

Research Article

Optimization of Backup Power System for a House in Libya Using HOMER Pro

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Received: 14 August 2025; **Revised:** 28 January 2026; **Accepted:** 3 February 2026; **Published:** 3 March 2026

Abstract: Power outages are a persistent and widespread issue in many developing countries, significantly affecting economic development, public health, education, and overall quality of life. These outages, often referred to as “load shedding,” occur due to a combination of inadequate infrastructure, poor maintenance, limited energy production, and mismanagement of resources. The increasing frequency of power outages and the growing interest in renewable energy technologies have driven the adoption of hybrid backup power systems for residential applications. However, the economic performance of such systems under subsidized fuel and electricity prices has not been sufficiently examined. This paper presents an optimal sizing and economic analysis of a hybrid Photovoltaic (PV), battery, and diesel generator system designed to supply residential loads in Libya during grid outages lasting from 1 to 7 hours. The system is modelled and optimized using Hybrid Optimization Model for Multiple Energy Resources (HOMER Pro) software. Since electricity, gas, and diesel are subsidized for the public in Libya, the optimization is conducted for three different load cases: 2,912.7, 4,855.89, and 7,538.434 kWh/yr. A comparison of the economic performance of the three residential backup power system configurations under varying power outage durations, along with sensitivity analyses, is conducted to evaluate system performance and the impact of variations in diesel and renewable energy component costs. Despite subsidized electricity and fuel prices, the results indicate that incorporating renewable energy with energy storage, in addition to a diesel generator, is more economical and reliable for residential backup power systems in Libya. Furthermore, integrating renewable energy systems reduces generator operating hours, thereby lowering maintenance costs and pollution. Renewable energy penetration generally increases with outage duration, with the medium-load case achieving the highest renewable fraction of 36.1% during extended outages.

Keywords: Photovoltaic (PV), power outage, renewable energy, energy storage

1. Introduction

Libya, located in North Africa, although endowed with abundant oil and gas reserves, has faced persistent difficulties in ensuring a consistent and dependable electricity supply. These issues stem from years of poor management, underdeveloped infrastructure, and inadequate energy planning. Even before the 2011 revolution, the national power grid exhibited significant vulnerabilities [1]. Following 2011, Libya plunged into political turmoil and armed conflict, which had a devastating impact on the electricity sector. Power generation facilities and transmission infrastructure were either left without proper maintenance, suffered damage, or were intentionally attacked, further worsening the crisis [2].

The General Electricity Company of Libya (GECOL), the country's main utility provider, has consistently reported shortfalls in electricity production, particularly during the summer months. These deficits are largely attributed to outdated power plants, fuel supply issues, and insufficient access to spare parts and maintenance resources [2]. Extended power outages have become a regular occurrence for many Libyans, especially in the western and southern regions, with some blackouts lasting over 12 hours in severe instances. These disruptions have negatively affected essential services such as hospitals, water distribution, and communication networks.

As a result, frequent blackouts, particularly during periods of high energy demand in summer and winter, have pushed many households to depend on backup and alternative energy solutions to power essential appliances such as lights, refrigerators, heaters, and communication devices. In such a challenging environment, designing and optimizing backup power systems that align with local conditions has become increasingly important.

Mostly the power outages in Libya are due to limited energy production, load shedding, and a combination of inadequate infrastructure and poor maintenance, which causes frequent power faults that often last for several hours. More specifically, power outages vary from a few minutes to 7 hours. However, in some cities, the outages last longer. This depends on the location of the city. The use of renewable energy has not been considered due to the low electricity tariffs and fuel prices in Libya. Regardless of the size of the electric load, most households use generators for very short, infrequent power outages because they are easy to manage during these brief outages. In areas with frequent or prolonged power outages, people tend to invest in more robust solutions, whereas in regions with stable power, smaller, more affordable setups may suffice. Ultimately, the choice of a backup power system is a balance between reliability, cost, and the desired duration of power supply during outages.

Over the past few decades, renewable energy sources were rarely used in Libya. Photovoltaic (PV) technology has been utilized since the mid-1970s, with various systems of different capacities and purposes deployed over the years. The country's first operational PV project was implemented in 1976 to power a cathodic protection system for the oil pipeline linking the Dahra oil field to the Sedra Port. By 2006, the total installed PV capacity for cathodic protection had reached 650 kilowatts peak (kWp), distributed across 320 systems. In 1980, a PV installation was established near Zella to power a microwave repeater station, and by 1983, PV systems were also introduced for water pumping applications [3]. Nowadays, the cost of renewable energy sources, particularly solar and wind, has decreased substantially, making it possible to produce renewable energy at a much lower cost than that of fossil fuels. Moreover, Libya possesses strong solar and wind energy potential. Recent studies conducted in the country have shown encouraging findings regarding the implementation of solar PV systems at various sites across Libya [4].

Solar energy is an ideal choice for future electricity generation, due to consistent availability of sunlight, silent operation, minimal maintenance requirements, independence from fuel sources, and environmentally friendly characteristics, particularly its role in reducing carbon emissions. Libya's geographic location in the Mediterranean and North Africa provides it with abundant solar resources. This gives the country strong potential to develop large-scale solar PV projects. Researchers view Libya as a promising candidate for the adoption and advancement of solar technology [5].

A recent study in Algeria, a country in North Africa, bordering Libya, investigated an off-grid hybrid solar energy system for residential use. The study provides valuable insights into the economic feasibility of small-scale hybrid configurations in the region. The analyzed household exhibits an average annual electricity demand of approximately 11.26 kWh/day. The study reports that the hybrid solar system achieves strong economic performance, with an estimated capital cost payback period of 1.58 years, indicating rapid recovery of the initial investment. Furthermore, the system achieves a Levelized Cost of Energy (LCOE) of 0.172 USD/kWh, highlighting its competitiveness relative to conventional diesel-based generation. Despite Algeria's low domestic diesel price, around 0.20 USD per litre, the findings underscore that hybrid PV-based solutions can remain cost-effective [6]. These results suggest a likely benefit from solar energy in Libya as they have approximately the same solar irradiation. Given that fuel prices in Libya are subsidized, choosing the appropriate capacity for a PV solar energy system with batteries and conducting an economic study are important for homeowners.

Given the Libyan government's subsidies for fuel and electricity prices to the public, this study presents the optimization of a hybrid solar energy system incorporating PV, battery storage, and a diesel generator as a backup power source to ensure electricity supply during outages lasting from 1 to 7 hours, as most power outages are within this range,

across three residential load scenarios: low, medium, and high. The optimization aims to determine the most cost-effective and optimal solution that mitigates the dependence on generators and high expenses associated with a backup system that relies solely on generators for different load categories and varying periods of outages, presenting the lowest-cost alternative for supplying electric power for essential, medium, and high loads during each outage period, as the frequency and duration of electricity outages in Libya vary across different regions.

2. Backup power system components in Libya

2.1 Diesel and gasoline generators

In Libya, diesel and gasoline generators have been widely used for decades as backup power systems in residential and commercial buildings due to their ease of use and the subsidized cost of fuel. However, with frequent power outages lasting many hours per day throughout the year, these generators are no longer suitable as backup power solutions for several reasons:

1) The accumulation of considerable fuel quantities in households, combined with the recurring refueling activities required to sustain small generators operating for many hours each day, presents significant safety hazards. In the Libyan context, the routine handling of domestic fuel storage during electricity outages has led to several fatal accidents, underscoring the hazardous nature of these practices.

2) Diesel generators cause both air and noise pollution, as observed in Libya during periods of load shedding, when thousands of generators were operated simultaneously, producing excessive noise and harmful emissions.

3) The daily operation of diesel generators for extended hours necessitates frequent monitoring to ensure timely refuelling and routine maintenance, especially for small generators. Due to their continuous and intensive use, these units incur relatively high maintenance and repair costs. Moreover, many of them experience complete failure before reaching their expected service life, as most generators available in Libya, particularly small units, are standby generators designed for limited annual operating hours, typically around 500 hours per year.

4) The data logger in the house, as shown in Section 3 of this paper, recorded that the power consumption is low, around 0.44 W and lower in low home loads, for several hours a day, especially after midnight. The generator works at less than 30% of its rated power. This reduces the generator's lifetime. Therefore, it is not economically feasible to rely solely on diesel generators.

5) Relying solely on a diesel generator is not practical after midnight. Most residents turn them off after midnight to avoid noise, since there is a very low load at that time. Additionally, they need monitoring, especially small generators.

2.2 Renewable energy and energy storage

Libya has high potential for PV solar energy, due to the country's abundant solar radiation and vast desert areas. Libya receives an average solar radiation of 7.1 kWh/m² per day in coastal regions and up to 8.1 kWh/m² per day in the southern desert areas [7]. Despite this potential, the use of PV systems in Libya remains limited. Most electricity is still generated using fossil fuels, and the country has faced challenges in maintaining and expanding its energy infrastructure due to years of political instability and conflict. Diesel and gas generators are still in use as a backup power source for residential and commercial buildings. However, small-scale PV installations have started to emerge, particularly for rural electrification, water pumping, and powering communication systems.

In recent years, PV systems combined with energy storage have begun to gain attention in Libya for residential and commercial applications due to their silent operation, decreasing technology costs, and low maintenance requirements. Nevertheless, their penetration remains limited, mainly due to uncertainties in the economic assessment and financial viability of PV systems with energy storage.

Libya is estimated to have around 1,596,069 housing units as of 2023, according to a projected population of 7,166,024 people [8]. The selected location for this study is in the middle region of Libya at Latitude: 31°44'45.52" N, Longitude: 14°2'1.08" E. Figure 1 shows the global horizontal irradiation with an average global horizontal irradiation of 1,950 kWh/m² in the coast region, and 2,250 kWh/m² in the south region of Libya in inhabited areas [9].

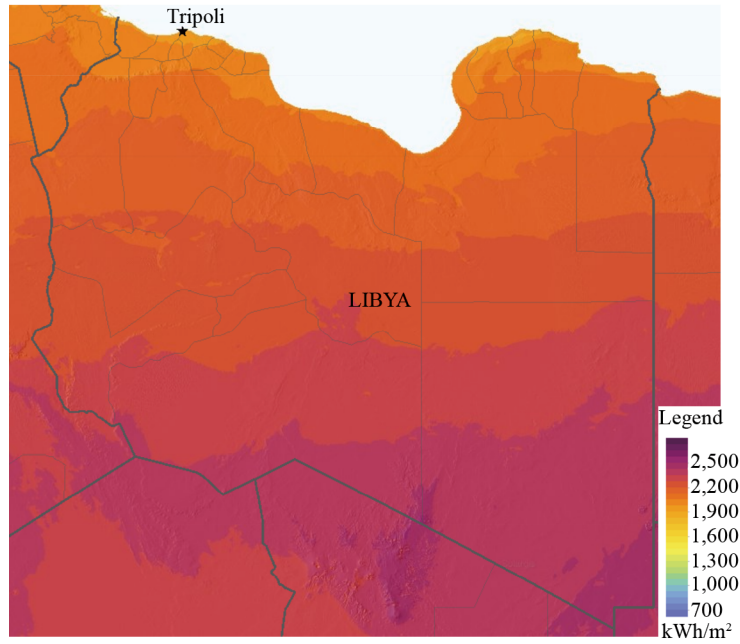


Figure 1. Global horizontal irradiation in Libya

3. Load profile

Electricity consumption in Libyan households varies according to the size of the home and the nature of electricity usage. In this study, renewable energy optimization is conducted for three different residential load cases recorded in Libya, using a clamp meter with a data logger to record a one-week load data sample in each case. Load profiles are categorized according to the actual loads that need to be supplied during a power outage. In Case One, the water pump, water heater, and air conditioner are not included, representing the minimum necessary load that needs to be supplied during the power outage, considering the other loads are deferrable. In Case Two, the water heater and water pump are included with external lighting. In Case Three, air conditioners and heaters are included. Figure 2 shows the typical daily power consumption for Case One; it can be clearly seen that the power consumption is lower than 0.44 kWh after midnight until 9 AM. In Case Two, power consumption is around 0.44 kWh from midnight until 8 AM, as presented in Figure 3. Figure 4 shows the typical daily power consumption for Case Three, which shows that the power consumption can be high during some hours and lower than 0.44 kWh during certain hours.

The three cases of load profiles that have been used in this simulation are as follows:

- 1) Case One: 2,912.7 kWh/yr with peak load of 0.88 kW.
- 2) Case Two: 4,855.89 kWh/yr with peak load of 1.47 kW.
- 3) Case Three: 7,538.434 kWh/yr with peak load of 3.46 kW.

Limited grid energy production is considered in the simulation. Therefore, during the one-hour power outage a day, the electric energy shortage in percent is:

$$\text{Electric energy shortage in Case One} = 2,912.7 - \left(\frac{2,912.7}{8,760} \times 365 \right) = 2,791.338 \text{ kWh/yr} \quad (1)$$

$$\text{Electric energy shortage in Case Two} = 4,855.89 - \left(\frac{4,855.89}{8,760} \times 365 \right) = 4,653.61 \text{ kWh/yr} \quad (2)$$

$$\text{Electric energy shortage in Case Three} = 7,538.434 - \left(\frac{7,538.434}{8,760} \times 365 \right) = 7,224.33 \text{ kWh/yr} \quad (3)$$

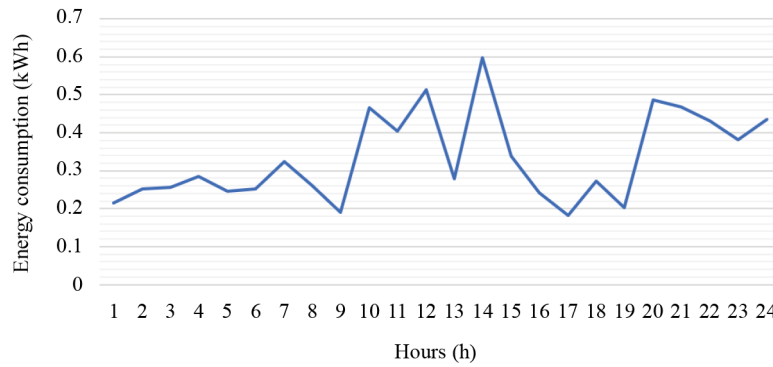


Figure 2. Typical daily energy consumption in Case One

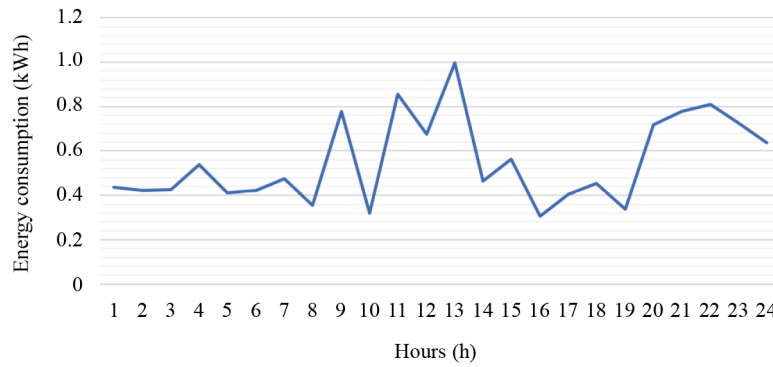


Figure 3. Typical daily energy consumption in Case Two

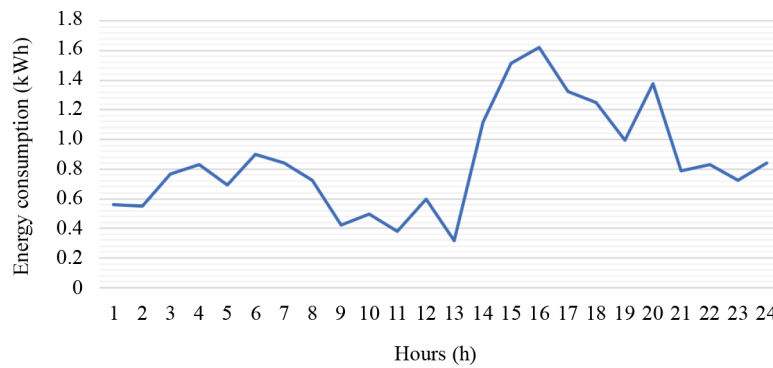


Figure 4. Typical daily energy consumption in Case Three

4. Optimization tool

Hybrid Optimization Model for Multiple Energy Resources (HOMER Pro) version 3.16 is used to optimize the three cases, originally developed by the U.S. National Renewable Energy Laboratory (NREL) and now maintained by

Underwriters Laboratories (UL) Solutions. It is a powerful tool that combines three advanced tools in one software solution, which are Simulation, Optimization, and Sensitivity Analysis, allowing technical and economic evaluations to be performed simultaneously. HOMER evaluates a wide range of possible system configurations in a single simulation and ranks them based on the selected optimization criterion. The Pro version incorporates an advanced optimization algorithm that streamlines the design process, facilitating the identification of cost-effective solutions for microgrids and other distributed generation power systems.

5. Input data and system components

To ensure the reliability of the techno-economic assessment, the input parameters including the technical specifications and market prices of PV modules, converters, batteries, and installation services were sourced from local suppliers in Libya, thereby reflecting actual market conditions. In the simulation model, the battery storage system is configured as four parallel strings of 12 V lead-acid units, each with a nominal capacity of 200 Ah, and an expected lifetime of four years. Table 1 shows the input data and price for each component. The HOMER Pro Optimizer feature is used for sizing PV, batteries, and converters.

Table 1. Input data of the system

	PV	Battery	Generator	Converter
Rated power (kW)	0.565	-	Auto-sizing	5.6
Nominal capacity (kWh)	-	2.41	-	-
Nominal voltage (V)	-	12	-	-
Unit price (USD)	142	225	212/kW	647
Efficiency (%)	20.9	85	-	95

Fuel cost data were also incorporated. Diesel and gasoline prices in Libya are the same, at 0.15 Libyan dinars per litre (Manager of Al-Majd Company for the Distribution of Fuel and Its Derivatives, personal communication, 2025). The GECOL has classified electricity consumers into several main categories, which are state-owned facilities, industrial, commercial, agricultural, and residential. The residential consumption tariff is 0.025 Libyan dinars per kilowatt-hour (Head of the Electricity Billing Office, GECOL, personal communication, June 30, 2025). Over the past decade, the currency exchange rate has changed between around 5 and 7 Libyan dinars per US dollar for an extended period. Using the average rate, the price of gasoline is 0.025 USD per litre, and the residential electricity tariff is about 0.005 USD per kilowatt-hour, including commission fees.

Global Horizontal Irradiation (GHI) input data and temperature at the selected location have been downloaded in 2024 from National Aeronautics and Space Administration (NASA) Prediction of Worldwide Energy Resources (POWER) database, using HOMER Pro software. Figure 5 shows the GHI per month at the selected location. The highest average GHI and Clearness index values are 8.03 kWh/m²/day and 0.713 in July, whereas the lowest GHI and Clearness index values are 2.65 kWh/m²/day and 0.507 in December. Figure 6 shows the average temperature chart for the selected location. The highest average temperature is 29.2 °C in August, and the lowest average temperature is 10.9 °C in January.

The block diagram of the designed system is shown in Figure 7, where the primary load changes according to the case study. The generator is set to auto-sizing and restricted to being off from midnight to morning. The PV panels are fixed on the roof with no tracking system.

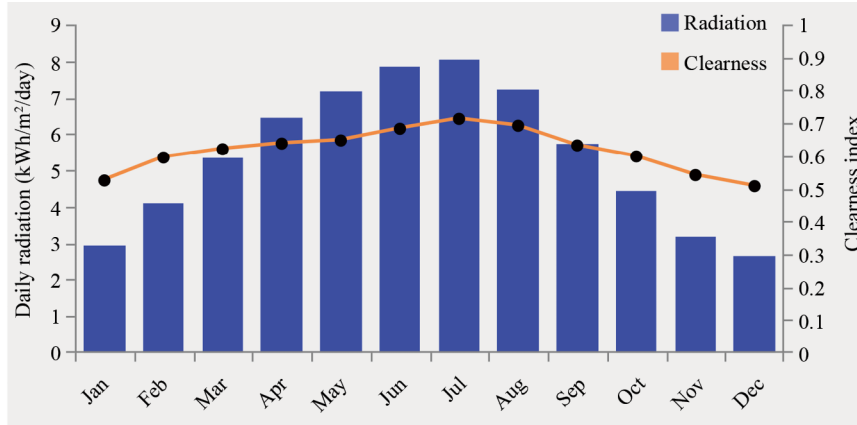


Figure 5. Average solar irradiation and clearness index per month for the selected location

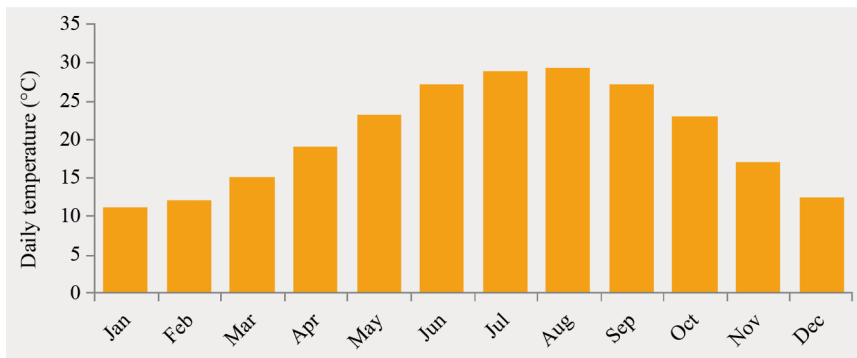


Figure 6. Average temperature per month for the selected location

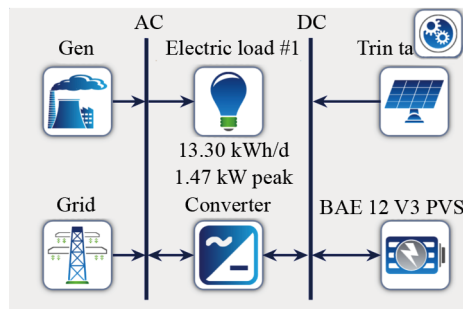


Figure 7. Block diagram of the backup power system

6. Optimization results of backup power systems

6.1 Optimization results of the backup power system for Case One

The optimization of the backup power system was performed in a single simulation for Case One, a low-load case, to assess optimization performance in Libya over 1 to 7 hours of power outages. The results indicate that using only PV systems, combined with energy storage for low loads, is more economical than either incorporating a generator or relying

solely on a generator for backup for up to 7 hours. PV with energy storage can provide sufficient power to the load during power outages for up to 7 hours. The renewable fraction reaches 30.6% during a 7-hour outage, as shown in Table 2.

Table 2. Optimization result of Case One

Power outage (h)	PV (kW)	Generator size (kW)	Generator hours (h)	Battery quantities (#)	Renewable fraction (%)
1	0.0922	-	0	4	4.3
2	0.179	-	0	4	8.43
3	0.27	-	0	4	12.9
4	0.346	-	0	4	16.7
5	0.428	-	0	4	20.9
6	0.506	-	0	4	25
7	0.608	-	0	4	30.6

Table 3 presents the results of the economic optimization for Case One. The lowest Net Present Cost (NPC) is 1,758 USD for a system designed to cover a 1-hour power outage. As the backup power duration increases, the NPC rises steadily, reaching 2,036 USD for the 7-hour backup power. Similarly, the Levelized Cost of Energy (LCOE) increases with longer backup durations, starting at 0.0467 USD/kWh for the 1-hour backup and reaching 0.0541 USD/kWh for the 7-hour backup.

Table 3. Economic result of Case One

Power outage (h)	Net Present Cost (NPC) (USD)	Levelized Cost of Energy (LCOE) (USD)
1	1,758	0.0467
2	1,807	0.048
3	1,847	0.049
4	1,891	0.0502
5	1,924	0.0511
6	1,959	0.052
7	2,036	0.0541

At a backup duration of 1 hour, the PV system produces its lowest renewable fraction of 4.3% and the annual energy output of PV is 167 kWh/yr, representing 5.66% of the total annual energy production. In combination with the grid supply, this contribution is sufficient to charge the batteries and meet the load demand for the 1-hour backup configuration. The average electricity production per month for this case for the 1-hour backup system is presented in Figure 8, where the orange bars indicate PV generation and the green bars indicate grid supply. In contrast, the 7-hour backup configuration has a maximum renewable fraction of 30.6% accounting for PV to share 35.3% of the total annual energy production, providing 1,103 kWh/yr, as illustrated in Figure 9. Libya experiences clear skies for the majority of the year, enabling PV systems to operate at high-capacity factors and achieve stable, predictable performance, as it can be seen in Figures 10 and 11 that the PV power output is high most of the days throughout a year for the 1- and 7-hour backup systems, respectively.

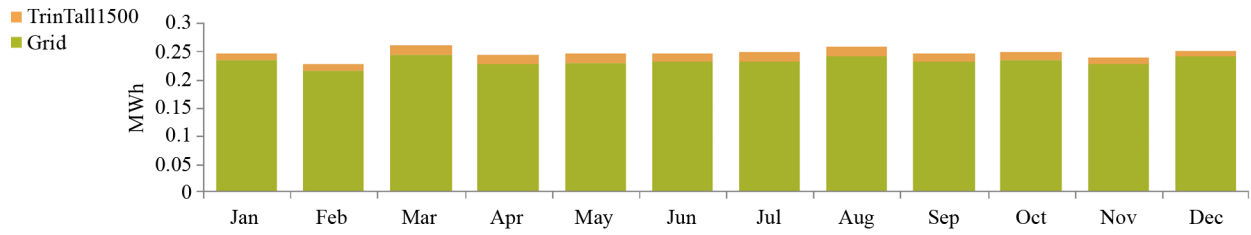


Figure 8. Average electricity production per month of PV and grid in Case One for the 1-hour backup system

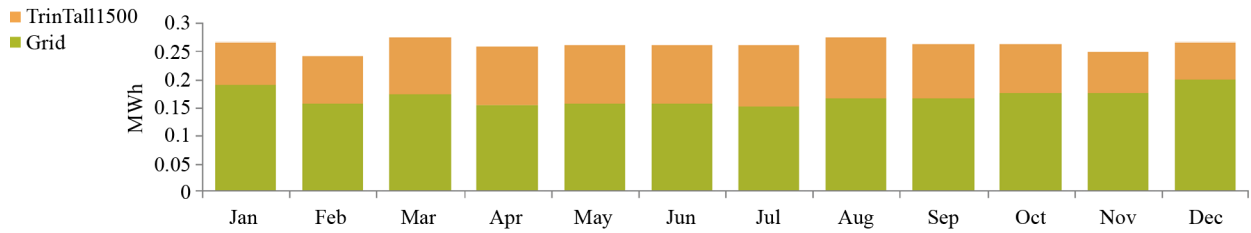


Figure 9. Average electricity production per month of PV and grid in Case One for the 7-hour backup system

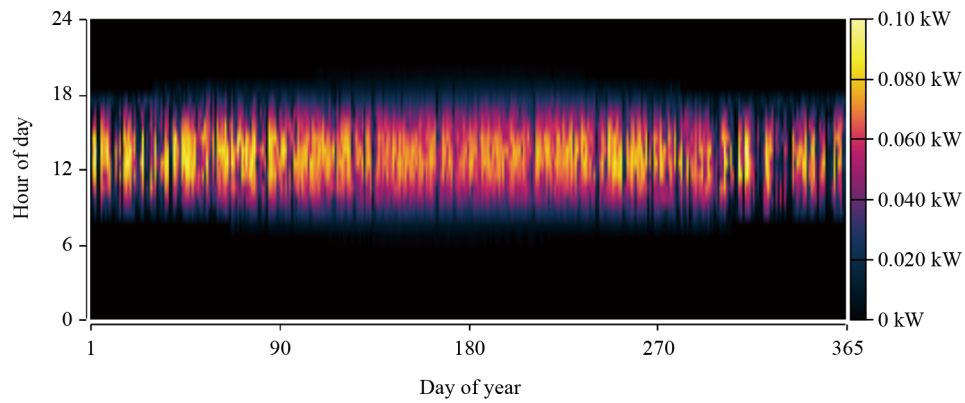


Figure 10. Daily PV power output over a year in Case One for the 1-hour backup system

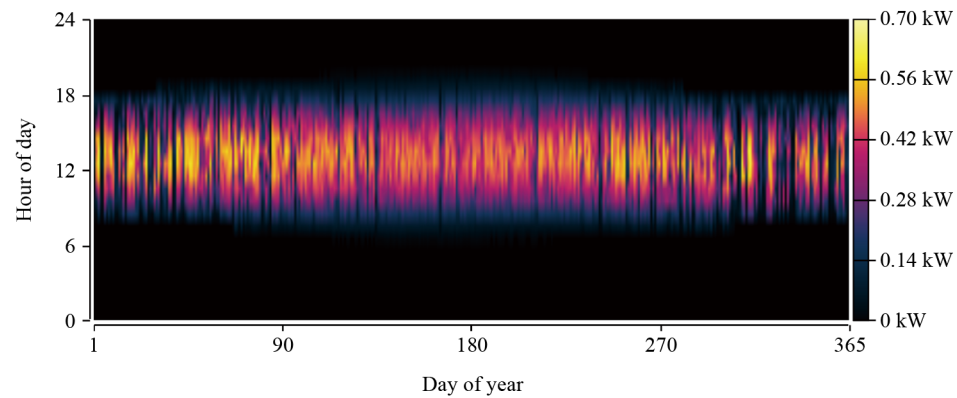


Figure 11. Daily PV power output over a year in Case One for the 7-hour backup system

6.2 Optimization results of the backup power system for Case Two

The optimization results for Case Two, a medium load, indicate that using only PV systems with energy storage is more economical than incorporating a generator for up to 5 hours of outage. For outage durations of 6 and 7 hours, a generator is used in combination with PV to supply electricity to the load and recharge the batteries. The energy contribution from PV and batteries significantly reduces generator operation time to 254 hours per year for a 6-hour backup system and 153 hours per year for a 7-hour backup system. This corresponds to reductions in the generator's operating hours of 88.4% and 94.01%, respectively. The renewable energy fraction increases with the increase in power outage duration up to 5 hours, reaching 21.2%, then decreases to 17% as the generator is incorporated to supply the load and charge the batteries. It increases again to 36.1% at the 7-hour outage, to cover the load demand, as shown in Table 4. The economic results show the NPC and LCOE for each desired backup power duration for Case Two. The lowest LCOE and NPC are 0.0314 USD/kWh and 1,972 USD, respectively, and occur at one hour of backup system. These values increase to 0.05 USD/kWh and 3,134 USD, respectively, for the 7-hour of backup system, as shown in Table 5.

Table 4. Optimization result of Case Two

Power outage (h)	PV (kW)	Generator size (kW)	Generator hours (h)	Battery quantities (#)	Renewable fraction (%)
1	0.15	-	0	4	4.16
2	0.297	-	0	4	8.37
3	0.448	-	0	4	12.8
4	0.593	-	0	4	17.3
5	0.723	-	0	4	21.2
6	0.602	1.7	254	4	17
7	1.24	1.7	153	4	36.1

Table 5. Economic result of Case Two

Power outage (h)	Net Present Cost (NPC) (USD)	Levelized Cost of Energy (LCOE) (USD)
1	1,972	0.0314
2	2,056	0.0328
3	2,125	0.0339
4	2,311	0.0368
5	2,499	0.0398
6	2,900	0.0462
7	3,134	0.05

In backup power configurations ranging from 1 to 5 hours, electricity generation is sourced exclusively from the PV system and the power grid. At a 1-hour backup duration, the PV system records its lowest annual contribution, producing 271 kWh/yr, and accounting for 5.51% of the total energy production. The average electricity production per month of PV and grid for the 1-hour backup configuration is presented in Figure 12. For the 7-hour backup configuration, as illustrated in Figure 13, the brown segments represent PV generation, the orange segments represent grid supply, and the green segments represent generator output in kWh for each month over a year. It can be seen that the grid delivers the largest share of energy at 53.8%, followed by the PV system at 42.1%, producing 2,257 kWh/yr, while the generator accounts for only 4.08% of the total annual energy production. The daily PV power output for the 1- and 7-hour backup system is shown in Figures 14 and 15, which illustrate a mostly stable PV power output over a year, similar to Case One.

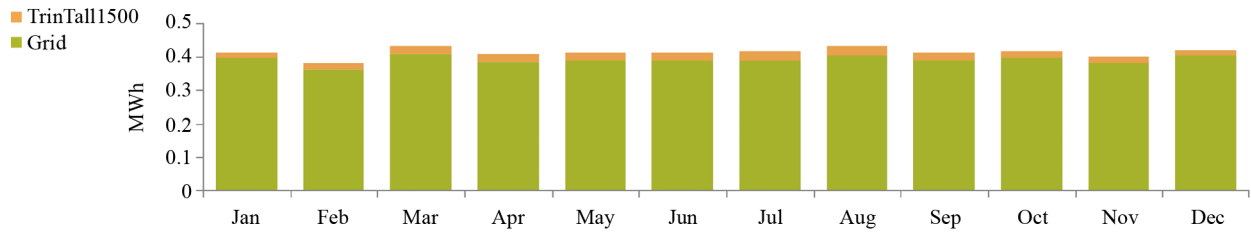


Figure 12. Average electricity production per month of PV and grid in Case Two for the 1-hour power outage

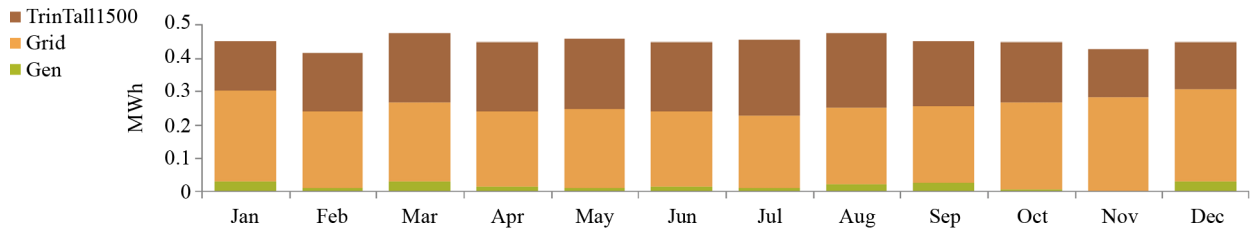


Figure 13. Average electricity production per month of PV, generator, and grid in Case Two for the 7-hour power outage

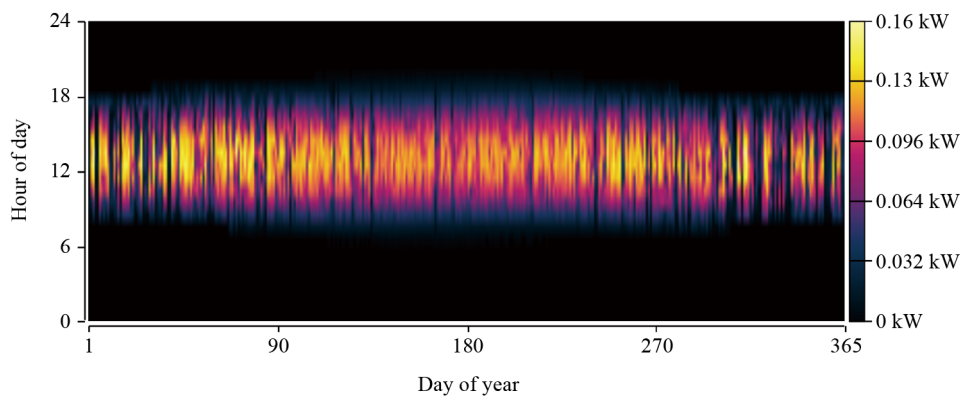


Figure 14. Daily PV power output over a year in Case Two for the 1-hour backup system

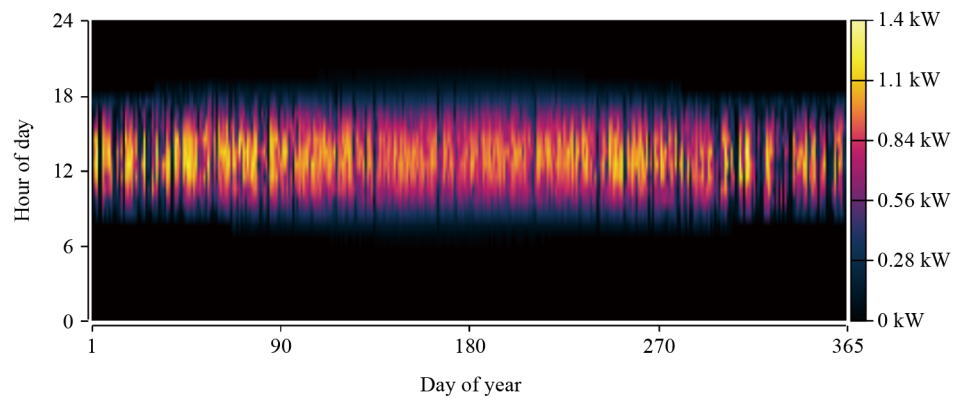


Figure 15. Daily PV power output over a year in Case Two for the 7-hour backup system

6.3 Optimization results of the backup power system for Case Three

Similar to Cases One and Two, the same simulation was performed for Case Three, which includes air conditioning and heating loads. The optimized system for the 1-, 2-, and 5-hour backup configurations consists of a PV with battery storage system, whereas the optimized system for the 3-, 4-, 6-, and 7-hour backup configurations includes the same system supplemented by a generator, as shown in Table 6. As in Case Two, in Case Three, this configuration reduces the generator's operating hours by at least 86.76% in the 3-hour backup configuration and by up to 93% in the 7-hour backup configuration.

Table 6. Optimization result of Case Three

Power outage (h)	PV (kW)	Generator size (kW)	Generator hours (h)	Battery quantities (#)	Renewable fraction (%)
1	0.242	-	0	4	4.3
2	1.3	-	0	4	24.7
3	0.398	3.9	145	4	6.9
4	0.582	3.9	163	4	10.4
5	1.18	-	0	8	21.9
6	0.88	3.9	213	8	16.1
7	1.29	3.9	179	8	23.9

The NPC for the 1-hour backup system is 0.0241 USD/kWh, which increases with the backup system hours increase, to reach 0.0562 USD/kWh for the 7-hour backup system. Similarly, the present cost increases from 2,350 USD to 5,482 USD as demonstrated in Table 7.

Table 7. Economic result of Case Three

Power outage (h)	Net Present Cost (NPC) (USD)	Levelized Cost of Energy (LCOE) (USD)
1	2,350	0.0241
2	2,882	0.0295
3	3,341	0.0342
4	3,695	0.0379
5	4,456	0.0457
6	5,101	0.0523
7	5,482	0.0562

Figure 16 shows the average electricity production per month of PV and grid for the 1-hour backup system, which has the lowest renewable fraction at 4.3%. The PV contributes 5.73% of the total annual energy production, generating 439 kWh/yr. In contrast, the highest renewable fraction occurs in the 2-hour backup system, reaching 24.7%, with PV providing 29.4% of the total annual energy, producing 2,363 kWh/yr. Figure 17 illustrates the average electricity production per month of PV and grid for the 2-hour backup system. For the 7-hour backup system, the renewable fraction is 23.9%, and PV accounts for 28.9% of total production, generating 2,334 kWh/yr. Figure 18 shows the average electricity production per month of PV, diesel generator, and grid for the 7-hour backup. The generator's contribution is only 7.22% in this case, with a maximum of 8.63% of the total annual energy production observed in the 6-hour backup system. Similar to Cases One and Two, PV power output throughout the year is mostly stable as demonstrated in Figures 19 and 20.

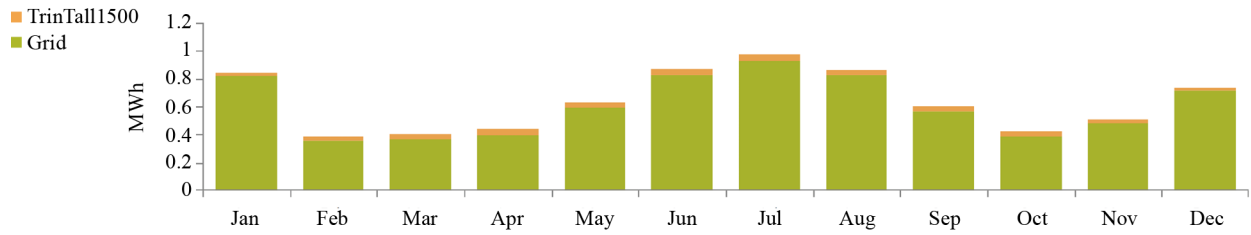


Figure 16. Average electricity production per month of PV and grid in Case Three for 1-hour backup system

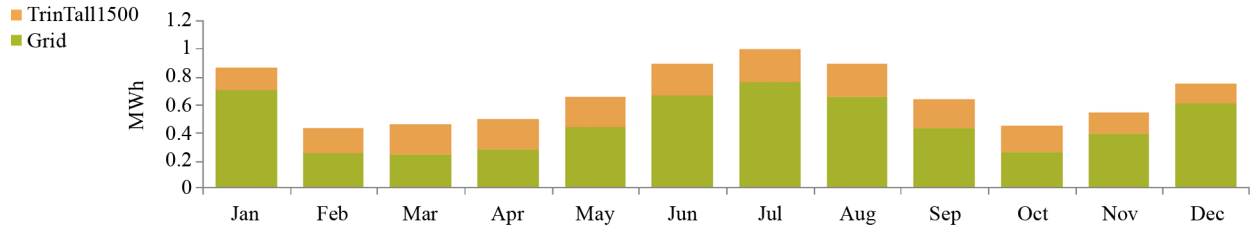


Figure 17. Average electricity production per month of PV and grid in Case Three for 2-hour backup system

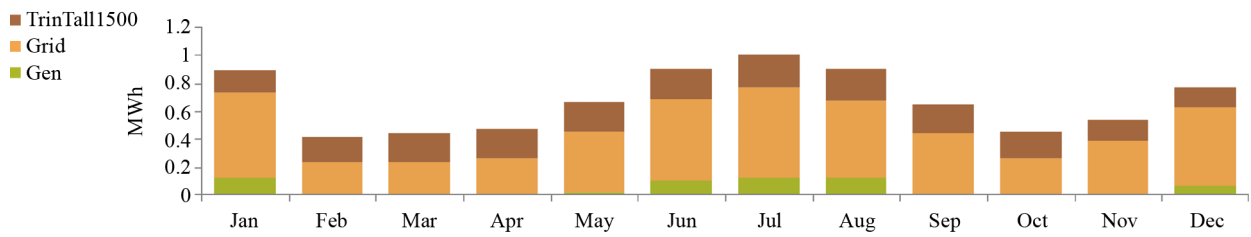


Figure 18. Average electricity production per month of PV, generator, and grid in Case Three for 7-hour backup system

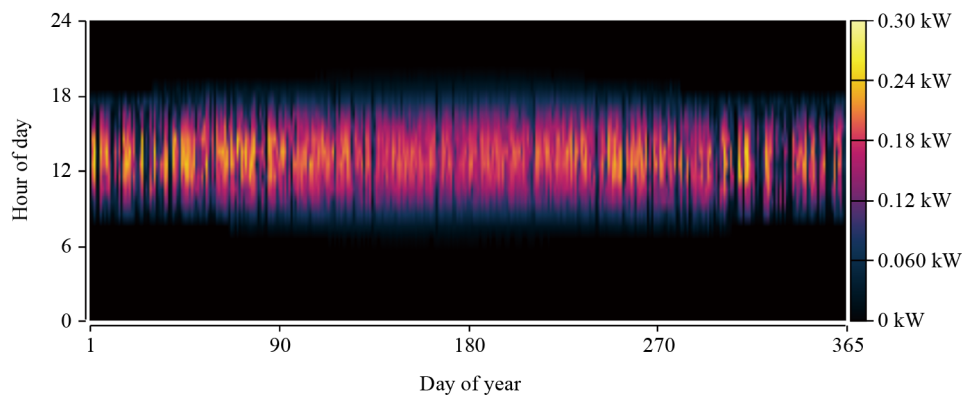


Figure 19. Daily PV power output over a year in Case Three for the 1-hour backup system

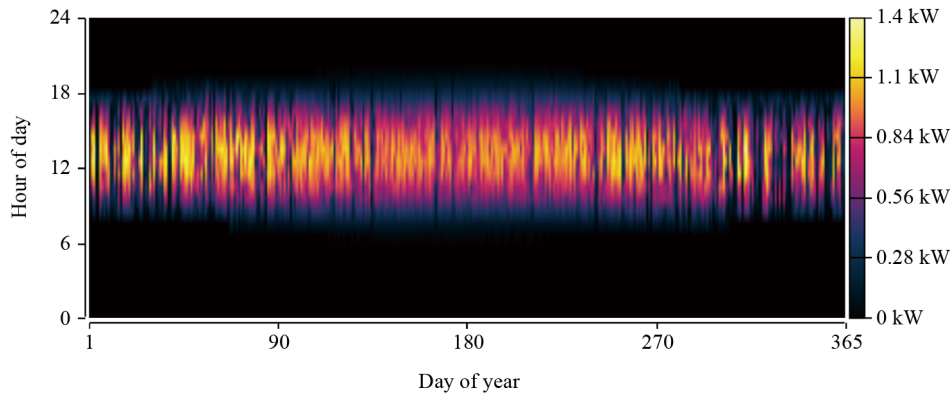


Figure 20. Daily PV power output over a year in Case Three for the 7-hour backup system

6.4 A comparison between the three cases

The comparison of NPC and LCOE results across the three load scenarios presented in Table 8 reveals pronounced economic differences influenced by both load magnitude and outage duration. Case One consistently yields the lowest NPC values, increasing moderately from 1,758 USD to 2,036 USD as the outage duration extends from 1 to 7 hours. These low costs reflect the system's small size across all outage scenarios. Case Two exhibits intermediate NPC values, ranging from 1,972 to 3,134 USD, with more pronounced cost increases at 6- and 7-hour outages due to the load demand and initiation of generator use. In contrast, Case Three records the highest NPC values among the three scenarios, rising sharply from 2,350 USD at a 1-hour outage to 5,482 USD at the 7-hour. This substantial increase is attributable to the higher energy demand and the more frequent reliance on generator operation during outages lasting 3, 4, 6, and 7 hours, as well as increased battery quantity and PV capacity during outages of 5, 6, and 7 hours to cover the load demand.

The LCOE comparison reflects similar patterns across the three cases. In Case One, LCOE increases gradually from 0.0467 to 0.0541 USD/kWh, remaining relatively high at shorter outages due to the lower energy consumption characterizing this scenario. Case Two produces moderate LCOE values, ranging between 0.0314 and 0.05 USD/kWh, consistent with its medium load profile. Case Three initially presents the lowest LCOE which is 0.0241 USD/kWh at a 1-hour outage, as the higher energy throughput reduces cost per unit of electricity; however, LCOE subsequently rises to 0.0562 USD/kWh as outage durations increase, and generator operation becomes more frequent.

Table 8. Economic comparison of the three cases

Power outage (h)	NPC for Case One (USD)	NPC for Case Two (USD)	NPC for Case Three (USD)	LCOE for Case One (USD)	LCOE for Case Two (USD)	LCOE for Case Three (USD)
1	1,758	1,972	2,350	0.0467	0.0314	0.0241
2	1,807	2,056	2,882	0.048	0.0328	0.0295
3	1,847	2,125	3,341	0.049	0.0339	0.0342
4	1,891	2,311	3,695	0.0502	0.0368	0.0379
5	1,924	2,499	4,456	0.0511	0.0398	0.0457
6	1,959	2,900	5,101	0.052	0.0462	0.0523
7	2,036	3,134	5,482	0.0541	0.05	0.0562

Taken together, the side-by-side comparison of NPC and LCOE shown in Figures 21 and 22 demonstrate that the increase rate of NPC and LCOE with increasing power outage hours is low in Case One, which represents low load, while

the increase of NPC is sharp in Case Three, which represents high load. For medium load, Case Two, the increase rate is moderate. However, the LCOE in Case Three is lower at 1- to 5-hour compared to Case One and at 1- to 2-hour compared to Case Two, and they reach almost the same value at 7-hour outage.

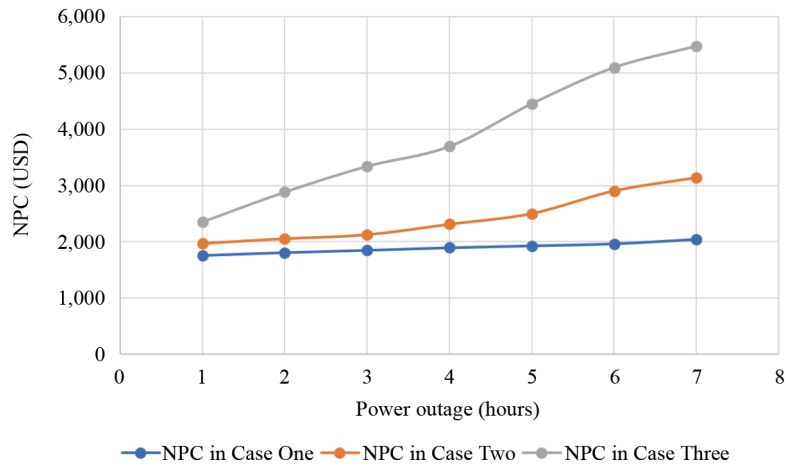


Figure 21. NPC for Cases One, Two, and Three across power outage duration

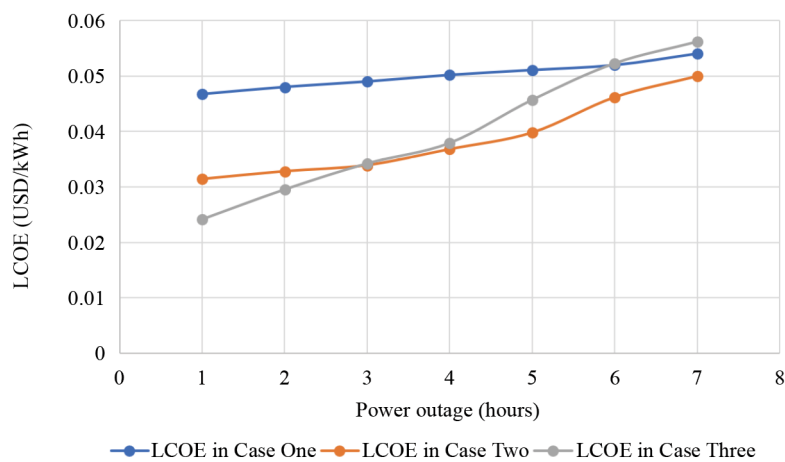


Figure 22. LCOE for Cases One, Two, and Three across power outage duration

The comparison of renewable energy fractions across the three cases, summarized in Table 9, illustrates clear patterns with increasing outage duration. In Case One, the renewable fraction increases progressively from 4.3% at a 1-hour outage to 30.6% at 7 hours. This steady rise reflects the greater contribution of PV generation and battery storage in compensating for the absence of grid supply in a more cost-effective manner, even during extended outages. Case Two demonstrates a similar upward trajectory, with renewable fractions ranging from 4.16% to 36.1%. The higher renewable share observed in Case Two at longer outage durations suggests that medium-load systems are able to utilize PV resources more effectively as the outage period expands. In contrast, Case Three exhibits a more irregular pattern. Although the renewable fraction reaches 24.7% at a 2-hour outage, it declines substantially at 3 and 4 hours, recording values of 6.9% and 10.4%, respectively, before rising again to 23.9% during the 7-hour outage. These fluctuations are attributable to the operational behavior of the diesel generator in this high-load scenario. When generator operation increases, particularly during the 3- and 4-hour outage, the proportional contribution of renewable energy decreases accordingly. As generator

reliance diminishes at longer outages, the renewable share correspondingly increases. In summary, the results indicate that while renewable penetration generally increases with outage duration, it differs across load levels. Case Two achieves the highest renewable fraction at extended outages, followed by Case One, whereas Case Three exhibits the greatest variability due to its higher demand and intermittent dependence on conventional generation.

Table 9. Renewable energy fraction comparison of the three cases

Power outage (h)	Renewable fraction in Case One (%)	Renewable fraction in Case Two (%)	Renewable fraction in Case Three (%)
1	4.3	4.16	4.3
2	8.43	8.37	24.7
3	12.9	12.8	6.9
4	16.7	17.3	10.4
5	20.9	21.2	21.9
6	25	17	16.1
7	30.6	36.1	23.9

7. Sensitivity analysis

This analysis examines how the NPC and LCOE vary in response to changes in diesel and solar energy system equipment costs. HOMER Pro is used to identify the optimal system configuration under each set of variable conditions. The sensitivity analysis considers two scenarios: a 10% reduction in the costs of PV modules, converters, and battery storage, and a 200% increase in diesel price, across outage durations ranging from 1 to 7 hours in each scenario.

7.1 NPC and LCOE response to solar equipment prices decreases for the three cases

Table 10 presents the sensitivity of NPC to a 10% reduction in PV, converter, and battery prices for all cases across the outage durations. In Case One, where the generator does not operate, NPC reductions remain stable around 7.3%, indicating a direct and proportional effect of solar equipment cost reductions on overall system economics. In Case Two, NPC decreases range from 6.8 to 7.3%, with the small variations linked to generator operation emerging at 3-, 4-, 6-, and 7-hour outages. In Case Three, the reduction varies more substantially from 4.7 to 7.2% due to increased generator usage at several outage durations, which reduces the share of NPC attributable to PV-battery investments.

Table 10. NPC response to solar equipment prices decreases for the three cases

Power outage (h)	NPC for Case One at base case (USD)	NPC for Case One at price decrease of 10% (USD)	NPC decrease (%)	NPC for Case Two at base case (USD)	NPC for Case Two at price decrease of 10% (USD)	NPC decrease (%)	NPC for Case Three at base case (USD)	NPC for Case Three at price decrease of 10% (USD)	NPC decrease (%)
1	1,758	1,629	7.3	1,972	1,838	6.8	2,350	2,196	6.6
2	1,807	1,674	7.3	2,056	1,913	7.0	2,882	2,689	6.7
3	1,847	1,713	7.2	2,125	1,977	7.0	3,341	3,185	4.7
4	1,891	1,752	7.3	2,311	2,146	7.1	3,695	3,511	5.0
5	1,924	1,783	7.3	2,499	2,318	7.3	4,456	4,136	7.2
6	1,959	1,816	7.3	2,900	2,747	5.3	5,101	4,813	5.6
7	2,036	1,886	7.4	3,134	3,059	2.4	5,482	5,153	6.0

Table 11 presents the corresponding effects of a 10% reduction in PV and converter prices on the LCOE for the three load cases under outage durations from 1 to 7 hours. Across all scenarios, a consistent decline in LCOE is observed following the reduction in component prices. The percentage reduction in LCOE closely corresponds to the magnitude of the NPC decrease, indicating a consistent economic response across both metrics.

Table 11. LCOE response to solar equipment prices decreases for the three cases

Power outage (h)	LCOE for Case One at base case (USD)	LCOE for Case One at price decrease of 10% (USD)	LCOE decrease (%)	LCOE for Case Two at base case (USD)	LCOE for Case Two at price decrease of 10% (USD)	LCOE decrease (%)	LCOE for Case Three at base case (USD)	LCOE for Case Three at price decrease of 10% (USD)	LCOE decrease (%)
1	0.0467	0.0433	7.3	0.0314	0.0293	6.7	0.0241	0.0225	6.6
2	0.0480	0.0445	7.3	0.0328	0.0305	7.0	0.0295	0.0276	6.4
3	0.0490	0.0455	7.1	0.0339	0.0315	7.1	0.0342	0.0326	4.7
4	0.0502	0.0465	7.4	0.0368	0.0342	7.1	0.0379	0.036	5.0
5	0.0511	0.0474	7.2	0.0398	0.0369	7.3	0.0457	0.0424	7.2
6	0.0520	0.0482	7.3	0.0462	0.0438	5.2	0.0523	0.0493	5.7
7	0.0541	0.0501	7.4	0.0500	0.0487	2.6	0.0562	0.0528	6.0

In summary, the results indicate that systems with lower generator dependence experience the greatest economic benefit from declining solar equipment costs.

7.2 NPC and LCOE response to diesel price increase for Cases Two and Three

Table 12 presents the results of the sensitivity analysis assessing the impact of a 200% increase in diesel price on the NPC for Cases Two and Three. Since the generator does not operate in Case One under any outage duration, diesel price fluctuations have no influence on its economic performance and are therefore excluded from this analysis.

Table 12. NPC response to diesel price increase for Cases Two and Three

Power outage (h)	NPC for Case Two at base case (USD)	NPC for Case Two at price increase of 200% (USD)	NPC increase (%)	NPC for Case Three at base case (USD)	NPC for Case Three at price increase of 200% (USD)	NPC increase (%)
1	1,972	1,972	0.0	2,350	2,350	0.0
2	2,056	2,056	0.0	2,882	2,882	0.0
3	2,125	2,125	0.0	3,341	3,384	1.3
4	2,311	2,311	0.0	3,695	3,748	1.4
5	2,499	2,499	0.0	4,456	4,456	0.0
6	2,900	2,937	1.3	5,101	5,164	1.2
7	3,134	3,273	4.2	5,482	5,532	0.9

For Case Two, medium load, the NPC remains unchanged for outage durations of 1 to 5 hours. This outcome directly reflects the system configuration in the base-case optimization, where the generator is not dispatched for these outage levels. Consequently, diesel price increases do not contribute to system cost. NPC increases only become evident at outage durations of 6 and 7 hours, corresponding to the hours in which generator operation was observed in the base-case results, reaching 1.3% at the 6-hour outage and 4.2% at the 7-hour. For Case Three with the high load, the sensitivity

to diesel price is slightly more pronounced but remains modest overall. Similar to Case Two, no NPC increase occurs at outage durations where the generator does not operate at 1, 2, and 5 hours. For the outage levels with generator usage at 3, 4, 6, and 7 hours, the NPC increases range from 0.9% to 1.4%, which is notably lower than the increases observed in Case Two at longer outage durations. This suggests that although generator operation occurs more frequently in Case Three, its contribution to the total NPC is still relatively small compared to PV and battery investment costs.

Table 13 presents the sensitivity of the LCOE to a 200% increase in diesel price for Cases Two and Three. As with the NPC results, the LCOE remains unchanged for outage durations in which the generator does not operate. For Case Two, NPC and LCOE rise by 1.3% and 4.2% at 6- and 7-hour outages, while Case Three exhibits smaller increases of 0.9-1.4% for the outage durations involving generator use.

Table 13. LCOE response to diesel price increase for Cases Two and Three

Power outage (h)	LCOE for Case Two at base case (USD)	LCOE for Case Two at price increase of 200% (USD)	LCOE increase (%)	LCOE for Case Three at base case (USD)	LCOE for Case Three at price increase of 200% (USD)	LCOE increase (%)
1	0.0314	0.0314	0.0	0.0241	0.0241	0.0
2	0.0328	0.0328	0.0	0.0295	0.0295	0.0
3	0.0339	0.0339	0.0	0.0342	0.0347	1.4
4	0.0368	0.0368	0.0	0.0379	0.0384	1.3
5	0.0398	0.0398	0.0	0.0457	0.0457	0.0
6	0.0462	0.0468	1.3	0.0523	0.0529	1.1
7	0.0500	0.0522	4.2	0.0562	0.0567	0.9

From an overall perspective, increasing the diesel price will raise both the NPC and the LCOE when the generator is operating. However, despite a 200% increase in diesel price, the NPC and LCOE show relatively minor increases, due to low subsidized diesel price in Libya and the minimal reliance on diesel generation in the optimized hybrid systems, which limit the impact of diesel price volatility on overall system costs.

7.3 Limitation and future work

The sensitivity analysis was performed based on assumptions regarding fluctuations in diesel and PV, converter, and battery prices, and how these factors influence both NPC and LCOE outcomes. In Libya, residential electricity tariffs and fuel prices are relatively low. Therefore, minor adjustments to these prices have a limited impact on the results. The findings indicate that the hybrid systems analysed in this study exhibit relatively low sensitivity even to a 200% increase in diesel price, a behavior that may not generalize to regions with higher or market-based fuel costs. Additionally, Libya experiences substantial volatility in currency exchange rates, which substantially affects the prices of solar-energy components. This highlights the need for a comprehensive assessment of Libya's economy and household income levels to ensure that residential solar-energy components are generally affordable and can contribute to strengthening the electric sector and the Libyan economy overall.

8. Conclusions

This study aimed to utilize solar energy alongside a diesel generator as a backup power system for a house in Libya and presented a comprehensive optimization of residential hybrid backup power systems that combine PV, battery storage, and a diesel generator, in the context of Libya's frequent power outages and heavily subsidized electricity and fuel prices.

Three representative residential load scenarios, low, medium, and high, were evaluated for outage durations ranging from 1 to 7 hours, reflecting typical grid unreliability conditions across different regions of the country.

The results clearly demonstrate that, even under extreme subsidy conditions that traditionally favor conventional generation, integrating PV and battery storage into residential backup systems is both economically advantageous and operationally beneficial. For low-load cases, PV with energy storage alone proved sufficient and more economical than generator-based solutions for all outage durations up to 7 hours. In medium- and high-load scenarios, PV with energy storage significantly reduced generator operating hours by more than 85% in most cases, thereby lowering maintenance requirements, extending the operational lifetime of standby diesel generators, reducing fuel consumption, and minimizing the extensive use of diesel and gasoline in houses. Additionally, reducing noise and environmental impacts in general. NPC and LCOE increased with outage duration and load size, but the rate of increase was substantially moderated by higher renewable energy penetration, particularly in the low- and medium-load cases, which achieved the highest renewable fractions of 30.6% and 36.1%, respectively, during extended outages.

The comparative analysis of the three cases demonstrates that both load magnitude and outage duration are the primary determinants of system economic performance. Case One is the most economical configuration, Case Two occupies a middle position, and Case Three incurs the greatest economic burden, particularly under longer outage durations where system size and generator dependency intensify markedly. Although the higher-load case experiences greater absolute costs, it can still achieve competitive LCOE values at short to moderate outage durations due to increased energy throughput. Furthermore, the sensitivity analysis confirms the robustness of the optimized hybrid system configurations. Reductions in photovoltaic and battery costs lead to reasonable decreases in both net NPC and LCOE, while even a substantial 200% increase in diesel price results in only marginal economic impacts. This limited sensitivity to fuel price escalation is attributed to the minimized generator operating hours in the optimized designs, together with the prevailing low diesel price.

Overall, the findings indicate that integrating PV with energy storage as a backup power system in Libya is an optimal solution and represents a cost-effective, reliable, and superior alternative to generator-only solutions for residential applications. Beyond immediate economic benefits to homeowners, widespread adoption of such systems could mitigate peak load demand on the power grid.

Conflict of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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