bahjat (2026). Hybrid Electricity Generation System for The Gali Zakho Tunnel in Iraq: A Comparative Study of Different Configurations Using Homer Pro. Journal of Solar Energy Research, 11(1), 2851-2866. doi: 10.22059/jsr.2026.406903.1672

DOI: 10.22059/jsr.2026.406903.1672



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1. Introduction

Due to the increased need for sustainable and robust energy production, hybrid renewable energy systems (HRES) are becoming increasingly important for critical infrastructure located in remote or isolated regions [1]. Traditional tunnel systems relying on grid-based or diesel power face challenges such as reliability, very high operational costs, and the emission of substantial volumes of greenhouse gases [2]. These issues are exacerbated in developing regions like the Kurdistan Region of Iraq due to frequent blackouts and relatively limited access to cleaner sources of energy [3].

The Gali-Zakho Tunnel in the Dohuk Governorate of Iraq is a crucial corridor connecting Iraqi and Turkish territories; thus, maintaining its efficiency is of immense importance for facilitating commerce between these countries and transportation across borders [4]. However, as the grid in the local area is unreliable, an off-grid hybrid renewable energy system would nominally seem to be both a sustainable and technically viable solution [5]. The proposed system, which integrates solar photovoltaic (PV) with wind and battery storage, will ensure the continuous availability of power, reduce carbon emissions, and boost long-term energy resilience.

Configurations of HRES such as the one examined herein have previously been shown to be efficient and environmentally friendly in terms of the electrification of remote villages and stand-alone systems. However, tunnel conditions that meet specific load profiles, safety conditions, and geometrical constraints rarely receive attention in terms of their design and optimization. The diverse terrain and weather conditions in the Gali-Zakho region, particularly its mountainous geography with variable wind speeds, also enhance the system's performance and design requirements.

In the present paper, we propose the design, simulation, and optimization of an off-grid solar-wind-battery hybrid renewable energy system for the Gali-Zakho Tunnel. The assessment combines local meteorological observations and on-site wind measurements with NASA's satellite reanalysis of solar radiation and ambient temperature to guarantee the accuracy and representativeness of datasets. The technical, economic, and environmental characteristics of the system are analyzed by means of state-of-the-art simulation tools such as HOMER Pro and MATLAB.

The outcomes of this study will serve engineers, policymakers, and researchers in the effort to assimilate renewable integration into transportation infrastructure; hence, they are congruent with Iraq's overall sustainable energy development and carbon abatement strategy.

2. Literature review

Energy is a key factor in economic growth [6]. Utilizing renewable resources advances sustainable development while improving public health and quality of life [7]. To meet the increasing global demand for energy and to address the urgent issue of climate change, attention has shifted significantly towards more sustainable and distributed power-generation systems [8].

HRES are widely recognized as one of the most viable solutions to these challenges, where intermittent power sources such as solar or wind are integrated with energy storage devices and backup sources [9]. In particular, several studies have reported on photovoltaic (PV)-diesel-battery configurations, which have received substantial attention with regard to supplying power in off-grid and critical infrastructure applications [10-12]. Previous studies demonstrated that by reducing dependency on fossil fuels and utilization of local renewable resources, HRES could potentially reduce the levelized cost of electricity (LCOE) and greenhouse gas (GHG) emissions without sacrificing reliability [13]. The design and optimization of such complex systems is dependent on advanced computer codes like HOMER Pro, which balance technical, economic, and environmental variables within a unified simulation model, and indeed are used extensively for this purpose [14].

The international transferability of HRES was tested in various settings and scales. In Africa, studies conducted in Ethiopia [10] demonstrated the viability of solar-wind hybrids for rural electrification. Similarly, investigations in Saudi Arabia by Rehman and Al-Hadhrani [11] evaluated PV-diesel-battery systems and reported significant diesel savings and emission reductions. The PV-diesel-battery configuration is especially well-suited for tropical and semi-arid regions, as reported by Nema et al. [15]. In Algeria, optimized system designs reduced diesel consumption by over 70% [16]. Furthermore, the commercial profitability of

such systems was confirmed by an analysis of the situation in Türkiye, where a low production cost of \$ 0.209/kWh [17].

These systems were fundamentally dependent on developments in energy storage. Driven by their higher energy density, longer lifetime, and greater efficiency compared to lead-acid options, lithium-ion batteries have become an important part of modern HRESs [18, 19]. Previous studies have validated such systems even under difficult operating conditions, making their application feasible even at a high altitude, for instance in Taiwan [18], whilst optimization efforts carried out in Cameroon generated LCOEs of \$0.198 per kWh [20]; the scale-up potential of PV–diesel–battery systems with storage has also been demonstrated by successful deployment in large renewable energy zones in Australia [1].

The effectiveness of HRES in achieving universal electrification encouraged their use in specific infrastructure projects. Research activities have also shifted toward transportation networks; for example, simulations carried out for the incorporation of renewables into the motorway infrastructure of China projected the generation of 1.09 GWh/year [21]. Additionally, an investigation conducted into renewable-powered highway tunnel output exceeded 1.1 GWh/year, along with significant CO₂ reductions [22]. In addition to transportation, HRES are well-suited to a multitude of other sectors, such as agriculture through large-scale irrigation in Canada [23], green hydrogen production in Egypt [24], and healthcare building electrification in Yemen with the introduction of PV-batteries, which covered 90% renewable energy at a cost of \$0.088/kWh [25].

Previous studies have demonstrated that this approach was effective in off-grid infrastructure applications. In China, off-grid solar/wind/hydropower hybrid systems with diesel backup achieved proportions of 97% renewables for Chinese motorways [21], and PV–wind–diesel–battery systems for highway tunnels were also reported to work extremely well [22]. These findings suggest a clear route to the decarbonization of remote critical infrastructure.

HRES studies have gained significant attention in the Middle East and North Africa (MENA) due to the high solar potential and high grid instability [26]. In Iran, PV–wind–diesel–battery generation systems have been shown to be economically viable [27]. Techno-economic studies in Iraq verified the feasibility of PV–diesel–battery configurations, such as an option in which 41.3% of the energy supply was provided from renewable sources and demonstrated a significant reduction in CO₂ emissions [14]. These results supported hybrid systems as a viable option for rural settings in Iraq. However, recent studies conducted in Iraq were based on a university campus building connected to the grid and with a typical daily loading consumption pattern (9:00–15:00) [28]; this study, however, did not cover 24/7 off-grid power for strategic infrastructure such as highway tunnels, which required balanced, non-discretionary loads, ultra-high reliability, and special safety isolation measures that fundamentally influenced system design and optimization options.

In conclusion, the novelty of this work is that it fills a research gap in the utilization of HRESs for vital remote transportation infrastructure, such as highways and tunnels, particularly in regions such as Iraq where detailed feasibility studies for off-grid highway tunnels are lacking. It provides the first integrated techno-economic-environmental optimization analysis of an isolated HRES for the Gali-Zakho Tunnel. The work presents three key innovations:

- A method for the generation of high-resolution data that includes NASA solar measurements and on-site wind readings, from which the load profile is simulated with high fidelity.
- A comprehensive comparison framework encompassing seven system options against an essential 24/7 load; and, most importantly,
- A demonstrated, replicable optimal solution (PV-Diesel-Battery) that is able to deliver power at \$0.065/kWh, with reliable supply and up to 94.8% renewable penetration.

Accordingly, the paper also offers a real-world, and data-based blueprint for sustainable electrification of similar isolated infrastructure.

3. Materials and Methodology

The following section introduces the data sources, study site, and optimization method applied to the design and assessment of an off-grid HRES for the Gali-Zakho Tunnel located in Duhok, Iraq. The study combines real-life meteorological and load data with simulation and optimization through the HOMER Pro software. Graphical analysis subsequent to conducting the simulation was performed using code written in MATLAB.

3.1 Study Area Description

The Gali-Zakho Tunnel is located in northwest Iraq, Duhok Governorate (36°55'20" N and 42°55' E), and constructed to consist of two parallel tunnels, each one having a length of 3604 m and a width of 12.4 m, allowing passage for two rows of traffic in opposing directions. The tunnel itself is a major transport corridor for trade and commerce between Iraq and Turkey.

Due to the need for the tunnel's continuous operation and its critical function, it was considered an ideal site to analyze whether a self-supporting hybrid renewable power system might be feasible. (See Figure 1).

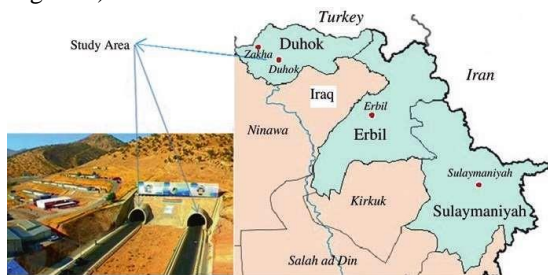


Figure 1 Photograph of the Gali-Zakho Tunnel with the spatial location of the study area [29]

3.2 Data Collection and Sources

The renewable energy potential and load demand for the Gali-Zakho Tunnel were analyzed using a combination of **external datasets** and **on-site measurements**.

3.2.1 Meteorological Data

Solar radiation and temperature: The hourly data for the period July 2024 – June 2025 were acquired from the NASA POWER database.

- Maximum solar radiation: 8.1 kWh/m²/day (June)
- Minimum solar radiation: 1.67 kWh/m²/day (January)
- Annual mean: 4.83 kWh/m²/day
- Wind speed: Monthly average values were measured at a site on the mountain above the tunnel for 1 year (July-2024 - June2025). The site was chosen due to its open environment and proximity to the ventilation location of the tunnel, which is suitable for wind turbine erection.
- The monthly wind speed varied between 3.5 m/s (February) and 5.14 m/s (June), with an annual mean of 4.25 m/s.

This integration of satellite and field data was considered to improve the accuracy and reliability of renewable resource estimation at the position where the tunnel is located. Total monthly solar radiation and wind speed variation for the Gali-Zakho Tunnel region are illustrated in Figure 2, which gives a clear picture of the seasonal availability and complementarity of these two renewable resources.

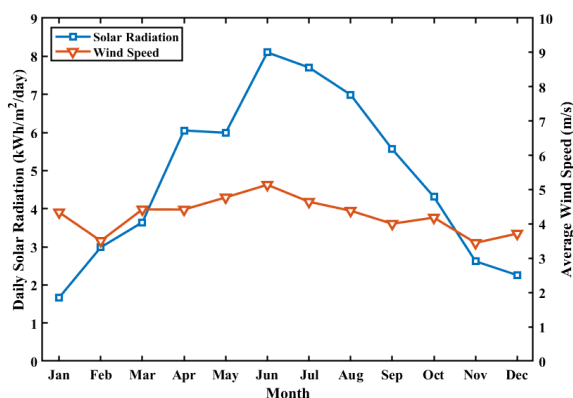


Figure 2. Monthly variation of daily solar radiation [30] and average wind speed measured on-site by the researcher in the Gali-Zakho Tunnel region

3.2.2 Electrical Load Data

Electricity data for the tunnel were collected from the General Electricity Directorate of Duhok. The average daily consumption is 12,704.44 kWh/day,

with a peak demand of 670 kW. The main consumers of power are lights, fans, emergency gear, and monitoring/office devices.

The load profile demonstrates only a low seasonal variation of between 400 and 670 kW for all seasons. This stable load profile facilitates the optimization of a hybrid renewable energy system and raises confidence in its design. Fig. 3 displays the yearly load schedules for the principal electrical loads.

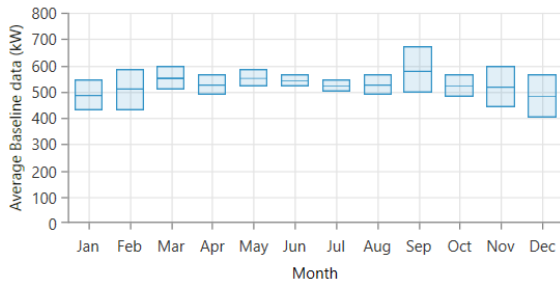


Figure 3. The annual electricity consumption profile of the main loads in the Gali-Zakho Tunnel [31]

3.3 Optimization Procedure

Optimization was conducted using the HOMER Pro software to determine the optimal hybrid renewable configuration with off-grid access. The process was conducted as follows:

3.3.1. Data Inputs: Import solar, temperature, wind, and electrical load data.

3.3.2. System Configuration For the optimization of hybrid systems, we will consider that the system is composed of certain potential components, such as PV panels, a wind generator, a storage battery, and a diesel generator connected by means of a converter.

3.3.3. Simulation Configuration: The system is simulated to operate continuously, both day and night, over a one-year period (8,760 hours), based on specified technical and economic conditions.

3.3.4. Economic Parameters: Realistic regional and technical assumptions were made for the economic parameters. A project lifespan of 25 years was selected, as this is a common lifetime for PV modules and is the standard design period for renewable energy projects, which allows the assessment of likely long-term costs [32]. The

selected discount rate of 6% was based on the average real return rate for the development of energy projects under Iraqi market conditions and considered investment risk and financial viability [33]. A 5% rate of inflation was used, based on recent national economic trends, to adjust for the projected rise in equipment prices and maintenance costs over time [34]. Finally, the annual capacity shortage allowance was set at 0% [35], which indicates that there is no power cutoff throughout the entire year required to achieve an uninterrupted and stable power supply for the hybrid system design, both of which are necessary in tunnel operation.

3.3.5. Optimization Objective: Minimize Net Present Cost (NPC) and Cost of Energy (COE) and explore renewable fractions as well as reductions in CO₂ emissions.

3.3.6. Scenario Analysis: Multiple system configurations (cases A-G) were simulated, and the most promising combination in terms of technical feasibility and cost efficiency was selected.

3.3.7. Post-Simulation Analysis: The results were imported into MATLAB to allow for the visual interpretation, which included the monthly power generation and energy contribution profiles for each case, as shown in Fig. 4.

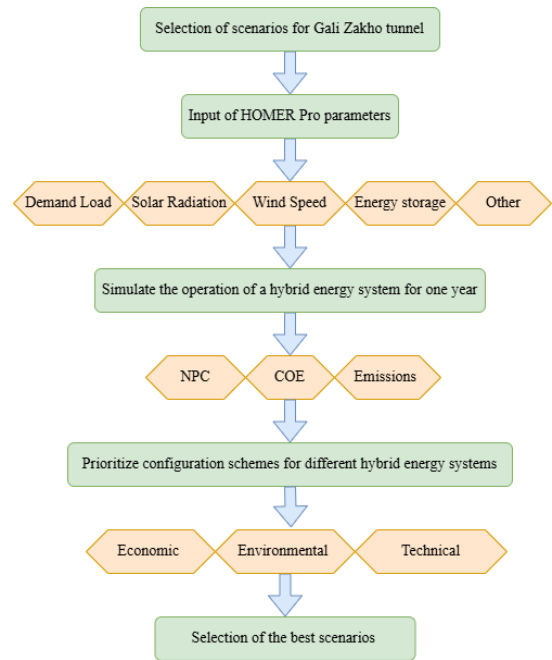


Figure 4. A flowchart illustrating the simulation procedure for the Gali-Zakho Tunnel Renewable Hybrid Energy System

3.3.8 Component Sizing Rationale

The PV array, diesel generator, and battery bank capacities were optimized in HOMER Pro based on the expected tunnel load profile, the renewable resources existing at the site, and appropriate economic restrictions.

The PV capacity was chosen to cover the majority of the tunnel's annual energy needs, taking advantage of the high solar potential of the area (average 4.83 kWh/m²/day). Several PV sizes were considered using HOMER Pro, and the capacity was optimized to help minimize the NPC of the system while maintaining acceptable reliability. Consequently, PV generation contributes 97.4% of the annual electricity production for the optimized configuration.

A diesel generator was properly sized to cover both peak load demand as well as low renewable generation backup. A zero annual capacity deficiency was assumed to guarantee uninterrupted tunnel service. The low generator annual energy contribution (2.6%) validates that the generator is primarily a reliability-based rather than a primary resource in supporting load.

The capacity of the battery bank was designed to allow for short-term energy storage, smooth the load, and provide nighttime power. The chosen capacity trades off between system reliability and economic viability by minimizing unmet loads without incurring unnecessary capital costs.

4. Hybrid Renewable Energy System Configuration

After effectively surveying the natural resources in the Gali-Zakho Tunnel area, particular emphasis was placed on the use of solar and wind energy as an addition to the renewable hybrid power generation system. However, the power generated from PV panels and wind turbines is unstable because of their intermittent nature and occasional standstill periods. To guarantee a stable and uninterrupted supply of electricity, the system includes a diesel generator as an alternative supply. Simultaneously, batteries were

arranged to serve as energy storage so as to shape the load-side voltage. Furthermore, a conversion was made to efficiently switch between AC and DC, making all system components compatible with tunnel loads. Fig. 5 shows a generalized block diagram of the hybrid renewable energy generation system as applied in the case of the Gali-Zakho Tunnel. Solar panels and wind turbines act as the main sources of renewable energy, while the diesel generator ensures backup power when required; the battery bank stores energy beyond what is needed and stabilizes the supply; and finally, the converter provides a stable AC-DC interface for energy transfer. This system setup was then assessed based on simulation and optimization in HOMER Pro to identify the most feasible and efficient design.

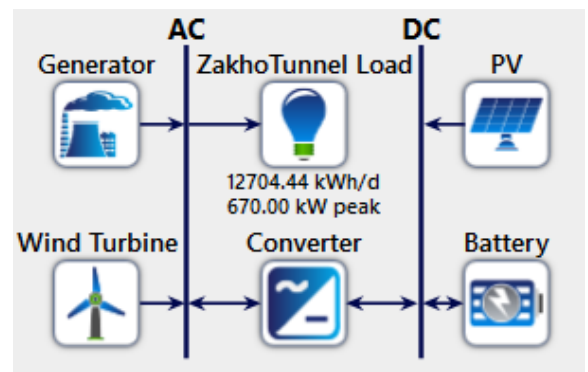


Figure 5. Schematic diagram of the proposed tunnel renewable hybrid energy system

5. Evaluation of Techno- Economic Parameters

It is crucial to determine appropriate input parameters for all units composing the Gali-Zakho Tunnel hybrid energy system to evaluate the potential environmental aspects and economic characteristics of this alternative through HOMER Pro. These parameters are reported in Table 1, with all component data sheets taken from the appropriate manufacturer's official sources; the manufacturers' recommended lifetimes on components were used. To ensure greater reliability and relevance, capital, replacement, and O&M costs were also calculated based on a local market survey, which was conducted with updated region-specific price conditions and service levels. This input was used for simulations and optimizations (Table 1).

6. Results and Discussion

Table 1. Input parameters for the hybrid energy system components

Component	Model	Capital Cost (\$/unit)	Replacement Cost (\$/unit)	Lifetime	O&M (\$/unit/yr)
PV Module [36]	LONGi Hi-MO X10 (LR7-72HVH-645M)	90	85	25yr	5
Wind Turbine [37]	Skystream 3.7	20,000	15,000	20yr	90
Battery [38]	Bluesun 1 MW / 4 MWh (LiFePO4)	700,000	700,000	15yr	10
Diesel Generator [39]	Teksan TJ1100PE-400-1	130,000	110,500	90,000h	5
Converter [40]	Bluesun BMPS-250 kW Hybrid Inverter	75,000	75,000	15yr	10

By running the simulation analysis in HOMER Pro, seven hybrid energy system combinations were designed and compared based on their technical, economic, and environmental properties. Table 2 shows the studies available in the literature for various types of hybrid renewable energy system, where the type of system, source of data, tool(s) used, and summary findings are given. Tools, including HOMER Pro, PVsyst, and WindSim, were employed in these investigations, with a range of both on-grid and off-grid systems being considered, with NASA Power being the most frequent data platform. The results indicate a broad spread of LCOE, NPC, and renewable energy fractions, as well as CO₂ reductions, where large potential advantages for optimized hybrid systems can be seen. This comparative analysis, therefore, presents a reference against which to compare the best system for application, as determined in this study, as based on technical–economic and -environmental criteria for the optimum system setup.

6.1 Technical Analysis

To optimize the hybrid energy system in the case of the Gali-Zakho Tunnel, HOMER Pro was used. The configurations under study were a mix of solar photovoltaics (PV), wind turbines, batteries, and diesel generators. System reliability and electricity generation performance were key aspects of the technical assessment.

The yearly profiles for electricity generation for the seven cases are depicted in Fig. 6, and the renewable fractions for all configurations (scenarios) are summarized in Table 3. These results offer a ready technical assessment of how the various system combinations help satisfy the tunnel's load demand under seasonal changes.

Table 2. Summary of hybrid renewable energy system studies available in the literature: a summary of system type, data sources, tools used, and key findings

Reference	System Type	Data Source	Tools Used	Key Findings
[41], Afghanistan	On-grid	NASA POWER	PVsyst & HOMER Pro	COE: \$0.0547/kWh, NPC: \$689M, Renewable Share: 31.4%, CO ₂ Emissions: 83.1 million kg/year, Unmet Load: 0.03%.
[42], Iraq	On-grid	Historical data	HOMER Pro	A 470 kW PV–50 kW diesel hybrid meets full demand at \$0.0595/kWh. Cuts fuel use by 65% and CO ₂ emissions by 45%.
[43], Cameroon	Off-grid	NASA POWER, local temperature.	HOMER Pro	RF: 92.5%, DPSP: 0%, COE: Not Explicitly Stated, CO ₂ Emissions: 1.69 kg/year, Oxygen Production: 50 kg/year.
[44], Thailand	Off-grid	NASA POWER, Local biomass potential.	HOMER Pro & WindSim	LCOE: \$0.215/kWh, RF: 100%, Optimal Config: 440 kW PV, 500 kW Biomass, 600 kWh Battery.
[23], Canada	On-grid and off-grid	NASA POWER	HOMER Pro	Optimized hybrid system LCOE: \$0.0154/kWh - Grid-only LCOE: \$0.1429/kWh - 100% RE system LCOE: \$1.1101/kWh - Grid connection and sellback critical to RE viability
[24], Egyptian	On-grid and off-grid	NASA POWER	HOMER Pro	- Lowest LCOH: \$0.177/kg (New Alamein, grid-connected) - 100% renewable fraction achieved - Significant NPC and LCOE reductions with grid export
[45], Bangladesh	On-grid	NASA POWER, NREL	HOMER Pro, PVsyst	LCOE: \$0.03–0.0136/kWh; NPC: \$3.95M; ROI: 25%; IRR: 30%; BEP: 2.3–3.4 years; Emissions reduction: 28,144 kg CO ₂ /yr
[46], Egypt	On-grid and off-grid	NASA POWER, NREL, Egyptian Meteorological Data.	HOMER Pro	Grid-tied LCOE: \$0.004–0.013/kWh; NPC: \$71k–\$228k; Off-grid LCOE: \$0.258–0.282/kWh; CO ₂ reduction: ~724 tons/year per site
[25], Yemen	On-grid and off-grid	NASA POWER, NSRDB	HOMER Pro	Optimal: PV/BES/Genset (off-grid), PV/BES/Genset/Grid (load-shedding), PV/BES/Grid (continuous grid); LCOE: \$0.0879–0.133/kWh; REF: 91.2–100%
[21], China	Off-grid	NASA POWER	HOMER Pro	Optimal: PV/Wind/Hydro/Battery/Genset; LCOE: \$0.22/kWh; NPC: \$1.73M; REF: 95%; CO ₂ reduction: 23.2 tons/year
[22], China	Off-grid	NASA POWER	HOMER Pro	Optimal: PV(805kW)-Wind(7kW)-Diesel(500kW)-Battery(150kWh); LCOE: \$0.176/kWh; NPC: \$1.36M; Annual generation: 1,112,392 kWh; Renewable fraction: 95.55%
[47], Iraq	off-grid	NASA POWER	HOMER Pro	- Optimal System: PV(39.8kW)/WT(1kW)/DG(10kW)/BESS(54 units) - LCOE: \$0.0521/kWh - NPC: \$40,681 - CO ₂ Emissions: 426 kg/year - Renewable Fraction: 99.29%
(Proposed study)	Off-grid	NASA POWER, Wind Speed On-site field measurements	HOMER Pro	- Optimal System: Case A (PV-Diesel-Battery) - NPC: \$6.68M - COE: \$0.065/kWh - Renewable Fraction: 94.8% (PV supplies 97.4% of energy) - CO ₂ Reduction: ~3.7 million kg/year vs. diesel-only - Payback Period: 5.2 years

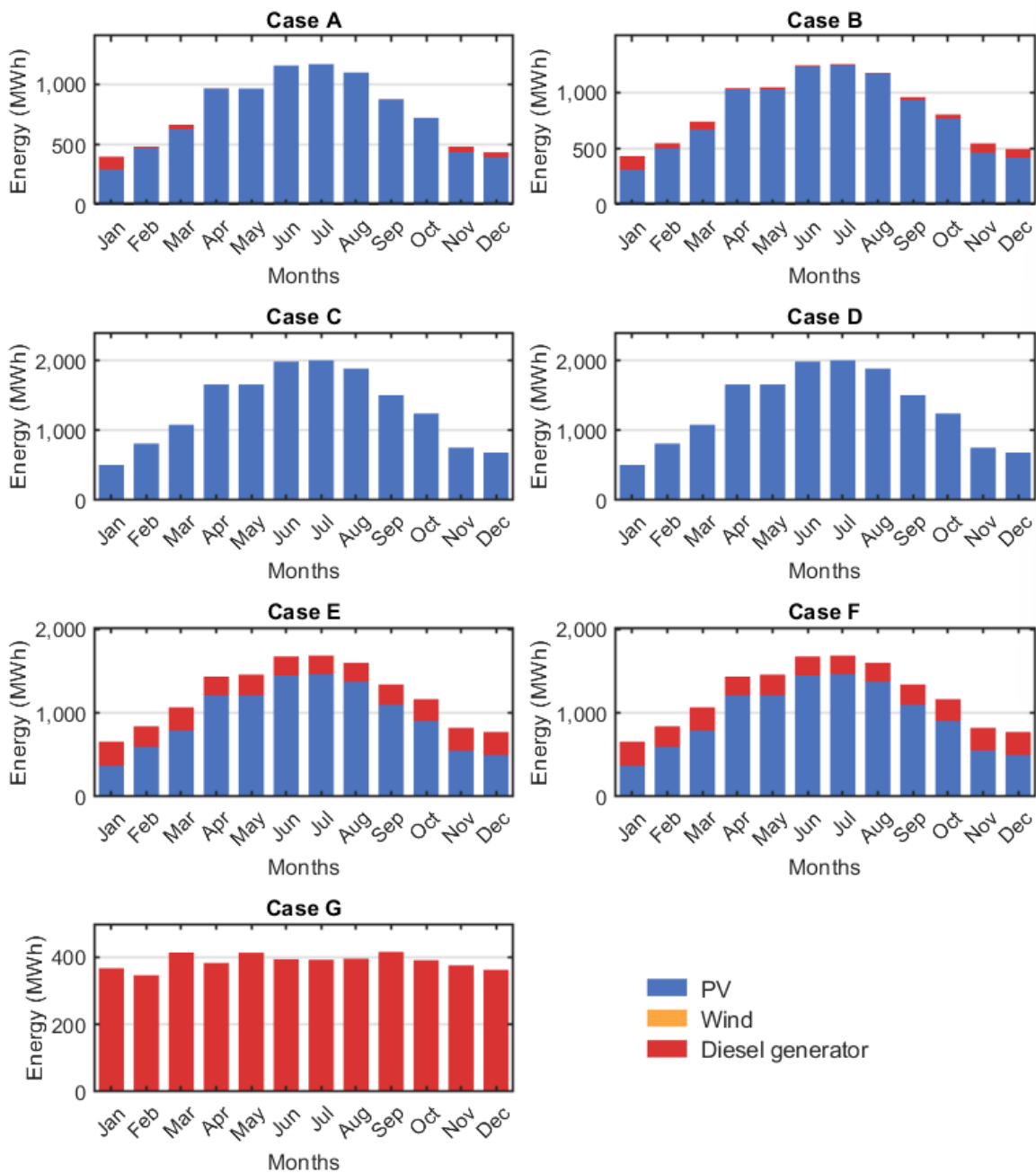


Figure 6. Monthly power generation profiles for renewable hybrid energy system cases A–G

6.2 Economic Analysis

The economic viabilities of each of the hybrid system configurations were determined through HOMER Pro using indicators such as NPC, COE, operating cost, and capital expenditure. As shown in Table 4, Case A (PV–Diesel–Battery) delivered the

lowest NPC of \$6.68 M, and Case G (Diesel only) gave the highest NPC of \$16.0 M.

The same trend was found for COE, with Case A and Case G showing the lowest (\$0.065/kWh) and highest (\$0.156/kWh) COE costs, respectively. This

Table 3. Optimized design results of the off-grid hybrid energy system for the seven cases (scenarios)

Case ID	System Configuration	Renewable Fraction (%)
Case-A	PV - Diesel generator - Battery	94.8
Case-B	PV – Wind - Diesel generator - Battery	89.2
Case-C	PV - Battery	100
Case-D	PV - Wind- Battery	100
Case-E	PV - Diesel generator	35.4
Case-F	PV - Wind-Diesel generator	35.5
Case-G	Diesel generator	0

result places the diesel-only systems at a significant cost disadvantage.

The cost nature of Case A also supports its feasibility with an investment requirement of \$3.36M and low annual O&M compared to diesel-driven configurations. The fully renewable cases (C and D) had higher upfront investments (approximately \$6M in each case), resulting in higher economic depreciation; they did eliminate the need for diesel fuel consumption, however.

In Case A, certain other economic indicators also support its desirability. The IRR was 18%, the ROI was 14%, and the simple payback period over the 25-year project was 5.2 years. These findings verify that Case A is not only the most economical in terms of NPC and COE but also has attractive investment cash recovery and future profit.

In general, the economic analysis shows that Case A (PV–Diesel–Battery) is the perfect solution, which is economically viable and sustainable compared to more diesel-reliant and high-capital options.

6.3 Environmental Analysis

HOMER Pro was also employed to assess the environmental impact of different hybrid energy system configurations. The emission characteristics of the six monitored pollutants (carbon dioxide CO₂, carbon monoxide CO, unburned hydrocarbons (UHC), particulate matter (PM), sulfur dioxide SO₂, and nitrogen oxides NO_x) and emission intensity are reported in Table 5.

For the cases considered, the 100% renewable systems (Case C: PV–Battery; and Case D: PV–Wind–Battery) achieved zero CO₂ emissions, and hence proved superior from an environmental perspective. In comparison, diesel-only generation (Case G) produced the greatest volume of emissions with annual carbon dioxide emissions of about 3.91 million kg/yr and an emission intensity of 847.26 g/kWh.

PV hybridized to diesel and storage (Case A and Case B) showed significant emission reductions compared to the diesel-biased cases. For instance, in Case A, 213.396 kg/yr CO₂ was released at a rate of 22.71 g/kWh, and in case B, 447.797 kg/yr CO₂

Table 4. Economic evaluation of the renewable hybrid energy system for the seven cases (scenarios)

Case ID	NPC (\$)	COE (\$)	Operating Cost (\$/yr)	Initial Capital (\$)
Case-A	6.68M	0.0650	149641	3.36M
Case-B	6.70M	0.0652	178589	2.74M
Case-C	10.5M	0.103	206510	5.97M
Case-D	10.6M	0.103	206759	5.99M
Case-E	13.7M	0.134	552439	1.49M
Case-F	13.7M	0.134	552492	1.51M
Case-G	16.0M	0.156	715359	130000

was released at an average rate of about 43.80 g/kWh. These cases are clearly not emission-free, but still illustrate the relative efficiency of including renewable energy sources in the effort to reduce the emissions derived from the use of conventional forms of fossil fuel.

In contrast, Cases E and F (PV–Diesel and PV–Wind–Diesel) resulted in considerable environmental burdens, emitting more than 2.6 million kg/yr CO₂ each with sustained emission intensities of about 180 g/kWh. This demonstrates the predominance of diesel fuel consumption in terms of environmental impacts in the absence of storage.

As a whole, the findings also illustrate that renewable-based system set-ups (Cases C and D) provide the cleanest solutions, while hybrid systems with storage (Cases A and B) offer a good trade-off between emission reduction and reliability of supply.

validates the idea that the optimal solution is basically all renewable solar power with very little use of diesel generators.

7. Validation and Comparison with the Literature

The HOMER Pro approach was verified by simulating the inputs of a similar model for a tunnel, HRES, proposed by [22]. Our modeled COE and renewable fraction were within $\pm 7\%$ of their reported values, demonstrating acceptable model accuracy.

Case A (PV–Diesel–Battery) realizes a much lower COE (\$0.065/kWh vs. \$0.176/kWh) than their best system (PV–Wind–Diesel–Battery), with comparable renewable fractions of 94.8% and 95.55%. The better economy is due to the larger solar resource at Gali-Zakho (4.83 vs. ~ 3.25 kWh/m²/day), which leads to a higher PV yield and removes the requirement for wind turbines in the optimal configuration. Both studies of high-renewable

Table 5. Environmental impact assessment of the renewable hybrid energy system for the seven cases (scenarios)

Case ID	CO ₂ (kg/yr)	CO (kg/yr)	UHC (kg/yr)	PM (kg/yr)	SO ₂ (kg/yr)	Nox (kg/yr)	Intensity (g/kWh)
Case-A	213,396	40.3	16.1	24.2	529	484	22.71
Case-B	447,797	84.7	33.9	50.8	1111	1,016	43.80
Case-C	0	0	0	0	0	0	0
Case-D	0	0	0	0	0	0	0
Case-E	2,608,552	493	197	296	6,469	5,919	180.93
Case-F	2,607,397	493	197	296	6,467	5,916	180.83
Case-G	3,908,819	739	296	443	9,694	8,869	847.26

6.4 Choice of the Best Case/Scenario

Case A (PV–Diesel–Battery) was found to be the most suitable hybrid form of energy from technical, economic, and environmental points of view. This system was found to have the lowest NPC and the smallest COE, which indicates that it is the economically superior case.

The photovoltaic panels were the main contributor to such, accounting for roughly 9.20 GWh/yr (or 97.4%) of the total production. The diesel generator contributed a mere 0.24 GWh/yr (2.6%) and was effectively acting as peaking backup to cover requirements during low-solar periods. This data

hybrid systems for off-grid tunnels indicate that the optimum design varies according to site conditions.

8. Conclusion

This research has investigated the potential of utilizing a renewable-based hybrid energy system for the Gali-Zakho Tunnel in northern Iraq. HOMER Pro was used to model and analyze seven system configurations in terms of their technical, economic, and environmental performances.

The findings of this study show that as long as there is moderate diesel backup capacity and renewable rates are high, economic returns can strongly

outperform diesel-only options for energy generation. Case A (PV–Diesel–Battery) was found to be the most suitable system among the configurations tested. This configuration had the lowest NPC of \$6.68 million, a COE of \$0.065/kWh, and an annual electricity generation of ~9,440,000 kWh. In the output, solar PV was responsible for 97.4% (9,198,414 kWh/yr), with the diesel generator contributed only 2.6% (242,382 kWh/yr), acting essentially as a backup.

From an environmental viewpoint, the best configuration allowed for a reduction of around 3.7 million kg CO₂ /year, demonstrating the possibility that PV-driven systems can significantly decrease pollutant emissions in comparison to diesel-only generation. Moreover, an economic survey demonstrated the strong financial potential of the project over a typical lifetime for such of 25 years, having a simple payback period of 5.2 years, an internal rate of return of about 18%, and an ROI of about 14%. Such signals indicate that the chosen configuration holds both technical and environmental benefits, as well as economic viability.

On the whole, the results demonstrate the feasibility of renewable-dominated hybrid systems in ensuring tunnel infrastructure for reliable power services that allow for a reduced dependence on fossil fuel. The presented solution represents a best-practice, transferable approach for equivalent infrastructure in similar climatic and power activity conditions, pointing the way to greener tunnel electrification that features broad applicability.

9. Study Limitations

Although this study offers valuable insights, it is important to acknowledge certain limitations.

- Uncertainty in the fuel price over the project lifetime.

Fuel price forecasts and stability over the 25-year lifespan of the project are, of course, uncertain and could affect the economic feasibility of the hybrid energy system should market conditions and policy change.

- Effects of climate change on system performance.

The presumed stability of the climate over the 25-year project lifetime carries a degree of uncertainty, as changes in long-term solar radiation, ambient temperature, and weather variability might influence PV system performance, energy output, and the overall reliability of the system.

- Limited renewable energy resource diversity at the study site.

The study area has only a limited range of renewable resources, and indeed the system primarily relies on solar energy. This minimizes system design flexibility in comparison to regions that have a greater variety of renewable resources like wind power available, which could result in a higher net present cost.

- Lack of prior research on the topic.

There are only limited existing studies on the topic, requiring the development of a new research framework, which restricts direct comparison with previous work.

10. Future Work

Based on the limitations identified above, several directions for future research can be recommended:

- Incorporation of fuel price sensitivity and scenario analysis.

Advanced sensitivity and scenario-based analysis may be used in future research to assess the effect of long-term fuel price volatility on system economics across various economic and policy environments.

- Assessment of climate change scenarios.

Further research could attempt to account for the predications of climate change projection models to assess the long-term impact of changes in solar radiation, ambient temperature, and weather conditions on PV system performance and overall system reliability.

- Time-series forecasting of renewable energy resources

Valuable ongoing research could attempt to forecast long-term solar radiation and wind speed using time-series forecasting methods. Statistical or artificial intelligence-based models (e.g., ARIMA-ANN, LSTM) might allow for the forecast of renewable resource availability over extended horizons (e.g., 25 years). These estimates would allow for a more practical rating of system performance, energy reliability, and longevity over the project's lifetime.

- Grid-connected and hybrid grid-interactive system configurations.

The system developed in this research is effectively an off-grid configuration, rather than on-grid power generation. Future studies could attempt to explore grid-connected or grid-interactive hybrids, considering more grid-only situations (technical performance and economic feasibility or emissions comparison among various scenarios under different grid integration strategies).

- Expansion to multisource renewable hybrid systems.

Implementation of the proposed methodology within areas with multiple renewable resources (e.g., combined solar and wind) would improve system flexibility and efficiency, and reduce total project costs.

Nomenclature

BEP	Break-Even Point, years
CO	Carbon Monoxide, kg/year
CO ₂	Carbon Dioxide, kg/year
COE	Cost of Energy, \$/kWh
DPSP	Deficiency of Power Supply Probability, %
GHG	Greenhouse Gas
HRES	Hybrid Renewable Energy System
IRR	Internal Rate of Return, %
kWh	Kilowatt-hour, unit of Energy
kW	Kilowatt, unit of Power
LCOE	Levelized Cost of Electricity, \$/kWh
LCOH	Levelized Cost of Hydrogen, \$/kg
MENA	Middle East and North Africa
MW	Megawatt, unit of Power
MWh	Megawatt-hour, unit of Energy

NO _x	Nitrogen Oxides, kg/year
NPC	Net Present Cost, \$
NSRDB	National Solar Radiation Database
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance, \$/year
PM	Particulate Matter, kg/year
PV	Photovoltaic
RE	Renewable Energy
REF	Renewable Energy Fraction, %
RF	Renewable Fraction, %
ROI	Return on Investment, %
SO ₂	Sulfur Dioxide, kg/year
UHC	Unburned Hydrocarbons, kg/year
WT	Wind Turbine

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