International Journal of Sustainable Energy

ISSN: 1478-6451 (Print) 1478-646X (Online) Journal homepage: www.tandfonline.com/journals/gsol20

Optimised sustainable energy supply alternatives for Libyan utilities under unsubsidised tariff conditions

Feras Alasali, Mohamed Almaktar & William Holderbaum

To cite this article: Feras Alasali, Mohamed Almaktar & William Holderbaum (2025) Optimised sustainable energy supply alternatives for Libyan utilities under unsubsidised tariff conditions, International Journal of Sustainable Energy, 44:1, 2509021, DOI: 10.1080/14786451.2025.2509021

To link to this article: https://doi.org/10.1080/14786451.2025.2509021

Published online: 26 May 2025.

INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2025, VOL. 44, NO. 1, 2509021
https://doi.org/10.1080/14786451.2025.2509021

Optimised sustainable energy supply alternatives for Libyan utilities under unsubsidised tariff conditions

Feras Alasali[a], Mohamed Almaktar[b] and William Holderbaum[c]

[a]Department of Electrical Engineering, Faculty of Engineering, The Hashemite University, Zarqa, Jordan; [b]Department of Electrical Technology, College of Electrical and Electronics Technology (CEET), Benghazi, Libya; [c]School of Science, Engineering and Environment, University of Salford, Salford, UK

ABSTRACT

With growing electricity demand and fossil fuel concerns, renewable energy (RE) solutions are becoming increasingly important. This paper explores sustainable energy alternatives to address the critical energy instability at an educational utility, namely the College of Electrical and Electronics Technology (CEET) in Benghazi, with potential applications for different Libyan sectors, including community areas and commercial entities. Four configurations were evaluated: standalone PV with storage, hybrid PV/wind/storage, grid-connected PV, and grid/diesel. The study aims to identify the optimal setup by minimising the net present cost (NPC) and levelised cost of energy (LCOE) over the project's operational period across varying fossil electricity and diesel rates. Sensitivity analysis indicates that higher diesel and grid electricity prices ($1.00/L and $0.10/kWh) reduce the LCOE of the hybrid system to $0.12/kWh, making it competitive with grid-based options. The study provides practical insights into addressing Libya's energy challenges using technically and economically feasible RE strategies.

ARTICLE HISTORY
Received 6 March 2025
Accepted 11 May 2025

KEYWORDS
Annual capacity shortage; energy transition; energy supply alternatives; excess electricity; renewable energy and storage; subsidy removal

Nomenclature

ACS	Annual capacity shortage (%)
CAP	Capital investment cost ($)
CEET	College of Electrical and Electronics Technology, Benghazi
CO_2	Carbon dioxide
CRF	Cost recovery factor (%)
DF	Derating factor (%) accounting for system losses
DG	Diesel generator
DOD	Depth of discharge (%)
ESS	Energy storage system
FC	Fuel cost ($)
$P_L(t)$	Total energy generated and imported at hour t (kWh)
SOC	State of charge (%)
TAC	Total annualised cost ($)
$PV_{capacity}$	Solar PV installed capacity (kW)
P_{PV}	Solar power produced (kW)
P_{WTG}	Wind turbine power output (kW)
$P_{WTG\ STP}$	Wind turbine power output at standard temperature and pressure (kW)
RE	Renewable energy
REP	Replacement cost ($)
RF	Renewable fraction (%)

CONTACT William Holderbaum w.holderbaum@salford.ac.uk

GECOL	General Electricity Company of Libya	E_B	Energy stored in the battery (kWh)
GHI	Global horizontal irradiation	E_{RE}	Amount of renewable energy available (kWh)
$G_{T,STC}$	Standard irradiance (kW/m^2)	ρ	The actual air density (kg/m^3)
G_T	Global tilted irradiance (kW/m^2)	ρ_0	The air density at standard temperature and pressure (kg/m^3)
HOMER	Hybrid Optimisation of Multiple Energy Resources	$\propto_{CC}$	Efficiency of charging regulator (%)
i	Interest rate (%)	σ_{Ch}	Battery charging efficiency (%)
kWh	kilowatt-hour	F_{DG}	Fuel consumption of diesel gen (l/hr)
LCOE	Levelised cost of energy ($)	P_{DG}	Rated power of the diesel gen (kW)
MW	Megawatt	P_{DG-out}	Output power of the diesel gen (kW)
LD	Libyan Dinar	A_g, B_g	Fuel consumption coefficients (l/kW)
l	litre	T_a	Ambient temperature (°C)
NPC	Net present cost ($)	W_s	Wind speed (m/s)
O&M	Operation and maintenance cost ($)	$	US dollar

1. Introduction

1.1. Background and motivations

While global electricity demand rises due to population growth, economic expansion, and the transition to electric vehicles, Libya faces significant energy challenges. Despite an installed power capacity of about 10,000 MW, only 61% (6110 MW) is operational due to ongoing political and security concerns (Ministry of Planning 2023). In 2023, peak electrical demand reached 8235 MW, creating a nearly 2000 MW shortfall during the summer peak, resulting in widespread power outages. Table 1 presents monthly demand variation during the year 2023. With the residential sector consuming 36% of Libya's electricity and annual demand growth averaging 4.12% over 2017–2023, demand could approach 14,000 MW by 2035, as presented in Table 2 (Alasali et al. 2023; Akroot, Almaktar, and Alasali 2024). This escalating demand underscores the critical need for infrastructure improvements alongside RE investments to ensure a stable and sustainable energy supply. Transitioning to renewables, especially solar, is essential for reducing the carbon footprint and achieving energy resilience.

Unfortunately, electricity production in Libya relies on exhaustible fossil fuels. One of the primary barriers to adopting RE in Libya is the government subsidy on diesel fuel and electricity. Being an oil-producing state, Libya's fuel prices rank among the lowest globally, with commercial electricity priced at 0.135 Libyan dinars (LD) per kilowatt-hour (equivalent to 0.024 $/kWh) and diesel at 0.15 LD per litre (equivalent to 0.026 $/l)

Table 1. Peak and minimum electrical demand over 2023 in Libya.

Month	Minimum demand (MW)	Peak demand (MW)
Jan.	4065	7603
Feb.	3771	7800
Mar.	3231	6230
Apr.	2875	6200
May.	2720	5900
Jun.	3315	7260
Jul.	5549	8200
Aug.	5126	8235
Sep.	2969	7880
Oct.	3416	6820
Nov.	2885	6232
Dec.	3336	6800

Table 2. Actual and projected maximum electrical demand in Libya between 2017 and 2035.

Year	Actual peak demand (MW)
2017	7383
2018	7185
2019	7639
2020	7350
2021	8150
2022	8200
2023	8235
2024	8574
Year	Projected peak demand (MW)
2025	8928
2026	9295
2027	9678
2028	10,077
2029	10,492
2030	10,925
2031	11,375
2032	11,843
2033	12,331
2034	12,839
2035	13,368

(Almaktar 2018). Hence, assessing both conventional electricity supply and renewable options under the current subsidised and future unsubsidised tariff conditions is an essential pathway to more sustainable and resilient energy solutions for Libya. The objective of assessing traditional and RE alternatives within different tariff policies is to understand these sources' economic and operational feasibility. This framework would better reflect true market conditions, providing insights into the real cost of energy production. This study is motivated by a hypothesis stating that under an unsubsidised structure, renewable sources such as solar and wind become increasingly viable compared to diesel or grid-supplied electricity as traditional energy prices rise. The validation of this hypothesis would be particularly relevant to the Libyan distribution grid, which has been impacted by years of underinvestment and rising peak demands that consistently outpace generation capabilities. By examining alternatives such as PV systems, wind energy, and hybrid configurations that integrate energy storage, the study can identify arrangements that ensure a reliable power supply, reduce grid dependency, and offer lower lifetime costs. For a university campus, in particular, renewable systems coupled with storage could offer daytime reliability, reduce operational disruptions due to outages, and mitigate long-term expenses (Alasali et al. 2022). These systems would stabilise energy costs under volatile conditions and contribute to Libya's broader sustainability goals, supporting the transition to a lower carbon footprint while addressing pressing grid limitations. In addition, the implications of this assessment extend beyond university campuses to benefit various sectors of Libyan society. Adopting decentralised, renewable-based solutions could alleviate pressure on the national grid, reduce transmission losses, and provide critical facilities with a dependable power source during grid instability. Furthermore, integrating RE into Libya's energy mix could also catalyse the development of local expertise in clean technologies, stimulate economic growth through renewable infrastructure investment, and lay the groundwork for future energy security.

1.2. Literature review

In line with economic growth, energy security and the protection of the environment are the essential pillars for sustainable development. However, fossil-based fluctuating energy costs and unreliable power systems adversely affect social welfare as discussed by Zakari, Oluwaseyi, and Musibau (2024). In recent years, the global focus on achieving high RE sources integration, particularly for local communities, has been intensified theoretically and empirically. Bhuiyan, Yazdani, and Primak (2015), H. C. Chen (2013), and Alsaidan, Khodaei, and Gao (2016) developed standalone microgrids using solar PV, wind turbines, and energy storage systems (ESS) to reduce energy costs and emissions. However, their designs incorporated diesel generation (DG) as backup power to ensure system reliability. Al-Shetwi et al. (2016) proposed a cost analysis and design of a standalone solar PV system to meet basic electricity needs, such as lighting, for a village of 126 homes in Yemen. However, it did not include ESS or an optimised energy flow system. In Ibrik (2020), Ibrik introduced two microgrids based on PV technology and battery storage for villages to lower emissions. However, the study did not consider optimising ESS and PV operations for better energy efficiency and cost. Alasali et al. (2023) identified key challenges in Libya's power generation sector, including increasing demand and insufficient generation capacity. As a potential solution, they emphasised the value of rooftop solar PV systems in reducing residential electricity consumption and supporting other applications. In Libya, small-scale PV systems have already been implemented for powering communication repeaters and remote residential communities (Alasali et al. 2023). However, their study did not explore the potential benefits and effects of integrating PV systems into the distribution power grid or campus. Following the political and security changes 2011, Libya experienced frequent power outages and blackouts. These disruptions can have significant health, educational and economic consequences if they continue. Alkar (2021) examined the effects of these blackouts on combined cycle power plants, specifically analysing the performance of the Al-Zawia CCPP during such events. The study suggested that RE sources could be a viable solution to reduce power outages in Libya. Although limited studies have been on integrating energy sources in Libya's power network, Alwehesh et al. (2019) and Mohamed, Al-Habaibeh, and Abdo (2013) explored their potential to meet energy demands and decrease outage incidents. Moreover, Embirsh and Ikshadah (2017) proposed PV power plants as a promising option, given Libya's abundant alternative energy resources, particularly solar.

Many studies aimed to design cost-effective and highly reliable RE systems for microgrids. For instance, Zhao et al. (2014) and Abdulgalil, Khalid, and Alismail (2019) explored the benefits of optimal sizing for standalone microgrids utilising RE sources and ESS regarding cost and emissions. Their findings demonstrated that these systems are both economically and environmentally viable. Research efforts, such as those by Zakari, Oluwaseyi, and Musibau (2024), focused on reducing energy costs and improving the reliability of ESS integration in settings such as urban university campuses. These studies emphasised the importance of load balancing to ensure a reliable power supply. While several researchers have investigated standalone microgrids' environmental and economic viability based on RE sources (Butturi et al. 2019; Al Garni et al. 2016), few have specifically analysed high-level RE sources and ESS. Krishan (2018) proposed optimal sizing approaches for islanded RE sources to meet household electricity demands, though neither study assessed the feasibility of PV systems equipped with ESS. Several studies (Alkar 2021; Alwehesh et al. 2019; Mohamed, Al-Habaibeh, and Abdo 2013; Embirsh and Ikshadah 2017) have examined the power generation capacity and economic viability of up to 100 MW of utility-scale PV plants. These studies concluded that integrating strategic PV plants with the grid benefits Libya economically. However, they primarily focused on the financial analysis rather than the technical aspect (Alwehesh et al. 2019; Mohamed, Al-Habaibeh, and Abdo 2013). The Guwaeder and Ramakumar (2017) conducted a preliminary study on the impact of different-sized PV plants on the grid, considering total power generation costs and losses. As for other sectors, several studies have demonstrated the applicability of RE, particularly solar PV, for healthcare facilities (Rahman 2024; Naveed et al. 2024; Koholé et al. 2024; Slathia et al. 2024; Albarsha, Almaktar, and Saehi 2024) and agricultural projects (Lachheb, Marouani, et al. 2024; Nurmalasari and Puspitasari 2024; Lachheb, Skouri, et al. 2024).

1.3. Contribution

While much of the research conducted within the Libyan context has emphasised the potential of RE, especially solar PV and wind, to date, there is a lack of detailed studies addressing the effects of hybrid systems from solar PV, wind, battery storage, utility grid and DG, under an unsubsidised tariff. This research evaluates the energy supply alternatives under unsubsidised tariffs for the CEET, which can be a model for other stakeholders. The contribution of this paper provides a valuable framework for evaluating hybrid renewable systems, supporting Libya's broader efforts towards sustainable energy transition. The primary goals and contributions of this article include:

- Detailed demand and scenario analysis: The college campus's load profile is examined in depth, exploring four distinct generation scenarios incorporating conventional and renewable sources. This analysis provides insight into configurations that sustainably meet the institution's energy demands.
- Optimal microgrid configurations for Libyan contexts: Tailored microgrid designs are developed for Libya's unique resource availability and grid constraints, emphasising PV and wind energy integration. The study also investigates the feasibility of fully renewable configurations, establishing a model applicable to higher educational institutions and similar facilities.
- Comprehensive technical and economic sensitivity analysis: Comparative analysis of grid/PV options alongside grid/DG, PV/battery, and wind/PV/battery systems highlights the most long-run viable economic and technical solutions.
- The study provides insight for all stakeholders, including end consumers and decision-makers, into the future beyond the oil depletion era and the importance of green and sustainable solutions.

1.4. Paper outline

The following sections provide a comprehensive overview of the research: Section 2 explores the current landscape of electrical energy in Libya. Section 3 details the case study, presenting and discussing the proposed models. Section 4 presents the results of the different energy network models. Section 5 concludes the discussion, summarising the findings and suggesting avenues for future research.

2. Challenges in Libya's electrical energy sector and integration of renewables and ESS systems: current state and methodology

Libya's electrical energy sector is currently facing a multitude of complex challenges. The country's electrical grid infrastructure, already weakened by years of conflict and instability, is further stressed by outdated equipment, insufficient maintenance, and a growing power demand. Libya's electricity sector, which covers generation, transmission, and distribution, is vertically regulated by the General Electricity Company of Libya (GECOL). The country's power generation primarily relies on thermal plants fuelled by oil and gas. Among the most significant power stations in the Libyan power system is the Misrata power plant, with a capacity of 1400 MW, making it the largest in the network, followed by Azzawia, with 1350 MW, and North Benghazi plant, with its six natural gas units producing a total of 1000 MW (Almaktar, Elbreki, and Shaaban 2021). However, the ongoing political conflict has severely affected the performance of the power sector, with only 6110 MW, with 61% of the approximately 10,000 MW installed capacity currently operational (Ministry of Planning 2023). This percentage is exacerbated by 19 of the country's power generation units being out of service. On the other hand, as electrical energy plays a crucial role in daily life, the growing population in Libya has led to a sharp rise in electricity demand (Ministry of Planning 2023; Akroot, Almaktar, and Alasali 2024). Over the past four years, with relative political stability, a surge in construction projects has further intensified this demand.

Despite this increase, Libya's electrical grid has not been modernised to accommodate future needs and faces numerous issues. One major challenge is the high level of energy losses, largely due to the lack of a proper maintenance schedule for power plants. Additionally, power outages are a significant concern, driven by shortages of essential spare parts. Environmental issues also pose a serious threat, with thermal power plants contributing heavily to greenhouse gas emissions. In 2022, Libya ranked 50th globally in carbon emissions, releasing more than 62 million metric tons of carbon dioxide (CO_2) (Alasali et al. 2022; Embirsh and Ikshadah 2017). To address these issues, the Ministry of Electricity and Renewable Energy has set a strategic goal to raise the country's generation capacity by integrating RE, focusing on solar PV and wind power, aiming to meet the increasing demand and reduce carbon emissions. While Libya has significant potential for RE development, progress has been slow due mainly to financial constraints and insufficient policy frameworks supporting renewable implementation. The reliance on conventional fossil fuels continues to dominate the energy landscape, delaying efforts toward a more sustainable and diversified energy mix. Libya's ongoing electricity crisis, with daily power outages sometimes lasting up to six hours, has brought serious attention to adopting renewable energy sources, particularly distributed generation. The country has significant potential for RE, with an average wind power density of 400 W/m^2 and an annual PV output exceeding 2000 kWh/kW installed (Almaktar and Shaaban 2021). Additionally, Libya enjoys about 3500 h of sunshine annually, making solar power a promising resource. In 2021, RE sources accounted for around 4% of the nation's energy demand. The government aims to expand this share to 22% by 2030 (Ministry of Planning 2023; Guwaeder and Ramakumar 2017). However, one major barrier to achieving this goal is the lack of a clear legal and regulatory framework for RE investment, making the integration of these systems into the existing power grid difficult. Moreover, Libya's current electrical infrastructure requires significant development to support this transition with large-scale projects.

Optimistically, the engineers and technicians of GECOL have tirelessly worked to rehabilitate as many power generation units as possible and the inoperative transmission lines and substations. Moreover, in October 2023, a ministerial decree was issued naming the Solar Energy Localisation Committee to accelerate investment in solar energy and concurrently issue incentive legislation for this purpose.

Considering these circumstances, this article explores solutions for integrating various RE resources, such as solar, wind, and energy storage systems, into Libya's grid distribution network for large customers. Specifically, it focuses on developing a model for integrating these technologies into an educational campus environment. By assessing the performance and feasibility of different energy sources, including the existing fossil and green electricity with storage systems, the study aims to encourage the oil state to eliminate its reliance on fossil fuel electricity, enhancing energy security and supporting the transition towards a more sustainable energy future. The practical implementation of this quantitative study can also serve as a supportive educational tool, enabling students to engage with real-world RE technologies and grid management solutions.

2.1. Methodology

This study employs a structured methodology to evaluate potential solutions for supplying an educational complex in Libya, namely the CEET, with electrical energy that is reliable, economical, and sustainable. Although Libya possesses substantial oil and gas reserves, the country's power infrastructure remains vulnerable due to ongoing recovery from internal conflicts. This has led to frequent power outages, particularly during high-demand summer months, primarily due to increasing demand for an ageing infrastructure with minimal maintenance and upgrades across power lines and substations. The approach focuses on identifying energy sources and configurations that can address these challenges, ensuring a stable and uninterrupted energy supply while balancing economic and environmental considerations. In addition, this section outlines the approach used to assess and design RE integration systems for CEET. The methodology sheds light on determining the optimal configuration of solar PV panels, wind turbines, and energy storage solutions using the specialised software Hybrid Optimisation of Multiple Energy Resources (HOMER Pro) for system design and economic feasibility analysis (UL Solutions 2024).

In light of the current subsidised energy landscape and anticipated government efforts to reduce subsidies, this study investigates alternative energy supply solutions for CEET and other educational institutions striving for sustainable campus models. In this respect, four scenarios are evaluated: first, a standalone PV system with ESS specifically lithium battery bank, operating independently from the grid; second, a standalone hybrid system combining solar, wind, and battery storage; third, a grid-connected solar system without storage; and finally, a fully fossil-based approach utilising a combination of grid power

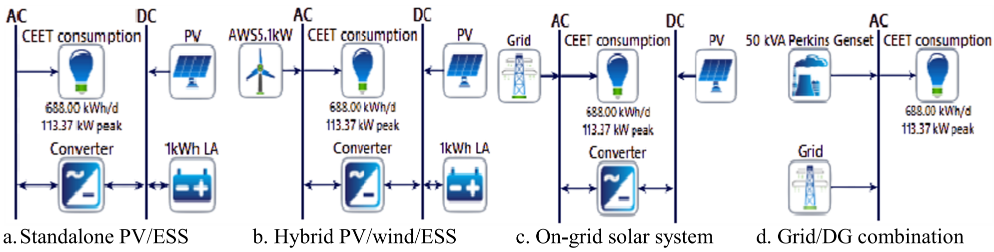

Figure 1. Energy supply alternatives for CEET: (a) Standalone PV/ESS, (b) Hybrid PV/wind/ESS, (c) On-grid solar system, (d) Grid/DG combination.

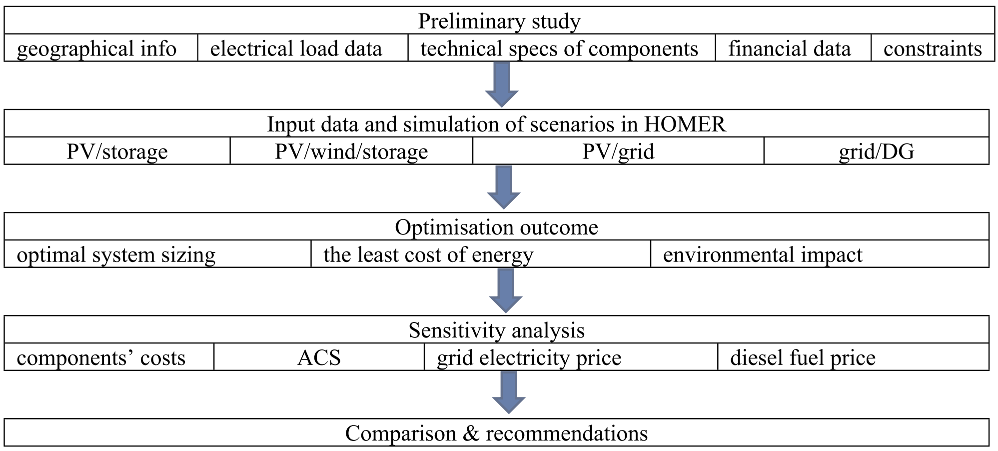

Figure 2. Methodology of the study.

and DG. The study exploited the proximity of the national grid, the abundance of solar and wind resources at the site, and the low-priced diesel fuel to create the four scenarios. The four configurations are illustrated in Figure 1.

The methodology of this quantitative study, as illustrated in the flowchart of Figure 2, begins with data collection, which is inserted into HOMER software. After designing each energy system option independently, HOMER performs comprehensive simulations to optimise system components technically and economically. The software identifies the optimal sizing of components to meet the required load, achieving the lowest possible NPC and LCOE, as described by Equations (1) to (4). Thus, the objective function is to minimise the NPC and LCOE, which can be calculated as [32], (Zhang, Xiao, and Razmjooy 2022):

$$NPC = \frac{TAC}{CRF} \tag{1}$$

$$TAC = CAP + O\&M + REP + FC \tag{2}$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

$$LCOE = \frac{NPC \times CRF}{\sum_{t=1}^{8760} P_L(t)} \tag{4}$$

where TAC is the total annualised cost ($), CRF is the Cost recovery factor (%), FC is the fuel cost ($), REP is the replacement cost ($), CAP is the capital investment cost ($), O&M is the operation and maintenance cost ($) i is the interest rate (%), $P_L(t)$ is the Total energy generated and imported at hour t (kWh). These equations are subject to a number of constraints, including Annual Capacity Shortage (ACS), Renewable Fraction (RF) and Depth of Discharge (DOD), as follows:

$$\begin{cases} ACS \leq ACS_{max} \\ 0 \leq RF \leq RF_{max} \\ 0 \leq DOD \leq DOD_{max} \end{cases} \tag{5}$$

One of HOMER's key features is its ability to assess future scenarios by analysing multiple values of critical influencing factors, known as sensitivity analysis. This study uses sensitivity analysis to evaluate the impact of cost reductions in RE components during optimisation. Specifically, the costs of PV panels, wind turbines, battery banks, and converters are reduced to 75% of their baseline values. Another significant factor affecting RE implementation is the maximum allowable ACS. The ACS is adjusted from 2% to 10% of the base value to increase flexibility and applicability. Additionally, the sensitivity analysis considers an unsubsidised scenario by increasing grid electricity prices to 0.05 and 0.1 $/kWh and diesel fuel costs to 0.25, 0.5, 0.75, and 1 $/l, respectively. From the technical perspective, the performance of the solar system is assessed using [32], (Mbasso et al. 2023):

$$P_{PV} = PV_{capacity} \times \left(\frac{G_T}{G_{T,STC}}\right) \times DF \tag{6}$$

HOMER multiplies the power value generated from the standard power curve by the air density ratio, as follows [32], (Oubouch et al. 2024):

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) \times P_{WTG.STP} \tag{7}$$

The quantity of energy stored in the battery at a given time is modelled as [32], (Araoye et al. 2024):

$$E_B(t) = E_B(t-1) + E_{RE}(t) \times \propto_{CC} \times \sigma_{Ch} \tag{8}$$

As for the DG, the hourly usage of fuel is formulated as [32], (Araoye et al. 2024):

$$F_{DG} = B_g \times P_{DG} + A_g \times P_{DG-out} \tag{9}$$

where P_{PV} is solar power produced (kW), $PV_{capacity}$ is the solar PV installed capacity (kW), G_T is the Global tilted irradiance (kW/m^2), DF is the derating factor (%) accounting for system losses, P_{WTG} is the wind turbine power output (kW), ρ is the the actual air density (kg/m3), $E_B(t)$ is the energy stored in the battery (kWh) at time t, $E_{RE}(t)$ is the amount of renewable energy available (kWh) at time t, $\propto_{CC}$ is the efficiency of charging regulator (%), σ_{Ch} is the battery charging efficiency (%), F_{DG} is the fuel consumption of diesel gen (l/hr), A_g and B_g are the fuel consumption coefficients (l/kW) and P_{DG} is the rated power of the diesel gen (kW).

3. Case study: college of electrical and electronics technology, Benghazi

The CEET, located in the Al-Qawarsha district to the west of Benghazi at coordinates 32.04N 20.07E, spans an area of approximately 24 hectares. Strategically located 11 km from Benghazi's city centre, 3 km from the University of Benghazi, and 4 km from the coastline, the campus comprises a set of facilities integral to its educational mission. These include seven main structures: engineering workshops, laboratories, scientific affairs, administration, services, and a student hostel with a footprint of about 2000 m^2. The lecture building hosts 11 classrooms and 5 auditoriums, supporting various instructional needs. Additionally, CEET offers an expansive open area of roughly 140,000 m^2, suitable for future development and outdoor activities. This site's spatial layout and infrastructure are pivotal in evaluating and designing sustainable energy solutions tailored to the institution's operational requirements. The study began in this section by assessing the physical and operational characteristics of the CEET. This involved analysing:

- Electrical consumption of the campus.
- Meteorological input data.
- Technical and financial data of the proposed system.

3.1. Electrical consumption of the campus

The CEET is a public higher education institution that offers a technical bachelor's degree in electrical and electronic engineering, offering three specialised tracks: power, telecommunications, and control technologies. This diverse curriculum reflects the institution's commitment to equipping students with the skills necessary to address contemporary challenges in the electrical engineering field. For this study, data regarding the college's electrical consumption were meticulously gathered from the billing division of the GECOL over an extended period from September 2022 to March 2024. The data collection involved a systematic approach to ensure accuracy and reliability, encompassing all relevant consumption metrics. Benghazi's coastal Mediterranean climate significantly influences the college's energy consumption patterns. The region experiences cold, rainy winters and hot, humid summers, which results in distinct seasonal variations in electrical demand. During the summer months, the demand for electrical energy surges, primarily due to increased air conditioning usage as students and faculty seek to maintain comfortable indoor environments. As tabulated in Table 3, analysis of the collected data shows that the average daily electrical consumption for CEET is approximately 688 kWh, while the peak load reaches 113 kW. These figures are crucial for understanding the institution's energy profile and are vital in informing the design and optimisation of potential energy supply solutions. By integrating this consumption data with climate considerations, the study aims to develop a comprehensive strategy for enhancing the sustainability and reliability of CEET's energy systems, ultimately contributing to the college's long-term operational efficiency and resilience.

Table 3. The daily average energy consumption for CEET.

Period		Number of days	Demand (kWh)
30/09/2022	31/12/2022	92	51,600
31/12/2022	02/02/2023	33	21,300
02/02/2023	30/03/2023	56	35,700
30/03/2023	14/06/2023	76	64,500
14/06/2023	17/09/2023	95	73,200
17/09/2023	06/12/2023	80	49,800
06/12/2023	11/03/2024	96	71,100
11/03/2024	05/06/2024	86	55,800
Total		614	423,000
The average of energy consumption (kWh/day)			688

Table 4. Electric load profile of CEET.

Hour	Power (kW)	Hour	Power (kW)
1	5	13	54
2	5	14	66
3	5	15	66
4	5	16	58
5	5	17	52
6	8	18	20
7	13	19	10
8	26	20	6
9	66	21	5
10	66	22	5
11	66	23	5
12	66	24	5

The actual daily load profile is illustrated in Table 4. The data shows that electrical consumption peaks during daytime hours, specifically between 09:00 and 17:00. This peak usage period correlates with the college's operational schedule when most classes and activities occur. Notably, there is a distinct reduction in power demand during the afternoon break, which suggests a temporary decline in energy use as students and faculty pause for lunch and other activities. In contrast, a substantial decrease in power requirements is observed outside of the designated peak hours. This pattern underscores the variability in energy consumption throughout the day and highlights the necessity for a dynamic energy management approach. Understanding these temporal variations is critical for developing effective energy supply solutions accommodating the college's unique operational characteristics. Additionally, the seasonal and annual distribution of electrical consumption provides further insight into how external factors, such as weather and academic calendar fluctuations, influence energy needs. For instance, the electricity demand may rise significantly during the hotter months, driven by increased air conditioning usage, while lower demand is likely during cooler months when heating requirements are less pronounced. This comprehensive load profile analysis is vital for informing the design of optimised energy systems responsive to the college's specific consumption patterns. By leveraging this detailed understanding of energy usage, the study aims to propose solutions that enhance efficiency, reduce costs, and promote sustainability in CEET's energy infrastructure.

3.2. Meteorological data

Libya benefits from a substantial solar energy resource, particularly in its southern regions near the Tropic of Cancer, where the annual solar insolation reaches approximately 3500 h of sunlight and an average daily global horizontal irradiation (GHI) of 7 kWh/m^2 is recorded. This abundant solar potential is complemented by favourable wind energy conditions, with specific locations within the country exhibiting average wind speeds that exceed 7 m/s at a height of 10 metres. Such climatic characteristics create an advantageous environment for developing RE projects, particularly PV and wind energy systems. The HOMER software was employed to analyse Libya's solar and wind energy resources comprehensively. This advanced modelling tool integrates and optimises various RE technologies alongside traditional energy sources. The meteorological data utilised within the HOMER framework is sourced from POWER (Prediction of Worldwide Energy Resource), a database developed by NASA. This extensive repository offers historical records of various meteorological parameters, including GHI, wind speed (Ws), and ambient temperature (T_a), which are crucial for accurate energy resource assessment and modelling. The analysis includes a detailed examination of the clearness index and monthly averaged GHI in Benghazi, as illustrated in Table 5. This data spans 22 years, from July 1983 to June 2005. The results indicate that the annual average daily GHI in Benghazi is 5.44 kWh/m^2, a value that underscores the region's potential for solar energy generation.

Additionally, Table 6 comprehensively summarises monthly averages for ambient temperature, total horizontal irradiation, and wind speed. This table highlights the seasonal variations and trends in meteorological conditions integral to understanding the feasibility of deploying solar and wind energy technologies in Libya. The ambient temperature data is critical for evaluating the performance of solar PV systems, as higher temperatures can influence the efficiency of solar panels. Similarly, the wind speed data aids in identifying optimal locations for wind turbine installations, ensuring maximum energy capture. To further enhance the robustness of the methodology, various simulations were conducted using the HOMER software to model different RE system configurations. These simulations incorporate historical meteorological data into energy production, assess system performance, and optimise the design of energy systems. By evaluating multiple scenarios that combine solar PV, wind, and potential energy storage options, this methodology aims to identify the most effective strategies

Table 5. Annual monthly averages of GHI at Benghazi.

Month	Daily radiation (kWh/m^2)	Clearness Index
Jan.	2.87	0.514
Feb.	3.87	0.565
Mar.	5.18	0.606
Apr.	6.56	0.648
May.	7.26	0.653
Jun.	7.92	0.69
Jul.	7.94	0.705
Aug.	1.26	0.695
Sep.	5.96	0.685
Oct.	4.55	0.62
Nov.	3.26	0.557
Dec.	2.63	0.508

Table 6. Meteorological data at the CEET site.

Month	T_a (°C)	GHI (kWh/m^2/day)	Ws @ 10 (m/s)
January	13.68	2.87	7.19
February	13.42	3.87	7.43
March	14.78	5.18	6.89
April	17.31	6.56	6.81
May	20.70	7.26	6.17
June	24.04	7.92	5.83
July	25.97	7.94	5.95
August	26.65	7.26	5.67
September	25.45	5.96	5.55
October	22.52	4.55	5.64
November	18.70	3.26	6.40
December	15.37	2.63	7.23
Annual Average	19.88	5.44	6.40

for harnessing Libya's RE resources, ultimately contributing to sustainable energy development in the region.

3.3. Technical and financial data

The assessments in Section 3.2 guided the selection of PV modules and wind turbines, considering the available space and energy generation capacity. Then, the design and optimisation of the RE systems were performed using the HOMER Pro software, which simulates and analyses various configurations to achieve the most cost-effective and energy-efficient system. The following four scenarios were considered:

- Scenario 1: PV and lithium battery: This scenario involves a standalone system using PV panels for energy generation, with lithium batteries for energy storage and a power controller to regulate the flow of electricity. The maximum number of PV modules and the capacity of the battery storage system were calculated based on the building's energy demand and available space.
- Scenario 2: Wind turbine, PV, and lithium battery: In this scenario, both wind turbines and PV panels are used for energy generation, combined with lithium batteries for storage and a power controller for system management. Wind turbines' capacity and power production were determined based on wind speed data and available tower space. The designed fully renewable option can form an ideal green island microgrid.
- Scenario 3: PV and Grid: This scenario considers a grid-connected system supplemented by PV panels. The HOMER Pro software calculated the optimal number of PV modules, while the grid provides supplementary power during periods of low solar output.
- Scenario 4: Grid and DG: A hybrid system was simulated where the campus is connected to the grid, with a diesel generator providing backup power. The power controller manages the energy distribution between the grid and the DG to meet the college's demand.

The specifications and operational parameters for the equipment utilised in assessing the optimal hybrid energy system for the CEET are detailed in Table 7 (T. Chen, Wang, and

Table 7. Technical and financial input parameters of hybrid system components.

Equipment	Model	CAP ($)	REP ($)	O&M ($/yr)	Lifetime (yrs)
Solar system	1 kW	800	0	20	25
Wind generator	AWS HC 5.1 kW, 12 m tower height	11,785	10,000	20	20
Converter	1 kW Generic bidirectional, $\eta = 95\%$	280	250	0	15
Battery Storage	Generic lead acid 12V 1 kWh, DOD = 60%, $\eta = 80\%$	200	180	10	7
DG	50 kVA Perkins	13,500	12,500	$1.5/hr	10,000 hr

Babaei 2023; Riayatsyah, Geumpana, Fattah, and Mahlia 2022; Thirunavukkarasu and Sawle 2020). The technical data about the listed components and associated costs have been gathered from various sources, including local suppliers and international markets. The capital costs associated with the PV system encompass installation, wiring, mounting, commissioning, and licensing fees. A DF of 80% has been applied to accurately reflect system performance, accounting for potential losses due to environmental factors, inefficiencies, and equipment degradation (Almaktar, Elbreki, and Shaaban 2021). To maximise solar energy capture, the solar PV system is designed with a fixed tilt angle, set to the latitude 32°. Critical financial parameters have been incorporated into the analysis from an economic perspective. The inflation rate has been assumed to be 2%, while a discount rate of 5% has been utilised for present value calculations (T. Chen, Wang, and Babaei 2023). These economic factors are essential for evaluating the financial viability of the hybrid energy system over its operational lifespan. The simulation employs a load-following (LF) strategy to meet electrical demand effectively. This approach ensures that the fossil-fuelled generator operates in a manner that provides only the necessary power to meet the primary load requirements. In parallel, the RE sources are configured to charge the battery storage system or supply power to deferrable loads. This operational strategy optimises the utilisation of RE while ensuring reliable service delivery, ultimately enhancing the efficiency and sustainability of the hybrid energy system. By integrating technical specifications, economic parameters, and operational strategies into the simulation model, this methodology aims to comprehensively assess the optimal hybrid energy configuration for CEET, aligning with contemporary energy demands and sustainability objectives.

In this study, the RE output percentages for the hybrid energy system under evaluation indicate that solar power contributes 80% of the total energy production, while wind power accounts for 50%. These values reflect the anticipated contributions of each energy source to the overall generation profile. Additionally, several operational constraints have been established to ensure the system's reliability and efficiency. One critical parameter is the maximum allowable ACS, limited to 2%. This constraint signifies that the electrical load demand for the college is met throughout the year with a tolerance of 2% for unexpected power fluctuations or demand peaks. This allowance is essential for accommodating sudden increases in electricity consumption, ensuring that the energy system remains responsive to real-time load requirements. Integrating these percentages and constraints into the hybrid energy model allows for a thorough system performance analysis. By carefully evaluating the RE contributions and establishing ACS limits, this methodology aims to optimise the design and operation of the hybrid energy system, ensuring that it can effectively meet the college's electrical demands while maximising the use of renewable resources.

4. Results and discussion

This section presents a comprehensive analysis of the data obtained from the simulations of the optimal hybrid energy systems for the CEET. This section aims to elucidate the performance metrics of the proposed system, focusing on the contributions of solar and wind energy sources, as well as the overall efficiency and reliability of the energy supply. Initially, the results will detail the different scenarios for different combinations, highlighting their respective shares in meeting the electrical demands of the college under the current subsidised energy prices. The implications of these outputs will be examined in the context of operational constraints, including the maximum allowable ACS and its significance for maintaining reliable energy delivery. Then, through a critical and sensitive analysis of the results, the findings would provide insights into the feasibility and effectiveness of deploying energy solutions with the effect of subsidy removal, thus contributing to the broader discourse on sustainable energy practices in Libya and similar contexts.

4.1. Optimisation results based on the current subsidised fuel and electricity prices

4.1.1. Scenario 1: PV and ESS

A comprehensive analysis of 322 configurations was conducted to identify the optimal hybrid system that integrates PV technology with lithium battery storage. Out of the total optimisations analysed, 126 were deemed feasible, with the remaining designs being classified as infeasible primarily due to the limitations imposed by capacity shortages. The optimal configuration was selected based on its performance in meeting load requirements, adherence to technical specifications, and economic factors, particularly the LCOE and the NPC. These metrics were essential in determining the most efficient and economically viable system for long-term operation. The technical and economic performance of the optimised standalone system which comprises 480 kW of PV panels, a 516 kWh battery bank, and a 114 kW converter, is presented in Table 8. These specific components were selected by a detailed analysis of their performance characteristics, ensuring an effective balance between energy generation, storage capacity, and power conversion efficiency. The PV panels were sized to maximise solar energy capture during peak sunlight hours, while the battery bank was configured to provide sufficient energy storage to address fluctuations in load demand and ensure a reliable supply during periods of low solar insolation. The converter, with its rated capacity of 114 kW, plays a critical role in managing the energy flow between the PV system, the

Table 8. Electrical performance of the standalone system of the 1st scenario.

Metric	Energy (kWh/yr)	%
Generic flat plate PV production	826,111	100
AC primary load	248,374	100
Excess electricity	555,738	67.30
Unmet Electric load	2746	1.09
ACS	5271	2.10
RF (%)	100	
Total NPC ($)	960,638	
LCOE ($/kWh)	0.221	
O&M ($)	25,190	

battery bank, and the electrical load. Its design ensures optimal power conversion efficiency and facilitates seamless storage system integration with the load requirements. The LCOE of the optimal standalone solar system is nearly 0.22 $/kWh. A study in a similar geographical context, specifically the Kingdom of Saudi Arabia, found that a standalone PV system with lithium battery storage yielded an LCOE of 0.19 $/kWh (Alzahrani 2023).

Economic characteristics associated with the optimal configuration of the standalone PV/storage system are detailed in Table 9. The table illustrates key financial metrics, including all the projected expenditures essential for evaluating the economic feasibility of the proposed energy solution. The economic analysis of the proposed standalone solar energy system shows that the total NPC is approximately $961,000 over the project's lifespan. Within this framework, the solar PV system accounts for the most significant portion of the total expenditure, amounting to nearly $552,000, corresponding to 57.5% of the overall cost. In contrast, the ESS represents 37.7% of the total price, equating to $363,000. This distribution of costs aligns with the operational profile of the CEET, where peak electrical demand typically occurs during daylight hours. Despite the high reliability of the system, with only 1% of the load remaining being unmet, there is a notable generation of excess electricity. This surplus production is seen as a disadvantage, indicating potential inefficiencies within the system. As reported in many similar research works, the excess electricity is common in the optimised off-grid RE systems (Elwalaty and Sow 2025; Adetoro et al. 2023).

To mitigate this excess energy generation, CEET could assess two options: The first possible option involves enhancing the storage capacity. Increasing storage capacity would allow for better energy utilisation and management of deferrable loads. Apart from the costing, an effective energy management system dealing with multiple ESS could be an effective mechanism to reduce the excess renewable electricity (Yadav, Kumar, and Kumar 2024). The second option is to reduce the number of installed solar panels. However, this solution would increase the ACS. On the other hand, the charging status of the battery bank throughout the year is depicted in Figure 3. Analysis of this data shows that the state of charge (SOC) is consistently maintained to as much as 40%; a critical constraint is incorporated into the system design to preserve battery health and longevity. The figure indicates that the ESS is more heavily utilised during winter; nevertheless, the DOD remains consistently as much as 60%. This seasonal variation in battery usage highlights the importance of understanding load profiles and renewable generation patterns when designing RE systems.

4.1.2. Scenario 2: PV, wind turbine and battery bank

In this configuration scenario, the optimal system design for meeting the load demand and minimising energy cost consists of a 199 kW PV array, 14 wind turbines rated at

Table 9. NPC by component for the optimised PV/ESS.

Component	CAP ($)	REP ($)	O&M ($)	Salvage ($)	Total ($)
Generic 1kWh lead acid	103,200	188,250	90,444	−19,285	362,609
Generic flat plate PV	384,055	0	168,291	0	552,346
System converter	31,861	18,416	0	−4594	45,684
System	519,116	206,667	258,735	−23,879	960,638

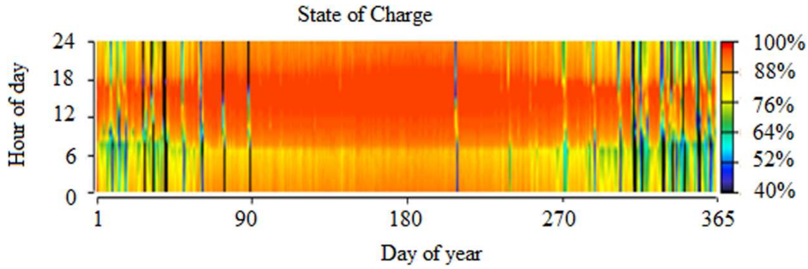

Figure 3. SOC of the battery bank of 1st scenario.

5.1 kW each, a 348 kWh lithium battery storage capacity arranged in 87 strings, and a 103 kW power converter, as illustrated in Table 10. This hybrid system powers from both solar and wind energy, allowing for enhanced generation flexibility and reliability. In contrast, ESS and a power management controller are incorporated to regulate supply and demand effectively. The capacity of the PV array was chosen based on site-specific solar radiation data, ensuring that the system could maximise energy capture during peak daylight hours. The rated power and number of wind turbines were determined based on the local wind speed profiles and the spatial layout available for tower installations, aiming to optimise energy generation across different weather conditions. This diverse generation setup ensures a stable energy supply and reduces reliance on a single source thereby enhancing resilience against seasonal and daily fluctuations.

Cost distribution for the hybrid setup shows that battery storage constitutes 34.3% of the total system expenses, reflecting the high costs associated with energy storage technologies. The PV system accounts for 32.1% of the total expenditures, while wind turbines represent 27.7%. This division of costs underscores the importance of each component in achieving optimal performance. It highlights the capital intensity of storage in hybrid systems where reliability and load management are critical. The total NPC for this hybrid configuration was calculated to be approximately $712,039, with an LCOE of $0.163 per kWh produced. These values reflect a more cost-effective solution compared to other configurations, providing an economically feasible model for RE integration. Compared to the standalone PV and battery storage setup, the PV-wind hybrid system demonstrates higher reliability and efficiency. Excess energy is also reduced significantly to 49.5%, thus minimising wasted energy. This reduction in surplus energy production is advantageous as it reflects more efficient utilisation of the available resources, with only 0.84% of the load unmet. Table 11 illustrates the system's performance and reliability in maintaining a consistent energy supply, meeting nearly all demand

Table 10. The most feasible three solutions of the standalone hybrid renewable system.

	Architecture				Cost				
Combination	PV (kW)	AWS5.1 kW	1 kWh LA	Converter (kW)	NPC ($)	LCOE ($/kWh)	O&M ($/yr)	CAP ($)	RF (%)
PV/wind/battery	199	14	348	103	712,039	0.163	16,522	422,451	100
PV/battery	480		516	114	960,638	0.221	25,190	519,116	100
Wind/battery		43	1032	98	1.37M	0.316	35,963	740,542	100

Table 11. Electrical characteristics of a standalone PV/wind/battery system.

Metric	Energy (kWh/yr)	%
Generic flat plate PV production	341,816	65.9
AC primary load	249,006	100
Excess electricity	256,875	49.5
Unmet Electric load	2114	0.84
ACS	5270	2.10
RF (%)	100	
Total NPC ($)	712,039	
LCOE ($)	0.163	
O&M ($)	16,522	

requirements while optimising resource use. The standalone wind-battery configuration was the most expensive among the configurations analysed, with an LCOE of $0.316 per kWh. This is attributed to the high costs of battery storage required to compensate for the variability in wind generation, highlighting the economic and operational benefits of a hybrid approach that balances PV and wind inputs.

The findings from this scenario underline the value of integrating multiple renewables to achieve a balanced and sustainable power supply by combining solar PV and wind power generation. The hybrid system benefits from complementary generation profiles, where solar resources are typically abundant during the day while wind generation can contribute at night or during low-sunlight periods. This synergy enhances the system's capacity to meet varying load demands efficiently. Moreover, the substantial cost associated with storage indicates the importance of strategic sizing and deployment of battery banks in hybrid systems, where excessive storage may increase costs without proportional gains in performance. Future studies and designs might consider advanced control algorithms to manage energy distribution dynamically, further optimising the balance between generation, storage, and load demand. Figure 4 presents a detailed hourly profile of the energy production throughout the year from the selected standalone hybrid renewable system, showcasing how each source contributes to the overall

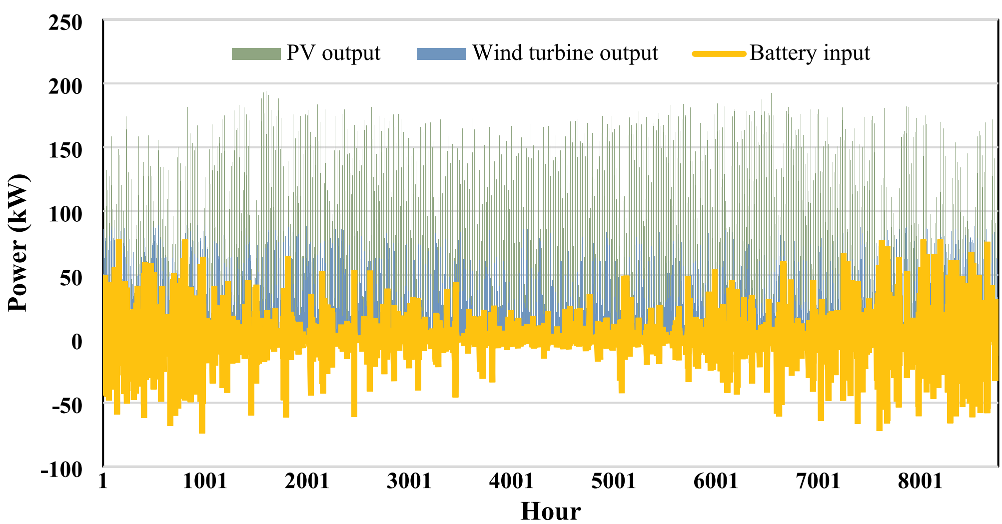

Figure 4. Year-round electrical production of the standalone PV/wind/battery system.

generation. The PV system is estimated to generate around 342 MWh annually, supplying approximately 66% of the system's total energy output. This substantial share highlights solar energy's role as the primary power source, effectively meeting demand during high irradiance periods, particularly in summer. Meanwhile, the wind energy system produces about 177 MWh per annum, accounting for 34% of the system's output. The seasonal and diurnal distribution of wind production complements solar generation by covering periods of reduced sunlight, providing a more consistent and balanced energy supply throughout the year. This production pattern significantly reduces reliance on a single energy source, enhancing the system's sustainability and reliability. The hybrid configuration leverages the complementary nature of PV and wind, which is particularly valuable in regions where weather patterns and seasonal shifts influence resource availability. The effective integration of these two sources helps stabilise supply across months, ensuring consistent power delivery and reducing the risk of shortfalls. As for the associated 348 kWh battery bank, negative values indicate discharge state, whereas positive values indicate charging status.

The SOC for the battery storage, shown in Figure 5, illustrates the storage performance over time, with the system effectively managing the ebb and flow of production and demand. The battery bank plays a crucial role in the energy management strategy, storing excess energy during peak production hours and discharging during peak demand periods or when production dips. This setup enables the system to bridge gaps between generation and demand without relying on external energy sources, thus improving overall self-sufficiency and reducing excess energy wastage. Analysing the SOC profile throughout the year, the battery system demonstrates high efficiency and robustness, rarely depleting below safe discharge levels (60%). The SOC remains optimal, meeting the imposed constraints to avoid deep discharge and maintain battery longevity. Seasonal trends in SOC levels highlight the storage system's adaptability to fluctuating conditions. During the summer, when solar generation is at its highest, the battery charges fully, ensuring ample reserves for cloudy days or night

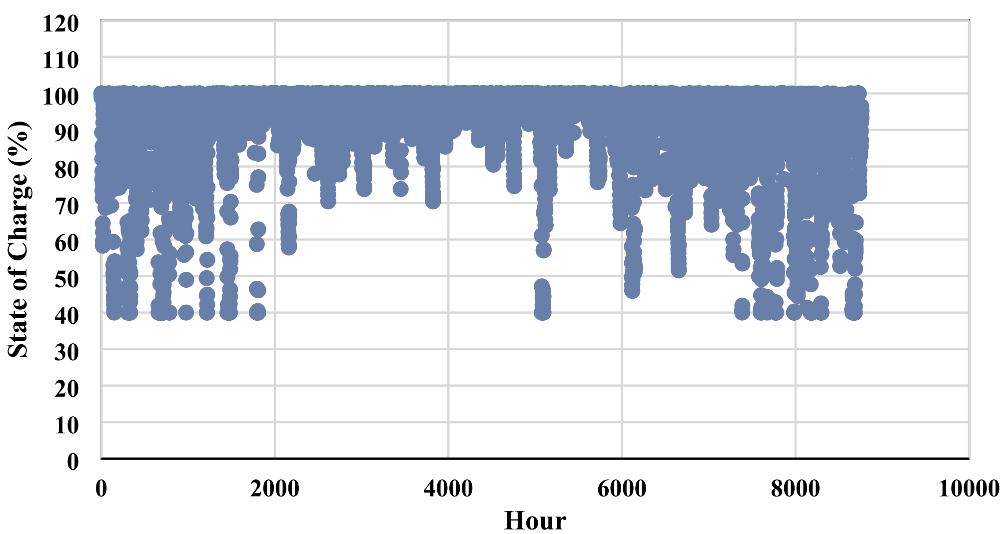

Figure 5. State of charge of the battery bank of the winner system in scenario 2.

hours. In contrast, during winter, the storage system operates with a more moderate SOC, reflecting the system's reliance on wind energy and occasionally requiring strategic discharge to meet evening and night loads.

The PV, wind, and battery storage combination enhances system resilience, balancing energy supply against demand fluctuations and maintaining reliability. The hybrid system minimises ACS by optimising the SOC parameters and leveraging solar and wind inputs. It maximises load coverage while keeping excess energy production to a manageable level. This approach minimises operational costs and enhances the system's economic viability, as stored energy is used efficiently, reducing the need for oversized generation or additional storage. This hybrid setup, characterised by the coordinated use of PV, wind, and battery storage, ensures a highly reliable and sustainable energy supply. The distribution of energy production between PV and wind reduces dependency on any one source, and the battery's SOC profile confirms that the storage system is adequately sized and effectively utilised, meeting demand without frequent deep discharges. The resulting system achieves high energy efficiency, with minimised losses and optimised resource allocation, offering a scalable model for similar RE applications that prioritise economic and operational performance.

4.1.3. Scenario 3: PV and grid

In the third scenario, the proximity of the national transmission grid to CEET is exploited; the energy system combines grid power with PV generation to provide a reliable and cost-effective solution. The local grid's energy cost is \$0.024 per kWh, with a sell-back rate of \$0.05 per kWh. As expected, due to the significantly subsidised grid tariff, optimisation results suggest that the grid should be the primary power source for CEET, as it remains the most economical option. However, to address frequent grid outages, a minimum RF of 20% is mandated to ensure that a portion of the college's daily energy demand is consistently met by solar power. The optimal configuration in this scenario comprises 32.3 kW of solar panels paired with a 21.4 kW inverter. This combination yields an LCOE of approximately \$0.029 per kWh. As illustrated in Table 12, the grid will meet 78.3% of the total demand, while the PV system will supply the remaining 21.7%. The solar array generates an average of 152 kWh per day, operating at a capacity factor of 19.6%, which demonstrates efficient utilisation under the given constraints. The PV system's production effectively complements grid power, ensuring system reliability while minimising operational costs and dependency on grid power alone.

Table 12. Electrical parameters of the winning on-grid solar system.

Metric	Energy (kWh/yr)	%
Generic flat plate PV production	55,577	21.7
Grid purchases	200,444	78.3
AC primary load	251,120	100
Excess electricity	2234	0.87
Unmet Electric load	0	0
ACS	0	0
RF (%)	20.2	
Total NPC (\$)	130,061	
LCOE (\$)	0.029	
O&M (\$)	5605	

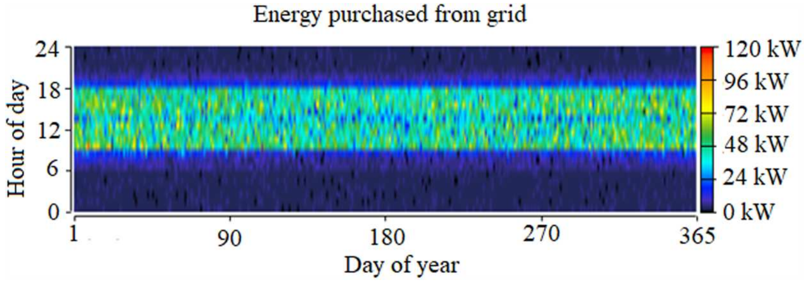

Figure 6. Annual energy contribution from the utility grid.

One key advantage of this configuration is the minimal excess energy production from the solar system, which aligns well with the load requirements and indicates an efficient balance between grid and renewable sources. The system has been fine-tuned to eliminate energy wastage while fully meeting the electrical demand. Figure 6 displays the average annual energy consumption from the national grid, which underscores the economic optimisation achieved through this combination. This methodology capitalises on the low-cost grid tariff and leverages renewable generation to buffer against power interruptions, ensuring an uninterrupted and economically sound power solution for CEET. This balanced approach demonstrates the feasibility of integrating PV power to supplement the grid, particularly in regions with inconsistent grid availability, providing a model for similar energy systems that prioritise economic and operational resilience.

4.1.4. Scenario 4: grid and DG

In this scenario, a fossil-fuel-centred configuration utilises the utility grid as the main energy source, supplemented by a 50kva DG, to enhance reliability during grid outages. Here, grid electricity costs \$0.024 per kWh, while diesel fuel costs \$0.0026 per kWh. Similar to the setup in scenario 3, a minimum backup threshold is set at 20% to mitigate frequent power interruptions. Given the intermittent nature of grid power, the DG is programmed to run for approximately 519 h annually, about 6% of the year. This distribution of generator use is represented monthly in Figure 7, with extended operation during peak outage months. Specifically, extended power outages from May to September necessitate up to three hours of daily generator operation, totalling about 60 h per month. July and August, however, experienced reduced generator use due to the summer break, aligning with lower demand. This setup optimises energy availability while ensuring diesel use remains economical and minimally intrusive, serving as a reliable backup to sustain operations and meet demand without significant cost increases or excess fuel consumption. This scenario provides an economically balanced solution with integrated reliability measures tailored to the seasonal demand and outage patterns specific to the location.

During the 519 h of anticipated grid outages each year, the DG is expected to produce approximately 25.5 MWh, covering about 10.2% of the college's total annual energy demand. Meanwhile, grid power accounts for the remaining 225.6 MWh annually, meeting 89.8% of the required energy. The generator's operational lifespan is set at

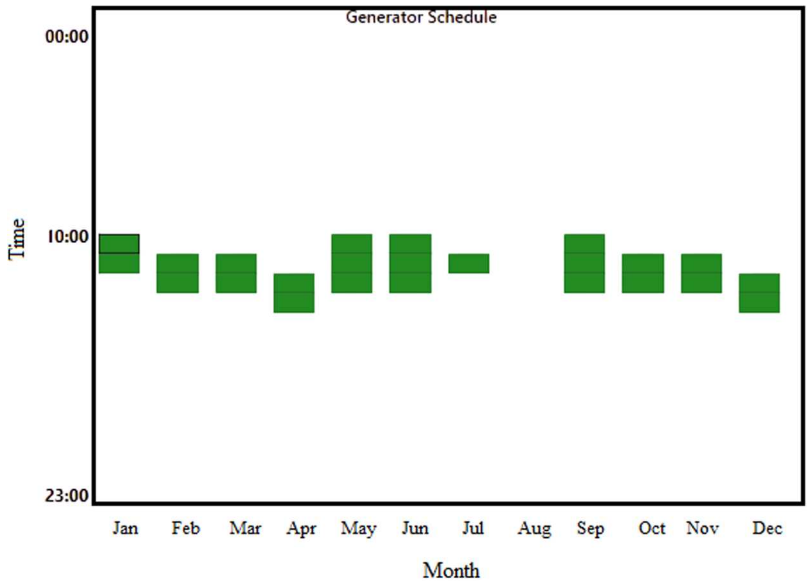

Figure 7. Operation hours of the DG.

10,000 h. Given its annual runtime, the generator would remain effective for roughly 19.3 years, with a planned replacement at the 20-year mark, as illustrated in Table 13. This approach ensures reliability while optimising costs associated with replacement and maintenance within the project's lifecycle.

As illustrated in Figure 8, the DG's operation is minimal in July and unnecessary in August, coinciding with the summer holiday when campus activity is reduced. The limited energy consumption in August is primarily attributed to air conditioning in administrative buildings and service offices operating on reduced schedules. Figure 9 highlights the utility grid's role in consistently supplying the CEET's electrical demands throughout the year. This data demonstrates the seasonal adjustments in generator use, reinforcing the grid's primary role in meeting energy needs, with the DG effectively serving as a supplemental source during peak outage periods.

Table 13. Electrical characteristics of the DG.

Quantity	Value
Hours of operation (hrs/yr)	519
No. of starts (starts/yr)	237
Operational life (yr)	19.3
Capacity factor (%)	5.83
Fixed generation cost ($/hr)	2.79
Marginal generation cost ($/kWh)	0.0071
Electrical production (kWh/yr)	25,527
Fuel consumption (l)	7825
Specific fuel consumption (l/kWh)	0.307
Total NPC ($)	128,508
LCOE ($)	0.029
O&M ($)	6561

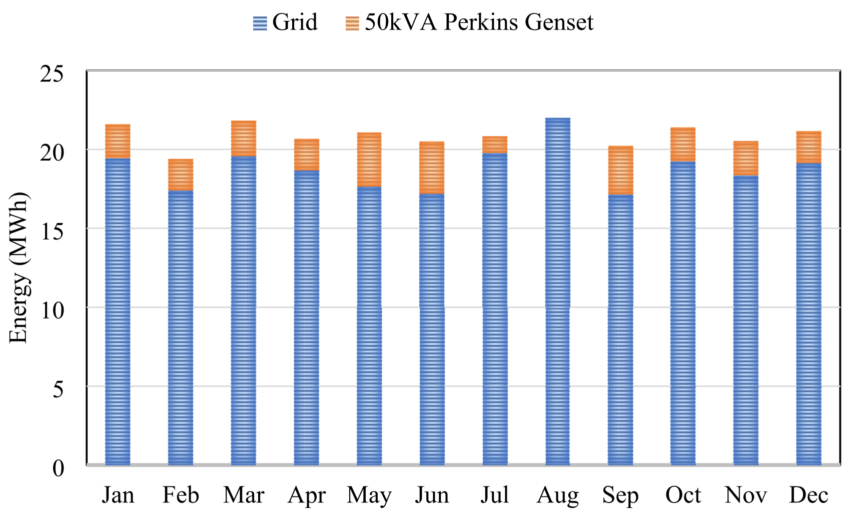

Figure 8. Distribution of electrical energy production among sources in scenario 4.

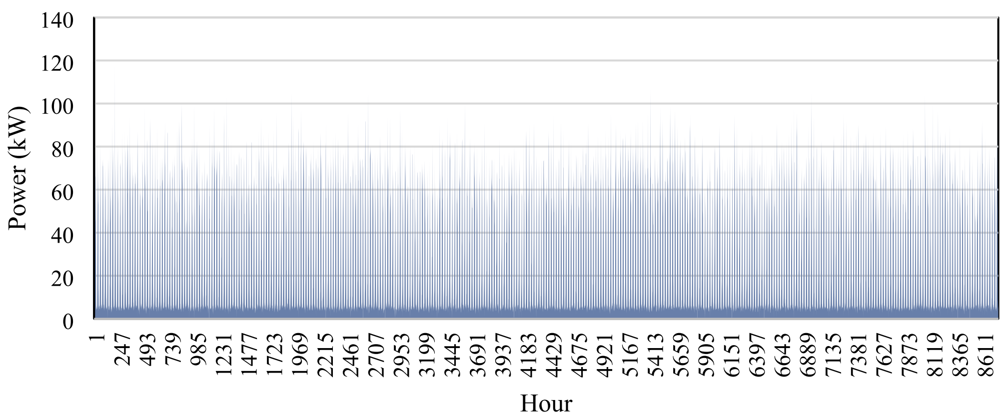

Figure 9. Energy supplied by the grid in the 4th scenario.

4.1.5. Summary of scenarios under subsidised energy conditions

Table 14 summarises the most feasible alternatives of energy supplies for CEET in the four scenarios. It can be concluded that with the current situation where the fuel price and grid electricity are subsidised, the fossil-based electricity (3rd and 4th scenario) demonstrates a superior economic advantage to the standalone RE source. Among the four evaluated scenarios, the third scenario, featuring a 32 kW on-grid solar system, is the optimal choice in both technical and economic dimensions despite its contribution to greenhouse gas emissions. This indicates that while economic factors currently favour fossil fuel reliance, environmental considerations must be accounted for. In contrast, should the objective shift towards a fully renewable autonomous system, the second alternative emerges as the preferred option, offering an LCOE of approximately $0.16/ kWh. Economies of scale would add to the system's advantages. A fully hybrid RE

Table 14. Summary results for the optimal solutions under subsidised tariffs.

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
PV system (kW)	480	199	32.3	–
Converter (kW)	114	103	21.4	–
Battery storage (kWh)	516	348	–	–
Wind turbine 5.1 kW	–	14	–	–
Grid (kW)	–	–	999,999	999,999
DG (kW)	–	–	–	50
NPC ($)	960,638	712,039	130,061	128,508
LCOE ($/kWh)	0.221	0.163	0.029	0.029
CAP ($)	519,116	422,451	31,823	13,500
O&M ($/yr)	25,190	16,522	5605	6561
RF (%)	100	100	20.2	0
CO_2 emissions (kg/yr)	0	0	126,680	163,060

system comprising 10 MW PV and 21 MW of wind generation, designed for an industrial entity, achieved a lower LCOE of 0.082 $/kWh (Al-Odat et al. 2024). This alternative aligns with sustainability objectives and maintains a competitive cost structure, highlighting the trade-offs in energy source selection and the importance of considering economic and environmental impacts in future decision-making.

4.2. Sensitivity analysis

In the first sensitivity analysis scenario, the optimisation process focuses on two critical parameters: the maximum allowable ACS and the cost of components associated with the autonomous PV/storage system. The permissible ACS significantly influences the sizing and economic viability of the standalone PV/battery storage system. When the maximum ACS is permitted to rise to 10%, in contrast to the baseline limit of 2%, the optimised system configuration comprises 285 kW of solar PV capacity, a 344 kWh battery bank, tied to 145 kW converter. Under these conditions, the NPC and the LCOE are calculated to be $637,126 and $0.152, respectively, as seen in Table 15. Additionally, the analysis shows that the annual unmet load is a mere 4.8%. This adjustment reduces excess electricity generation to 46.8%, a significant improvement compared to the 67% excess observed in the initial standalone system configuration. This reduction enhances the practical feasibility and operational efficiency of the system. Moreover, when the maximum allowable ACS is increased to 20%, the system is optimised to include a battery storage capacity of 248 kWh, which results in 34% excess electricity and a 9% unmet load. This configuration further reduces the LCOE to $0.126. Notably, this

Table 15. Electrical performance of standalone PV/storage with 10% ACS.

Metric	Energy (kWh/yr)	%
Generic flat plate PV production	490,345	100
AC primary load	239,045	100
Excess electricity	229,617	46.8
Unmet Electric load	12,075	4.81
ACS	25,178	10
RF (%)	100	
Total NPC ($)	637,126	
LCOE ($)	0.152	
O&M ($)	17,105	

adjustment reflects the daily load patterns at CEET, where most energy demand occurs during daylight hours, indicating the potential for a smaller battery bank without compromising system performance.

Additionally, an analysis was conducted to evaluate the impact of reducing the PV system, converter, and battery costs by up to 25%. This adjustment resulted in a significant decrease in the NPC, which was lowered to $786,483. Consequently, the LCOE also experienced a reduction, falling to $0.181 compared to the base case values of $960,638 and $0.221, respectively. In the second scenario, the ACS was initially set at 10%. Under these parameters, the optimised system configuration comprised 167 kW of PV panels, eight 5.1 kW wind turbines, a 244 kWh battery storage system, and an 81 kW converter. This configuration produced an NPC of $510,000. It reduced the LCOE to $0.12, as detailed in Table 16. In this scenario, the excess energy generation was calculated at 33.7%, a marked improvement from the 49.5% observed in the baseline PV/wind/battery system, with only 3.6% of the load remaining unmet.

Conversely, maintaining the ACS at 10% while applying a 25% reduction in the costs associated with wind turbines, PV panels, batteries, and converters results in a lowered LCOE of $0.097. Among the extensive range of simulated optimisation scenarios, the configuration that yielded the lowest life cycle cost (net present cost, NPC) and LCOE included 150 kW of PV capacity, ten 5.1 kW wind turbines, a 240 kWh battery bank, and a 77 kW converter, as illustrated in Table 17. In this optimised system, the PV array accounts for 67% of the total energy production, with the remaining energy generated by the wind energy conversion system. Under this arrangement, the unmet load is approximately 3.5%.

Figure 10 presents a bar chart illustrating the cash flows associated with the components of the second scenario, factoring in a 25% reduction in costs and a 10% ACS. The storage component costs $140,000 in this hybrid standalone system, constituting approximately 34% of the total system expenditure over the project's lifespan

Table 16. Characteristics of standalone PV/wind/storage with 10% ACS.

Metric	Energy (kWh/yr)	%
Generic flat plate PV production	287,698	74
AWS 5.1kW wind turbine	101,278	26
AC primary load	242,125	100
Excess electricity	131,168	33.7
Unmet Electric load	8995	3.58
ACS	25,270	10.1
RF (%)	100	
Total NPC ($)	509,753	
LCOE ($)	0.12	
O&M ($)	11,994	

Table 17. Optimisation results of scenario 2 under sensitivity costs of different components.

	Architecture				Cost	
Combination	PV (kW)	AWS5.1 kW	1 kWh LA	Converter (kW)	NPC ($)	LCOE ($/kWh)
PV/wind/battery	150	10	240	77	412,421	0.097
PV/battery	273		376	144	517,098	0.124
Wind/battery		33	712	83	802,599	0.195
PV/wind	915	37		98	1.29M	0.302

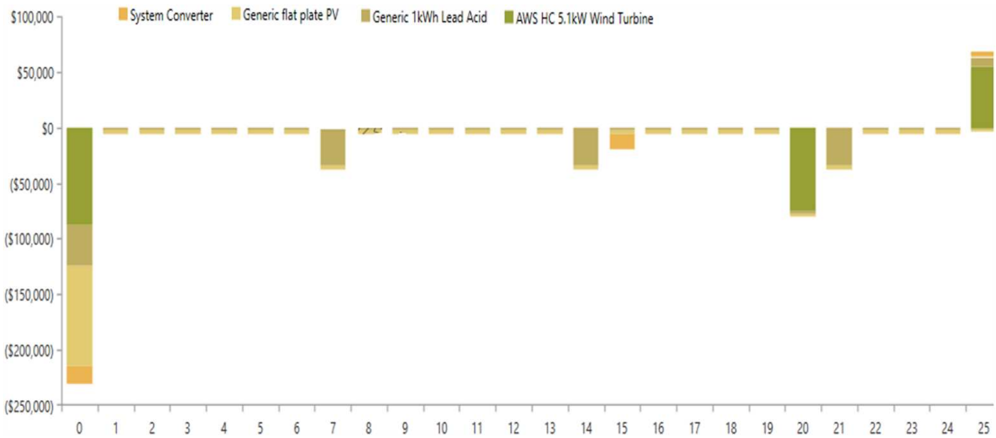

Figure 10. Cash flow by components of the optimal system in Table 13.

($412,421). A reduction in storage capacity is advisable to enhance the system's affordability, particularly given that the load demand for CEET is predominantly concentrated during daytime hours. This scenario demonstrates that the college can achieve a reliable and economically viable energy solution based entirely on renewable sources, with energy costs significantly below 0.10 $/kWh. Notably, the yellow triangle preceding the hybrid PV/wind system without storage, as described in Table 13, suggests potential instability in this configuration, making it an infeasible option.

In the third scenario, the ACS is maintained at 2%, with the cost of the solar system fixed at the original rate of $800 per kW installed. This sensitivity analysis explores the impact of varying grid electricity tariffs, specifically examining the implications of unsubsidised fossil electricity pricing. The simulated grid electricity tariffs range from the base case to 0.15 $/kWh. As illustrated in Table 18, an increase in the percentage of subsidy removal correlates with a greater allowance for solar energy penetration. The grid electricity purchase price of 0.10 $/kWh emerges as the most advantageous scenario. Under these conditions, the optimal configuration consists of a 157 kW on-grid PV system paired with a 114 kW converter, resulting in an LCOE of 0.04 $/kWh. This arrangement facilitates RE penetration of approximately 78%, as detailed in Table 19. With an RF of 82%, a grid-connected hybrid renewable system powering a higher educational campus in Indonesia achieved an LCOE of 0.045 $/kWh (Riayatsyah, Geumpana, Fattah, Rizal, et al. 2022), validating the outcome of this study.

Figure 11 presents the average monthly energy production for the optimised grid-connected solar system. The analysis reveals a notable increase in clean energy generation

Table 18. Sensitivity analysis for scenario 3 under unsubsidised tariffs for grid electricity.

Sensitivity	Architecture			Cost				System
Power price ($/kWh)	PV (kW)	Grid (kW)	Converter (kW)	NPC ($)	LCOE ($/kWh)	O&M ($/yr)	CAP ($)	RF (%)
0.024	32.3	999,999	21.4	130,061	0.029	5605	31,823	20.2
0.05	32.3	999,999	23.2	221,168	0.050	10,774	32,321	20.6
0.1	157	999,999	114	225,385	0.039	3859	157,739	78.4
0.15	157	999,999	114	225,385	0.039	3859	157,739	78.4

Table 19. Electrical characteristics of scenario 3 under the unsubsidised grid tariff of $0.1.

Metric	Energy (kWh/yr)		%
Generic flat plate PV production	270,822		79.5
Grid purchases	69,806		20.5
AC primary load	251,120		77.9
Grid sales	71,331		22.1
Excess electricity	4880		1.43
Unmet Electric load	0		0
ACS	0		0
RF (%)		78.4	
Total NPC ($)		225,385	
LCOE ($)		0.039	
O&M ($)		3859	

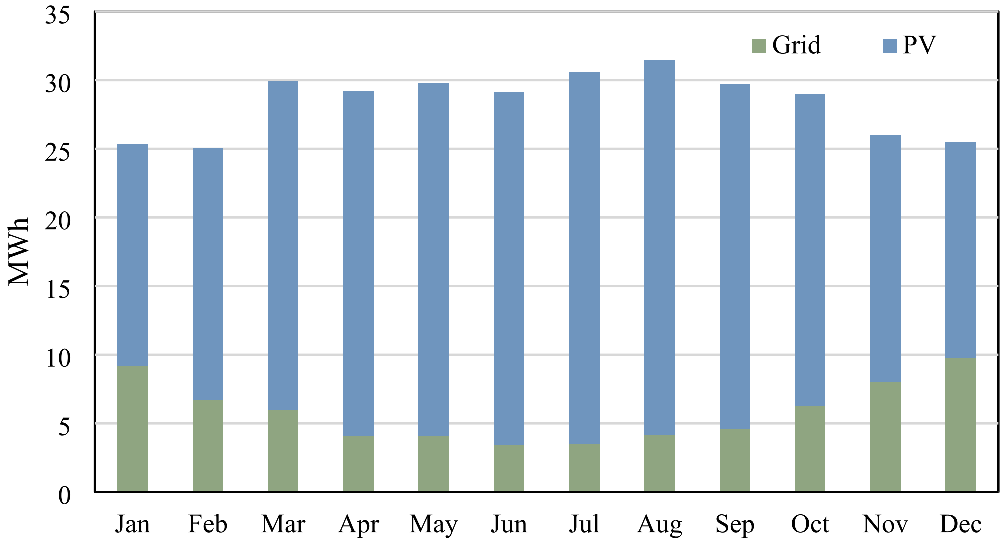

Figure 11. Energy production by source in scenario 3 at $0.1 grid price.

during the summer months, particularly in July and August, aligning with the academic calendar's summer holiday period. This seasonal peak in solar energy production is critical, as it corresponds to reduced energy demand from educational facilities, thereby maximising the utilisation of generated energy. By implementing an energy sale policy, the solar system is projected to contribute approximately 71.3 MWh of RE to the grid annually. This contribution is compensated at 0.05 $/kWh, effectively creating a financial incentive to adopt solar technologies. This grid-connected solar system's optimisation enhances the institution's energy self-sufficiency and facilitates a more resilient energy framework. Achieving an RF of 78.4% is pivotal in reducing the institution's carbon footprint. The system's operation significantly lowers CO_2 emissions to 960 kg a year, a marked decrease from the base case scenario, which reported emissions of 126,680 kg with only a 20.2% RE penetration. This reduction underscores the environmental benefits of transitioning to RE sources and highlights the potential for institutions to contribute to broader sustainability goals.

Furthermore, Figure 12 illustrates the hourly distribution of solar penetration throughout the year. The data show high fluctuations in renewable penetration, which

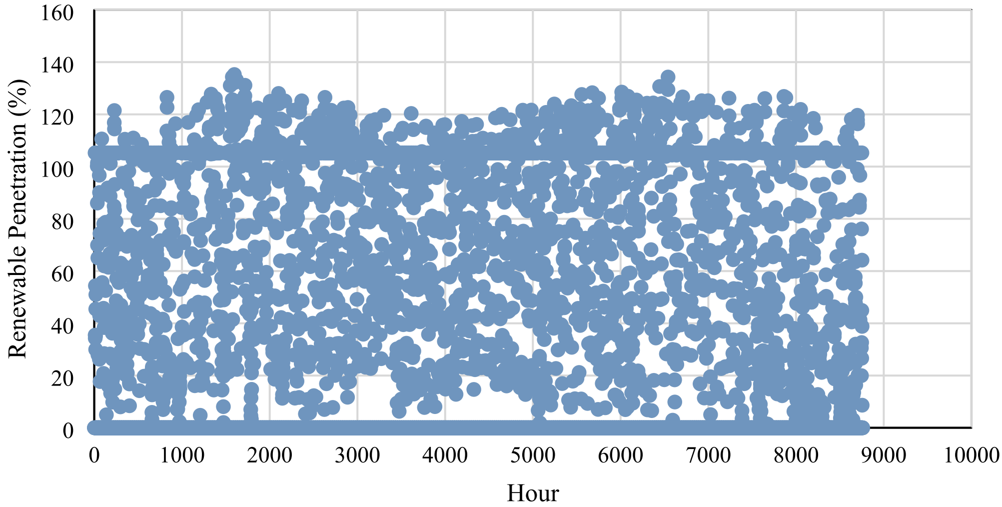

Figure 12. Renewable penetration on an hourly basis for scenario 3 at $0.1 grid price.

correlate with variations in solar irradiance and energy consumption patterns. The maximum penetration observed was at 135%, while on average, the renewable penetration was at a margin of 42% throughout the year. It is worth mentioning that when the renewable penetration exceeds 100%, it is a favourable time for the college to sell its clean energy back to the grid.

A comprehensive sensitivity analysis assessed the impacts of varying grid electricity tariffs and diesel fuel prices in the fourth scenario. The grid tariffs analysed were set at 0.05 and 0.10 $/kWh, while the diesel fuel prices were adjusted to multiple levels, specifically 0.25, 0.50, 0.75, and 1.00 $/l, following the removal of subsidies. The results of this analysis, illustrated in Table 20, demonstrate a direct correlation between increased fuel and grid electricity prices and the resultant NPC and LCOE. As the prices rise, both NPC and LCOE exhibit an upward trend, highlighting a growing economic incentive for transitioning to RE sources; for instance, under conditions where the grid electricity price is set at 0.10 $/kWh and the diesel fuel price at 0.50 $/l, the LCOE is calculated to be approximately 0.11 $/kWh. This rate represents a substantial increase of 267% compared to the baseline established in the fourth scenario. This sensitivity analysis underscores the significance of external economic factors in shaping the viability of RE solutions. By

Table 20. Sensitivity cases for scenario 4 with different grids and fuel prices.

Sensitivity		Architecture		Cost			
Power price ($/kWh)	Diesel fuel ($/l)	Perkins genset (kW)	Grid (kW)	NPC ($)	LCOE ($/kWh)	O&M ($/yr)	CAP ($)
0.05	0.25	50	999,999	255,949	0.058	13,832	13,500
0.1	0.25	50	999,999	459,747	0.104	25,459	13,500
0.05	0.5	50	999,999	267,462	0.061	14,489	13,500
0.1	0.5	50	999,999	481,856	0.109	26,721	13,500
0.05	0.75	50	999,999	278,976	0.063	15,146	13,500
0.1	0.75	50	999,999	493,370	0.112	27,378	13,500
0.05	1.00	50	999,999	290,489	0.066	15,803	13,500
0.1	1.00	50	999,999	504,883	0.115	28,034	13,500

illustrating the financial implications of fluctuating fuel and grid prices, this methodology emphasises the importance of policy decisions regarding energy pricing and subsidies, which can influence the overall attractiveness and priority of RE investments. Future studies may build upon this analysis by exploring additional variables, such as carbon pricing and technological advancements in RE and storage systems, to further evaluate their impact on the economic feasibility of sustainable energy solutions.

5. Conclusions

This study addresses the critical challenge of unreliable energy supply for essential facilities in Libya, adopting the College of Electrical and Electronics Technology in Benghazi as a case study. The research explores optimal energy supply solutions by evaluating various options under the current subsidised and projected unsubsidised energy prices, including fossil fuel and RE sources. Four distinct scenarios were analysed: the first scenario involved a standalone PV and battery storage system isolated from the grid; the second added wind turbines to the first scenario. The first two options would enable the college to form an autonomous microgrid with renewable electricity generation. The third alternative examined a grid-connected solar system without storage, while the fourth assessed a hybrid system combining grid and diesel generator sources. The findings indicate that scenarios three and four emerged as the most viable options under the current governmental subsidies for fuel and fossil electricity, with scenario three being preferable regarding sustainability and environmental impact. The optimal configuration identified consists of a solar system with a capacity of 32.3 kW and a converter rated at 21.4 kW, achieving a renewable fraction of 20.2%. The winning on-grid solar system yields an LCOE of 0.029 $/kWh.

Conversely, the autonomous renewable-based energy systems revealed significant challenges at present. The standalone PV and battery storage system was projected to generate electricity at approximately 0.22 $/kWh. The generated electricity from the hybrid PV/wind/storage system was estimated at 0.16 $/kWh. Nonetheless, the economic competitiveness of the standalone hybrid renewable system can be improved by increasing the allowable capacity shortage, a marginal increase in unmet load, thereby reducing the required storage capacity. This adjustment is practical because most of the college's energy consumption occurs during daytime hours. On the other hand, eliminating governmental subsidies on diesel fuel and fossil electricity would significantly enhance the attractiveness and competitiveness of RE options. For instance, increasing the grid electricity and diesel fuel prices to 0.10 $/kWh and 1.00 $/l would generate an electricity cost of around 0.12 $/kWh. This pricing aligns with the attainment of a hybrid solar/wind/storage system with a 10% capacity shortage, which includes 167 kW of PV panels, eight 5.1 kW turbines, 244 kWh of storage, and an 81 kW converter, yielding a cost of 0.12 $/kWh.

The results also demonstrated that excess electricity is a critical index influencing the viability of standalone RE systems. With a minimum annual capacity shortage of 2%, the off-grid PV/battery produced an excess electricity of 67%, while the autonomous hybrid PV/wind/storage system produced about 50%. This wasteful excess electricity no doubt hinders the choice of such independent energy systems due mainly to the energy cost and the absence of further utilisation of surplus electricity. However, the surplus excess electricity can be reduced by increasing the maximum allowable annual capacity shortage. When the maximum yearly capacity shortage is set to 10% instead, the excess electricity generation is reduced to 46.8% and 33.7% in the first and second scenarios, respectively. Additionally, considering foreseen scenarios such as subsidy removal, economies of scale of global RE projects, and further advancements of energy storage technologies would intensify the adoption of renewable installations. These findings highlight the importance of policy frameworks and pricing structures in facilitating the transition to sustainable energy solutions in Libya and similar contexts. Future research should continue to explore innovative strategies for enhancing the practicality of other RE alternatives in regions characterised by energy supply instability. With the employment of dynamic variation of load demand, critical assessment of various optimisation algorithms for minimisation/elimination of excess electricity produced from fully RE systems is another interesting area of research.

Authors' contributions

Conceptualisation, F.A., M.A and W.H; methodology, M.A, F.A and W.H; software, M.A and F.A; validation, M.A and F.A; formal analysis, F.A., M.A and W.H; investigation, F.A. and M.A; resources, F.A., M.A and W.H; data curation, F.A., M.A and W.H; writing – original draft preparation, F.A. and M.A; writing – review and editing, F.A., M.A and W.H; visualisation, F.A., M.A and W.H; supervision, F.A., M.A and W.H; project administration, F.A and M.A. All authors have read and agreed to the published version of the manuscript.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Availability of data and materials

The derived data supporting this study's findings are available from the corresponding author upon request.

Consent of publication

The authors guarantee that this manuscript has not been previously published in other journals and is not under consideration.

References

Abdulgalil, A., M. Khalid, and F. Alismail. 2019. "Optimal Sizing of Battery Energy Storage for a Grid-Connected Microgrid Subjected to Wind Uncertainties." *Energies* 12:2412.

Adetoro, S. A., L. Olatomiwa, J. Tsado, and S. M. Dauda. 2023. "Techno-economic and Environmental Impact Assessment of a Hybrid Renewable Energy System Employing an Enhanced Combined Dispatch Strategy." *Green Energy and Resources* 1 (4): 100044. https://doi.org/10.1016/j.gerr.2023.100044.

Akroot, A., M. Almaktar, and F. Alasali. 2024. “The Integration of Renewable Energy Into a Fossil Fuel Power Generation System in Oil-Producing Countries: A Case Study of an Integrated Solar Combined Cycle at the Sarir Power Plant.” *Sustainability* 16 (11): 4820. https://doi.org/10.3390/su16114820.

Al-Odat, M., M. Al-Hasan, F. Obeidat, and A. J. Chamkha. 2024. “Optimization of ON-Grid Hybrid PV/Wind System for a Cement Factory in Kuwait Using HOMER pro Software.” *International Journal of Low-Carbon Technologies* 19:120–126. https://doi.org/10.1093/ijlct/ctad117.

Al-Shetwi, A., M. Sujod, A. Tarabsheh, and I. Altawil. 2016. “Design and Economic Evaluation of Electrification of Small Villages in Rural Area in Yemen Using Stand-Alone PV System.” *International Journal of Renewable Energy Research* 6:289–298.

Alasali, F., A. Saidi, N. El-Naily, O. Alsmadi, M. Khaleel, and I. Ghirani. 2023. “Assessment of the Impact of a 10-MW Grid-Tied Solar System on the Libyan Grid in Terms of the Power-Protection System Stability.” *Clean Energy* 7 (2): 389–407. https://doi.org/10.1093/ce/zkac084.

Alasali, F., M. Salameh, A. Semrin, K. Nusair, N. El-Naily, and W. Holderbaum. 2022. “Optimal Controllers and Configurations of 100% PV and Energy Storage Systems for a Microgrid: The Case Study of a Small Town in Jordan.” *Sustainability* 14 (13): 8124. https://doi.org/10.3390/su14138124.

Albarsha, A., M. Almaktar, and I. Saehi. 2024. “Optimization of Solar Energy System Integration for a Sustainable Healthcare Facility.” In *2024 IEEE 12th International Conference on Smart Energy Grid Engineering (SEGE)*, 211–215. Oshawa, ON, Canada: IEEE. https://doi.org/10.1109/SEGE62220.2024.10739491.

Al Garni, H., A. Kassem, A. Awasthi, D. Komljenovic, and K. Al-Haddad. 2016. “A Multicriteria Decision Making Approach for Evaluating Renewable Power Generation Sources in Saudi Arabia.” *Sustainable Energy Technologies and Assessments* 16:137–150.

Alkar, K. 2021. “Assessment of Power Plants in the Western Region of Libya During a Period of Insecurity.” *Smart Metering Technologies Intech Open*. https://doi.org/10.5772/intechopen.97208.

Almaktar, M. 2018. “Towards an Extensive Exploitation of Solar PV Technology in Libya: Legislative, Economic and Environmental Considerations.” *Libyan Journal of Science & Technology* 7 (2): 103–113. https://doi.org/10.37376/ljst.v7i2.2289.

Almaktar, M., A. M. Elbreki, and M. Shaaban. 2021. “Revitalizing Operational Reliability of the Electrical Energy System in Libya: Feasibility Analysis of Solar Generation in Local Communities.” *Journal of Cleaner Production* 10 (279): 123647. https://doi.org/10.1016/j.jclepro.2020.123647.

Almaktar, M., and M. Shaaban. 2021. “Prospects of Renewable Energy as a Non-Rivalry Energy Alternative in Libya.” *Renewable and Sustainable Energy Reviews* 1 (143): 110852. https://doi.org/10.1016/j.rser.2021.110852.

Alsaidan, I., A. Khodaei, and W. Gao. 2016, July 17–21. “Determination of Battery Energy Storage Technology and Size for Standalone Microgrids.” In *Proceedings of the 2016 IEEE Power and Energy Society General Meeting (PESGM)*, 1–5. IEEE: Boston, MA, USA.

Alwehesh, S., A. Abdelali, Z. Rajab, and A. Khalil. 2019, March 26–28. “Photovoltaic Solar Energy Applications in Libya: A Survey.” In *10th International Renewable Energy Congress (IREC)*, 1–6. IEEE: Sousse, Tunisia. https://doi.org/10.1109/IREC.2019.8754527.

Alzahrani, A. 2023. “Energy Management and Optimization of a Standalone Renewable Energy System in Rural Areas of the Najran Province.” *Sustainability* 15 (10): 8020. https://doi.org/10.3390/su15108020.

Araoye, T. O., E. C. Ashigwuike, M. J. Mbunwe, O. I. Bakinson, and T. I. Ozue. 2024. “Techno-Economic Modeling and Optimal Sizing of Autonomous Hybrid Microgrid Renewable Energy System for Rural Electrification Sustainability Using HOMER and Grasshopper Optimization Algorithm.” *Renewable Energy* 229:120712. https://doi.org/10.1016/j.renene.2024.120712.

Bhuiyan, A., A. Yazdani, and L. Primak. 2015. “Optimal Sizing Approach for Islanded Microgrids.” *IET Renewable Power Generation* 9:166–175.

Butturi, M. A., F. Lolli, M. A. Sellitto, E. Balugani, R. Gamberini, and B. Rimini. 2019. "Renewable Energy in Eco-Industrial Parks and Urban-Industrial Symbiosis: A Literature Review and a Conceptual Synthesis." *Applied Energy* 255:113825.

Chen, H. C. 2013. "Optimum Capacity Determination of Stand-Alone Hybrid Generation System considering Cost and Reliability." *Applied Energy* 103:155–164.

Chen, T., M. Wang, and R. Babaei. 2023. "Technoeconomic Analysis and Optimization of Hybrid Solar Wind-Hydro Diesel Renewable Energy Systems Using Two Dispatch Strategies." *International Journal of Photoenergy* 2023:3101876. https://doi.org/10.1155/2023/3101876.

Elwalaty, M., and S. Sow. 2025. "Enhancing Rural Electrification in Mauritania through Hybrid Energy Solutions: A Techno-Economic Analysis Using HOMER Software." *Journal of Power and Energy Engineering* 13:1–15. https://doi.org/10.4236/jpee.2025.133001.

Embirsh, H., and Y. Ikshadah. 2017. "Future of Solar Energy in Libya." *International Journal of Scientific and Research Publications* 7:33–35.

Guwaeder, A., and R. Ramakumar. 2017. "A Study of Grid-Connected Photovoltaics in the Libyan Power System." *Energy and Power* 7:41–49.

The HOMER Pro® microgrid software by UL Solutions. 2024. https://homerenergy.com/products/pro/index.html.

Ibrik, I. 2020. "Micro-Grid Solar Photovoltaic Systems for Rural Development and Sustainable Agriculture in Palestine." *Agronomy* 10:1474.

Koholé, Y. W., F. C. Fohagui, C. A. Ngouleu, and G. Tchuen. 2024. "An Effective Sizing and Sensitivity Analysis of a Hybrid Renewable Energy System for Household, Multi-Media and Rural Healthcare Centres Power Supply: A Case Study of Kaele, Cameroon." *International Journal of Hydrogen Energy* 2 (49): 1321–1359. https://doi.org/10.1016/j.ijhydene.2023.09.093.

Krishan, O. 2018, December 10–12. "Optimum Sizing and Techno-Economic Analysis of Grid-Independent PV System under Different Tracking Systems." In *Proceedings of the 2018 IEEE 8th Power India International Conference (PIICON)*, 1–6. IEEE: Kurukshetra, India.

Lachheb, A., R. Marouani, C. Mahamat, S. Skouri, and S. Bouadila. 2024. "Fostering Sustainability through the Integration of Renewable Energy in an Agricultural Hydroponic Greenhouse." *Engineering, Technology & Applied Science Research* 14 (2): 13398–13407. https://doi.org/10.48084/etasr.6939.

Lachheb, A., S. Skouri, R. Ayed, S. Bekkouche, and S. Bouadila. 2024. "Harvesting Sustainability: Vertical Agricultural Greenhouses Powered by Renewable Energy Technologies." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* 46 (1): 4688–4703. https://doi.org/10.1080/15567036.2024.2329814.

Mbasso, W. F., S. R. D. Naoussi, R. J. J. Molu, K. T. Saatong, and S. Kamel. 2023. "Technical Assessment of a Stand-Alone Hybrid Renewable System for Energy and Oxygen Optimal Production for Fishes Farming in a Residential Building Using HOMER Pro." *Cleaner Engineering and Technology* 17:100688. https://doi.org/10.1016/j.clet.2023.100688.

Ministry of Planning. 2023. "National Strategy for Renewable Energy & Energy Efficiency Libya 2023–2035." Accessed April 4, 2025. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://reaol.ly/wp-content/uploads/2024/04/NSREEE_23_35_REAOL_EN.pdf.

Mohamed, A., A. Al-Habaibeh, and H. Abdo. 2013. "An Investigation Into the Current Utilisation and Prospective of Renewable Energy Resources and Technologies in Libya." *Renewable Energy* 50:732–740.

Naveed, A., S. Iqbal, S. Munir, A. U. Rehman, M. Eslami, and S. Kamel. 2024. "Renewable Energy Integration in Healthcare Systems: A Case Study of a Hospital in Azad Jammu and Kashmir." *IET Renewable Power Generation* 18 (5): 796–809. https://doi.org/10.1049/rpg2.12946.

Nurmalasari, R., and P. Puspitasari. 2024. Variety of Agricultural Machine Innovations by Utilizing Renewable Energy. In *Advanced Materials towards Energy Sustainability*, 37–61. CRC Press.

Oubouch, N., A. Redouane, A. Makhoukh, and A. El Hasnaoui. 2024. "Optimization and Design to Catalyze Sustainable Energy in Morocco's Eastern Sahara: A Hybrid Energy System of PV/Wind/PHS for Rural Electrification." *Cleaner Energy Systems* 9:100141. https://doi.org/10.1016/j.cles.2024.100141.

Rahman, A. 2024. "Assessing the Role of Renewable Energy Integration in Modern Healthcare Settings: Strategies for Reducing Dependency on Non-Renewable Sources and Enhancing Energy Resilience." *Journal of Sustainable Urban Futures* 14 (5): 1–10.

Riayatsyah, T. M. I., T. A. Geumpana, I. M. R. Fattah, and T. M. I. Mahlia. 2022. "Techno-Economic Analysis of Hybrid Diesel Generators and Renewable Energy for a Remote Island in the Indian Ocean Using HOMER Pro." *Sustainability* 14 (16): 9846. https://doi.org/10.3390/su14169846.

Riayatsyah, T. M. I., T. A. Geumpana, I. M. R. Fattah, S. Rizal, and T. I. Mahlia. 2022. "Techno-Economic Analysis and Optimisation of Campus Grid-Connected Hybrid Renewable Energy System Using HOMER Grid." *Sustainability* 14 (13): 7735. https://doi.org/10.3390/su14137735.

Slathia, P., A. Vashishtha, P. K. Jena, and P. K. Sahu. 2024. "Examining the Dynamic Impact of Carbon Emissions, Renewable Energy and Economic Growth on Healthcare Expenditure in Asian Countries." *Heliyon* 10 (9): e30136. https://doi.org/10.1016/j.heliyon.2024.e30136.

Thirunavukkarasu, M., and Y. Sawle. 2020. "Design, Analysis and Optimal Sizing of Standalone PV/Diesel/Battery Hybrid Energy System Using HOMER." *IOP Conference Series: Materials Science and Engineering* 937 (1): 012034. https://doi.org/10.1088/1757–899X/937/1/012034.

Yadav, S., P. Kumar, and A. Kumar. 2024. "Techno-Economic Assessment of Hybrid Renewable Energy System with Multi Energy Storage System Using HOMER." *Energy* 297:131231. https://doi.org/10.1016/j.energy.2024.131231.

Zakari, A., M. Oluwaseyi, and H. Musibau. 2024. "Sustainable Economic Development in OECD Countries: Does Energy Security Matter?" *Sustainable Development* 32 (1): 1337–1353. https://doi.org/10.1002/sd.2668.

Zhang, G., C. Xiao, and N. Razmjooy. 2022. "Optimal Operational Strategy of Hybrid PV/Wind Renewable Energy System Using Homer: A Case Study." *International Journal of Ambient Energy* 43 (1): 3953–3966. doi: 10.1080/01430750.2020.1861087.

Zhao, B., X. Zhang, P. Li, K. Wang, M. Xue, and C. Wang. 2014. "Optimal Sizing, Operating Strategy and Operational Experience of a Stand-Alone Microgrid on Dongfushan Island." *Applied Energy* 113:1656–1666.