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Renewable-Energy-Based Microgrid Design and Feasibility Analysis for King Saud University Campus, Riyadh

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Abstract: The world is forced to think about alternate energy sources because fossil fuel stocks are unreliable, harmful, and depleting quickly. Deployments of microgrids powered by renewable energy are some of the most economical, effective, dependable, and sustainable answers to this problem. The design of a power system with the least amount of economic and environmental impact is the main challenge because the world is currently facing climate change disasters on a scale that has never been seen before. As a result, there is an urgent need to transition to renewable energy resources to meet energy demands. This study examines the creation of a hybrid microgrid to meet the electrical load requirements of the King Saud University campus in Riyadh by utilizing the site's solar and wind potential. A software called HOMER Pro Version 3.14.5 is used to simulate the planned microgrid system. The software can run numerous simulations while taking into account various system configurations. The ultimate objective is to choose the best combination of different power sources to create a microgrid with low energy costs, dependability, minimal GHG emissions, and a high penetration of renewable energy. The solar, wind, and battery system connected to the grid was shown to be the most advantageous choice in terms of cost of energy (COE), net present cost (NPC), operational costs, and GHG emissions after the software ran numerous simulations. The most economically advantageous way to meet the load demands of a university campus while still achieving more than 82% renewable penetration is to use an optimal system architecture. In this study, the ideal system configuration is subjected to sensitivity analysis to confirm the system's performance. This optimal system design is used as a benchmark for examining the potential usage of renewable energy in the education sector in Saudi Arabia in particular and in any educational facility worldwide in general.

Keywords: microgrid; optimum design; wind; solar; battery; grid

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1. Introduction

Global greenhouse gas (GHG) emissions have risen dramatically as a result of the exponential increase in the demand for energy and the use of conventional energy resources. Using renewable energy sources such as solar, wind, and hydropower or a combination of conventional and renewable energy sources is the most effective strategy to address this issue. These hybrid energy systems will not only meet our energy needs but also reduce greenhouse gas emissions and advance the worldwide environmental conservation movement.

Microgrids are majorly designed for supplying electricity to the load demands of a specific infrastructure, such as the residential, commercial, and industrial sectors. The design of a microgrid is heavily dependent upon the local environment and electricity demand conditions [1–3]. The environmental conditions aid in the selection of appropriate renewable energy resources, such as solar, wind, biomass, and hydro, whereas the energy demand affects the selection of the standalone or grid-connected operation of the microgrid as well as the size selection of the energy resources.

A standalone microgrid powered by locally available renewable energy resources may be a preferable option for decentralized and remote power distribution. Such activities, however, are problematic because of the stochastic nature of solar and wind energy resources [4], which may produce significant uncertainty in a standalone microgrid. Power system reliability has always been a crucial challenge for a standalone renewable microgrid due to the significant variance in both power usage and power output [5]. Furthermore, frequency and voltage fluctuations can occur as a result of rapid and unexpected changes in power consumption in the distribution system, resulting in system instability [6,7].

Grid-connected microgrid structures are preferred for those locations that are present in the developed region and where the grid infrastructure is easily available with the lowest grid power prices. This microgrid configuration does not only compensate for the local energy demands without any major power quality issues but can also sell any excess energy generated from the renewable energy resources to the grid [8,9]. This system design configuration has much lower energy generation and transportation costs as it readily utilizes the grid infrastructure. The capital cost of the system is also much lower than the standalone system as the size of renewable energy components is small, and less storage backup is required.

The utilization of solely renewable energy resources for energy generation is a better option for most locations in the world; however, the high costs of renewable systems make this option less suitable for places such as the Middle East, where fuel prices are much lower than in other areas and where the use of hybrid systems is a very viable option [10]. However, global warming has generated a considerable increase in temperature throughout the years, altering global climatic conditions. Climate change has brought new difficulties in the form of torrential rains, flooding, and cyclones around the world, particularly in the nations most exposed to rapid climatic changes. To combat global warming, a rapid transition to renewable energy generation is the main goal at the global level. Therefore, the primary research objective of most global renewable-energy-based research studies is how to develop a power system that is more robust, clean, and dependable. Therefore, this paper, we propose a renewable-energy-based microgrid to supply the King Saud University campus, Riyadh, which is expected to reduce the cost of the supply of electricity to the university community.

The rest of this paper is divided into different sections. Each section explains a different aspect of the research work. The literature review is presented in Section 2. Section 3 describes the site selected for the research study as well as the load and system performance assessment criteria. Section 4 describes the existing system characteristics. The renewable energy potential of both the study location and Saudi Arabia is presented in Sections 4 and 5, respectively. Section 6 discusses the system performance criteria, Section 7 explains the existing system, and proposed microgrid proposed in this paper is presented in Section 8. The system model is provided in Section 9. In the same way, the economic and emission comparisons of different design options are presented in Sections 10 and 11, respectively. Sections 12 and 13 provide the sensitivity analysis and a comparison of this research with other existing papers respectively, and a conclusion as to the optimal system configuration is also provided in Section 13 in Saudi Arabia.

2. Literature Review

This section investigates the previous and recent literature related to the optimum design of microgrids across the globe. Drawbacks and shortcomings and the differences between them and this paper are also outlined. Furthermore, since the microgrid is site-specific, it is clear that there is no study of this type of microgrid in the proposed study area. In addition, this section identifies the novelty of the proposed system design method and a sensitivity study of various system parameters.

Given the above, many efforts have been made in the literature toward the optimum design of renewable energy microgrids across the globe. Such efforts include the works presented by the authors of [11–13]. These studies investigate the potential for renewable energy to mitigate the impacts of carbon dioxide emissions on the socio-economic development of the world's main consumer market [1–3]. The findings support that carbon dioxide emissions have undeniably negative consequences for economic growth and human prosperity, and the overall implications of the relationship between sustainable energy and CO_2 emissions on human socioeconomic development are detrimental [14–17]. There is a need to work on the development and deployment of renewable energy generation over a considerable portion of every state to achieve the global objectives of green energy generation.

The possibility of installing a PV hybrid-energy microgrid at a new industrial city in Jeddah was presented in [18]. The optimum design was developed in HOMER software Version 3.13. In this design, the best system configuration was determined considering the original cost, ongoing cost, cost per unit, and total system net present value (NPV). However, the design ignored the environmental aspect of the proposed system. In the same country, the authors of [19] designed a microgrid for the Yinbu region of the Kingdom. The design objective was the economic development of a microgrid for the region, and the study considered the NPC, the levelized cost of energy (LCOE), and technical variables such as the availability index and loss of power supply probability (LPSP). In another development, HOMER software Version 3.13 was used in the design of a hybrid microgrid for a rural community in India, as presented in [20]. The research showed that it would be more economical if solar energy was the primary source of power for the site under consideration. Other factors used in this design included the load demand, derating factors, and the lifetime of the project. Similarly, this design ignored the environmental issues.

Recently, mixed-integer programming was used to design a hybrid renewable energy microgrid by considering the aging of the battery storage. In the same design, the use of a superconductor offered the possibility of reducing battery storage degradation. The proposed model was tested in some special loads in Columbia. The advantage of using the degradation factor was presented in the design, and the result showed that neglecting the battery degradation factor could overestimate the system energy, not the supply. This could affect the system benefit, as shown in [21]. In [22], the Internet of Things was used in conjunction with adaptive optimization and control for the optimum utilization of energy by residential appliances. The proposed method showed the benefit to all prosumers with the aid of real-time monitoring and controller design. Furthermore, the model has a self-healing ability and the possibility of improving the battery life. However, if more sources are introduced, the model might not be optimum.

Furthermore, three stages were proposed for the optimal sizing of network microgrids, considering resilience factors in resilience constraints [23]. The stages used in the optimum design were the power between the upstream and network microgrids and the upstream part of the network. The second part was the implementation of decisions in state one, and the last phase was the resynchronization of the unintentional island of the microgrid. The proposed optimization problem might not be optimum when other sources are added; furthermore, sensitivity analyses could have been carried out on other system parameters.

Several research studies have examined the design of microgrid systems for certain locations/buildings, such as university campuses, structures, and particular areas. One such research study is [24], which involved feasibility studies for the creation of a microgrid for the King Abdullah campus of the Azad Jammu and Kashmir University in Pakistan. Solar energy was incorporated into the architecture as a hybrid microgrid framework. According to the study's findings, the suggested hybrid microgrid system, which uses solar energy as its green energy source, can provide the required load demand while achieving the lowest cost of energy (COE) and being the most effective and dependable. Moreover, the authors of [25] thought about designing a hybrid microgrid for Eskisehir Osmangazi University with a diesel generator, grid, and other components.

Similarly, one study [26] conducted a feasibility study for the design of a hybrid microgrid for Assiut University, utilizing HOMER software with a main focus on PV system sizing and considering centralized and decentralized load demands. This approach was adopted to decrease the overall system finances while assuring reliability and efficient performance. It was concluded that the system performance is better when the centralized load demand configuration is selected for the microgrid design. In addition, a solar, grid, and battery microgrid was designed for Abdelmalek Essaâdi University in Morocco [27]. The authors concluded that the proposed system configuration was capable of compensating for the energy load demands with a COE as low as 0.187 USD/kWh, with solar PV as the highest energy contributor.

A techno-economic analysis of a microgrid on the campus of Madinah University was proposed in [28]. The authors analyzed PV and wind energy and their combination as three different configurations for selecting the solution with the lowest economic and environmental footprint. The findings from the research concluded that for current load requirements and design constraints, the PV system could provide a lower COE of around 0.051 USD/kWh, with a payback period of 18.6 years, and could be considered an optimal microgrid design configuration. Similarly, a combined heat and power microgrid design for a remote community in Canada was presented in [29]. They considered different approaches to analyzing the system variables and utilized different energy resources for the microgrid design. They concluded that a microgrid structure with solar thermal, wind, hydro, and fuel cells as energy resources was the optimal system configuration, with a COE of around −0.0245 USD/kWh and a reduced diesel consumption of around 71%.

In another development, the authors of [30] considered the design of an optimal microgrid for an urban university campus. Both grid-connected and isolated microgrid configurations were considered for their load demand compensations by considering solar power, wind and batteries, and energy resources. Eventually, the researchers concluded that the grid-connected configuration can reduce the COE by half when compared to the islanded model and is more suitable for the current load conditions. However, the proposed method could be more complicated to apply when introducing more resources into the design. In a similar development, the authors of [31] conducted a techno-economic analysis of a PV, wind, and biomass energy resource-based microgrid for a university campus. This microgrid was also integrated with hybrid energy storage systems to achieve autonomy. It was observed that the proposed system, which used PV, wind, and biomass as energy resources, was capable of providing the required load demands and that the integration of hybrid energy storage systems with this configuration could increase the autonomy of the system by up to 99%. They also concluded that the excess energy generated by the optimal system configuration could be utilized to compensate for the thermal load demands of the campus. Other analyses, such as environmental and other sensitivity studies, were ignored in the design.

Furthermore, the authors of [32] performed a microgrid design and feasibility study for KIIT University, Campus 3. They considered solar and wind as renewable energy resources for designing a microgrid structure for the university campus. A sensitivity analysis was implemented to assess the reliability of the system, and it was concluded that the system configuration using solar and wind as renewable energy resources was the most cost-effective and reliable solution for the microgrid designed. In the same vein, the design of an optimal microgrid structure for another university campus with an unreliable grid connection was investigated in [33]. They proposed a novel methodology based on a genetic algorithm and dynamic programming to optimally size the microgrid components and control the energy flow. They concluded that the proposed microgrid structure, with PV panels and a battery, was the optimal system configuration that provided the lowest economic values while assuring better reliability.

In Saudi Arabia, the authors of [34] developed an optimal microgrid structure for the deployment of renewable energy resources in the Yanbu region of the Kingdom. They evaluated the optimal system design by considering the COE and NPC as the main economic parameters, utilizing the Giza Pyramids Construction (GPC) optimization algorithm. They concluded that the a solar and biomass hybrid microgrid structure was the most optimal solution with the lowest economical values. In the same country, the authors of [35] performed a techno-economic feasibility analysis for a microgrid design for the Baha University building. They developed a microgrid using solar, wind, and a fuel cell as energy resources and analyzed the system's performance under two different optimization algorithms. They concluded that the NPC and COE of the proposed system were very much affected by the initial cost considered for the solar and fuel cell systems, while the cost of the battery had the least effect.

For analyzing and assessing microgrids, numerous computer-aided design approaches are available. HOMER is well-known computer software that is used to effectively build power system models for techno-economic analyses. It also allows for the comparison of various design configurations so that the optimal design configuration may be finalized. HOMER examines a microgrid that may be classified as a standalone or hybrid microgrid in three stages: modeling, optimization, and sensitivity analysis. The HOMER software utilizes all these parameters to assess every possible system design configuration and provides the most optimal techno-economic analysis. Furthermore, the optimum design of a microgrid is site-specific and depends on many factors, such as economic and social factors and system demand, to mention just a few. In addition, the new Sustainable Development Goals (SDGs) 7, 12, and 13 of the United Nations demand measures that combine environmental conservation with economic growth. Additionally, none of the previous works were designed for the university campus under consideration.

This research work is aimed at designing a cost-effective, green, and reliable hybrid microgrid structure for the university campus in Riyadh, Saudi Arabia, by considering the solar and wind energy resources available on the university premises. The renewable energy potential in Saudi Arabia is immense, and the proper utilization of this potential can revolutionize the energy generation sector of Saudi Arabia in general. This research work can be considered a benchmark for assessing the microgrid potential in Saudi Arabian Universities specifically and for any commercial or industrial sector in general. Therefore, this research article explores the potential for renewable energy in Riyadh, Saudi Arabia, to compensate for the energy demands of King Saud University. The main objective of this study is to design a renewable-energy-based microgrid structure that is more economically feasible while also being reliable and energy efficient.

From the above-mentioned literature, it can be seen that the optimum design of a microgrid can be achieved economically or technically. In some cases, it may be a hybrid of the two techniques. Furthermore, these techniques can be categorized as a probabilistic, iterative, or trade-off methods. However, these methods are time-consuming and cause difficulty when performing sensitivity analyses. In addition, it has been established that the optimum design of a renewable energy system is site-specific and depends on many factors. In this case, the use of HOMER software is proposed due to its ability to consider many decision variables. In this design, the software takes the rated power of each unit and battery storage charging and discharging characteristics at each interval. In the same vein, the proposed approach allows for the determination of the emissions into the atmosphere. Given these factors, this paper proposes the use of HOMER software for the optimum design of a microgrid. In addition, it proposes a sensitivity analysis to study the effects of some parameters on the optimum design of the proposed microgrid.

3. Site Description

In this research work, the design of a hybrid microgrid is proposed for King Saud University, which is situated in Riyadh, Saudi Arabia. Riyadh is the capital city as well as the largest city in Saudi Arabia, and King Saud University is the largest university in Saudi Arabia. This university has a vast land area of around 900 hectares and is located at a site that is appropriate for the installation of renewable-energy-based hybrid microgrid structures. The longitude and latitude of King Saud University are 24.7252 N and 42.237 E, as shown in Figure 1.

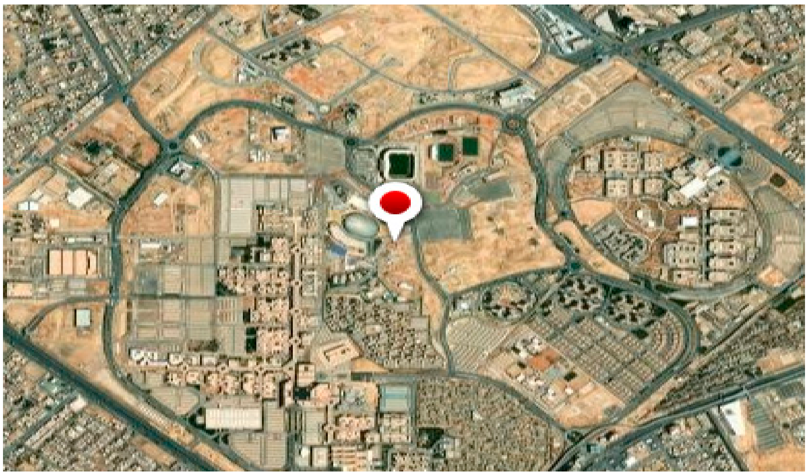


Figure 1. Geographical view of the university campus.

4. Renewable Potential in Saudi Arabia

Saudi Arabia is one of the most abundant countries when it comes to renewable energy resources, specifically solar and wind. The country excessively utilizes its solar and wind potential, and the total production from these renewable energy resources has been increasing exponentially over the last decade. According to the latest report published by Bloomberg New Energy Finance (BNEF), Saudi Arabia is planning to install a total of approximately 9.5 Gigawatts of renewable energy capacity by the year 2023, with a solar PV contribution of around 5.9 GW [36]. The Saudi Arabian government recently revised its Vision 2030 to further increase the planned solar capacity for both the target years of 2023 and 2030, and its planned capacities for the years 2023 and 2030 are around 20 GW and 40 GW, respectively [37]. Due to these goals, the country is working hard on the utilization of its wind energy potential. With the initial wind power plant installation in 2018, the Saudi Arabian government is planning to install around 7 GW of wind energy by the year 2023, thereby creating more than 75,000 jobs and USD 15 billion for Saudi Arab's GDP [38]. Additionally, in the revised vision for 2030, this potential is aimed to increase to 16 GW by the year 2030, as depicted in Figure 2. The transition toward renewables is accompanied by an effort to diversify the economy away from oil and gas, satisfy local demand, and, in the long term, consider exporting renewable energy.

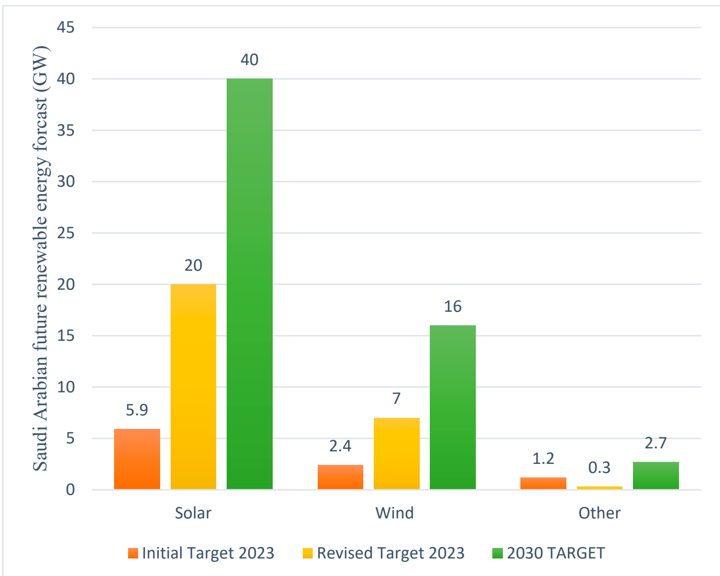


Figure 2. Revised planned renewable capacity from Vision 2030 [37,38].

5. Renewable Energy Potential at the University Campus

The immense potential of renewable energy at the University campus in Riyadh is the key motivation for the development of a hybrid microgrid structure at that particular location. Several renewable energy resources can be analyzed for the development of microgrids, but solar and wind potential are selected in this benchmark study as the two renewable energy resources. These resources are selected for the study due to the availability of wind speed and solar radiation in similar sites in the Kingdom [37,38].

5.1. Solar Potential

The solar energy potential at the university premises was assessed via the NASA database, which is interlinked with the HOMER software. The software showed an average solar irradiance at the university of approximately 5.77 kWh/m^2/day, with peak solar radiation occurring in June at a value of around 7.87 kWh/m^2/day, while the lowest solar potential is found in December, with an irradiance value of around 3.520 kWh/m^2/day. The solar irradiance and the clearness index for the selected site are presented in Figure 3. In addition, to analyze the cleanliness of the atmosphere, the clearness index, which measures the proportion of sunlight that reaches the Earth's surface, was utilized in the design. The solar intensity is lower on cloudy days than it is on bright days. The output power of the solar PV array is obtained using Equation (1) [39,40].

$$P_{PV} = Y_{PV} F_{PV} \left[\frac{\overline{G_T}}{G_{T,STC}} \right] [1 + \alpha_P (T_c - T_{c,STC})] \quad (1)$$

Here, Y_{PV} is the representation of the rated PV array capacity, while F_{PV} is the derating factor of the solar PV array. $\overline{G_T}$ and $G_{T,\,STC}$ represent the incident radiation in the current condition and during standard test conditions, respectively, and α_P, T_c, and $T_{c,\,STC}$ reflect the temperature coefficient, solar cell temperature during current conditions, and the solar cell temperature during standard test conditions, respectively. The installation of solar PV panels on the rooftops of the university building, which comprises different departments and administrative and hostel buildings, is planned. The installed solar capacity is limited because of the limited rooftop space available and is considered to be no more than 1 MW.

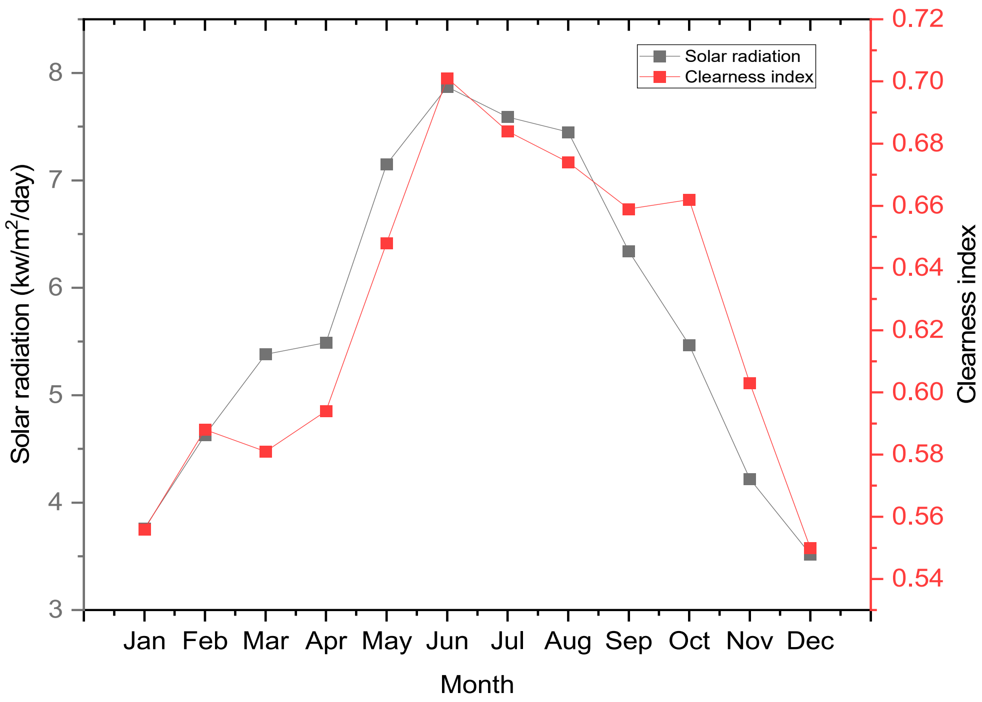


Figure 3. Solar potential of the King Saud University campus.

5.2. Wind Potential and Average Temperature

The annual wind potential at the university premises was again assessed through the NASA database, as presented in Figure 4. It can be seen that the scaled annual average wind speed at the King Saud University campus is around 5.76 m/s. The peak wind potential in July has a value of around 6.440 m/s, whereas the lowest wind potential exists in October, with an average value of around 5.070 m/s. This average value can be used for the generation of electricity on the site. Hence, according to the wind energy potential classifications, the site is suitable for electricity generation using wind resources.

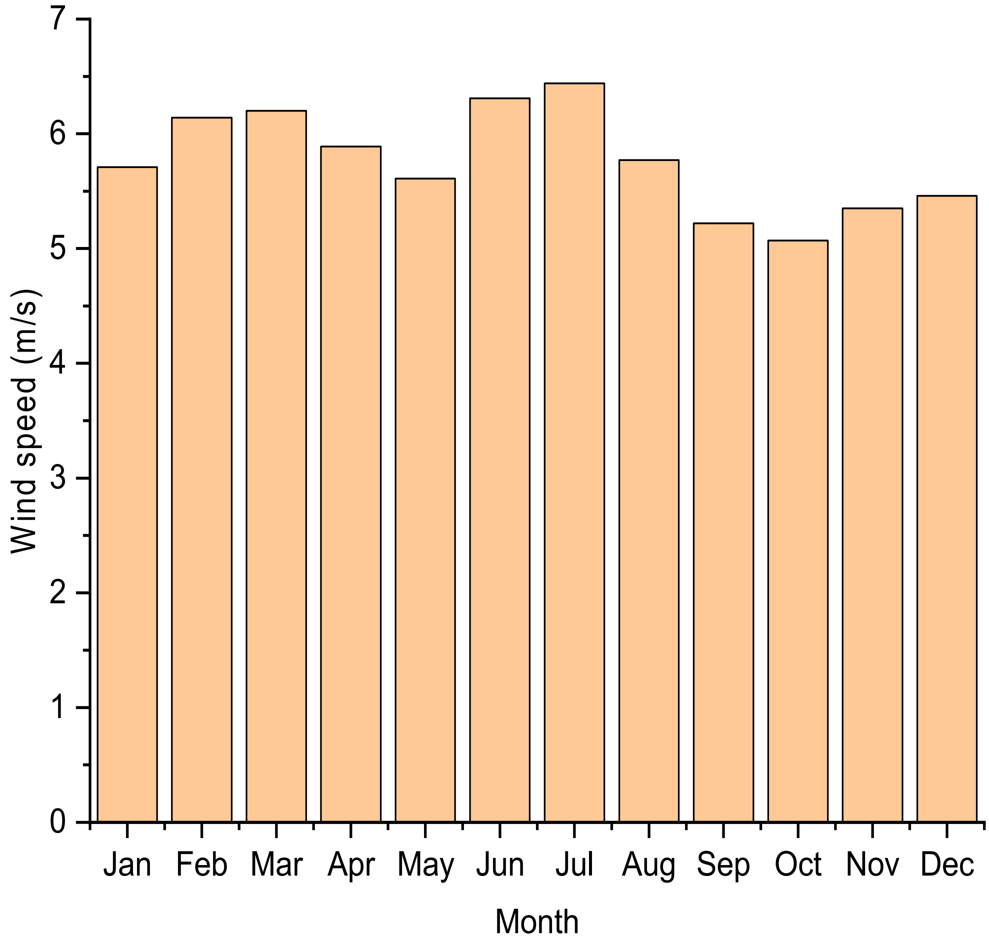


Figure 4. Wind energy potential of the King Saud University campus.

The installation of wind turbines on a wind farm, which must be established first in an area with the least human activity so that the safety of the students and staff is assured, is planned. The electrical energy generated by the wind turbine can be assessed in Equation (2) [40,41].

$$P_{WTG} = \left[\frac{\rho}{\rho_o}\right] P_{WTG,STP} \quad (2)$$

Here, ρ represents the actual air density, while ρ_o represents the air density under standard test conditions, and $P_{WTG,\ STP}$ is the output power of the wind turbine under standard test conditions. This study utilized wind turbines of an average size of 10 kW so that the ground appearance of the wind turbine is kept as low as possible. The annual temperature at the university premises is depicted in Figure 5. The highest temperature at this particular location occurs in July, while the lowest temperature occurs in in January, in the winter season. In the same way, the site is suitable for electricity generation due to the solar energy conversion system.

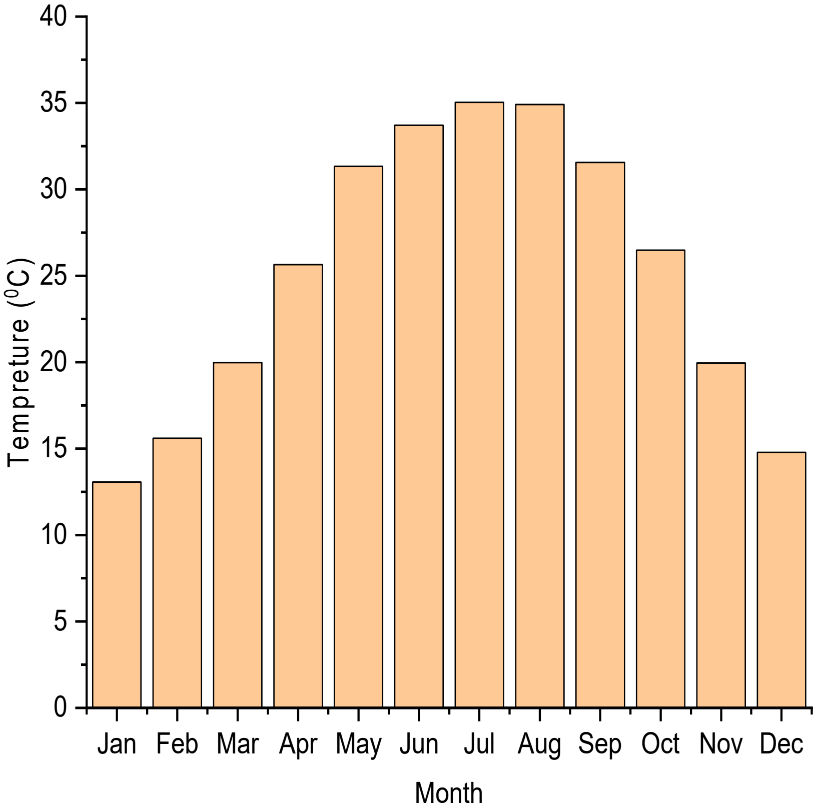


Figure 5. Daily temperature.

5.3. Load Assessment for the University Campus

The annual energy requirements of the university campus were assessed using the actual load data, which were collected from the university. The average daily electrical load requirements of different departments of the university, collected over a complete year, are presented in Figure 6. It can be seen that the highest energy requirements come from the academic departments during working hours. This is because of the presence of heavy lab equipment and air-conditioned class and faculty rooms. The lowest energy requirements come from the residential buildings. The seasonal load profile is presented in Figure 7, where it can be easily seen that the highest energy requirement of around 2 MW occurs in the summer season because of the additional air conditioning requirements of the campus during working hours.

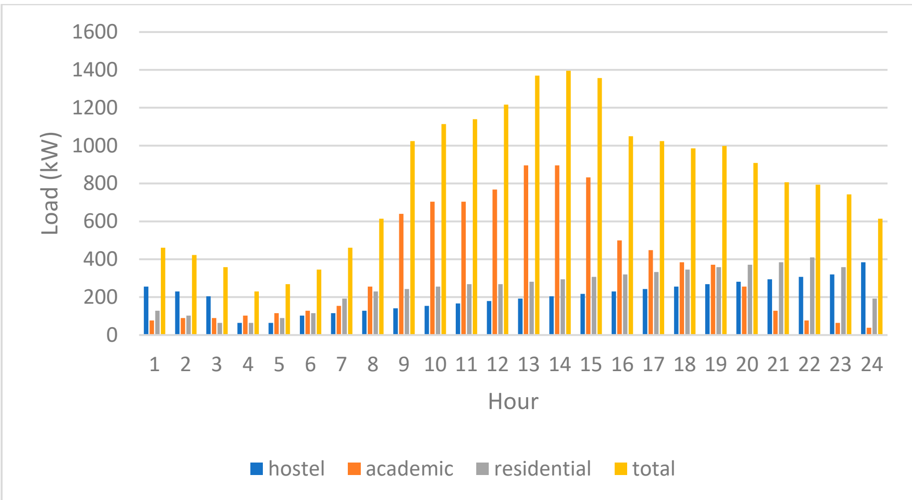


Figure 6. Departmental load profile.

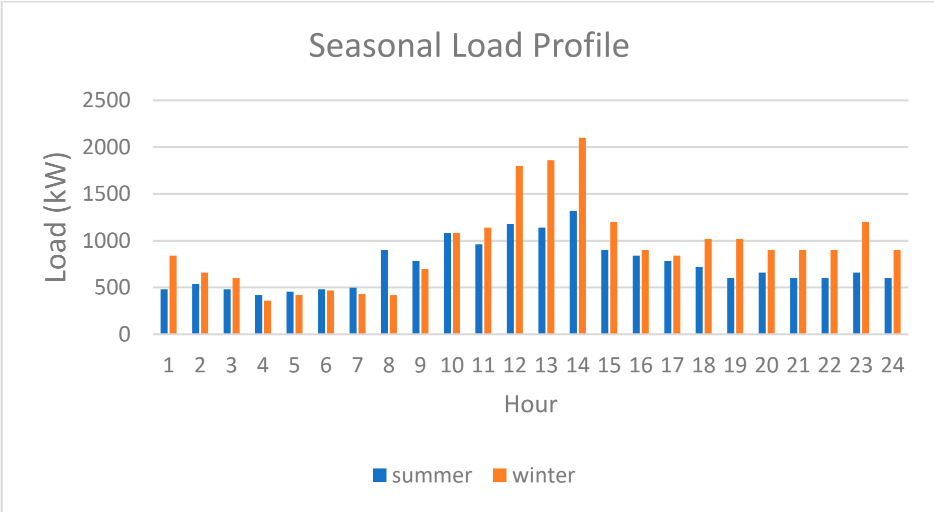


Figure 7. Seasonal load profile.

The combined load profile of the university campus utilized for the hybrid microgrid design is presented in Figure 8. In the HOMER optimization software, the daily average energy requirement of 22,724 kWh/day is considered to be compensated by the hybrid microgrid, with a peak load of around 3402 kW and a load factor of 0.28. It can be observed that the highest energy demand occurs during working hours, and the lowest energy requirement occurs during the early morning hours. In a similar manner, the load requirements gradually increase as the winter season is approached and then decreases similarly as the season changes from summer to winter.

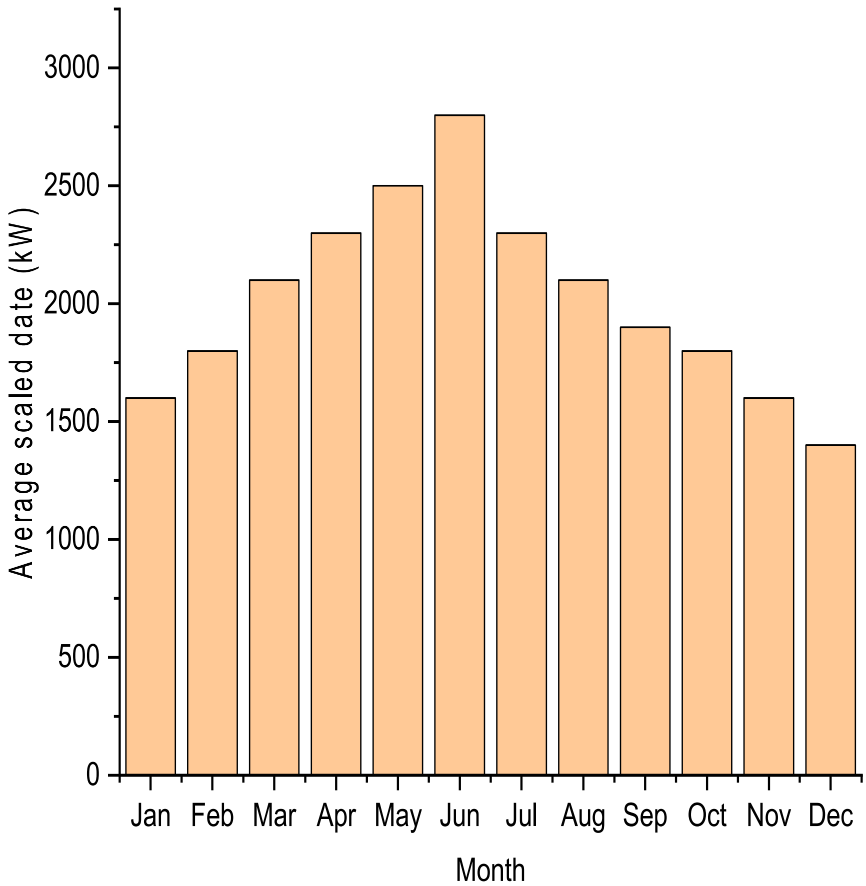


Figure 8. Annual load profile for the university campus.

6. System Performance Assessment Criteria

HOMER an optimization software utilized in this research work to assess the system design and performance under the conditions of different economic variables. The design of a cost-effective hybrid microgrid with the lowest economical parameters is considered an optimal system design for the respective electrical load requirements. The main objective of utilizing this software is to assess the designed system as well as the existing system over a sum of well-known economic variables to first analyze the existing system and then design a cost-effective, efficient, and reliable microgrid structure according to those predefined economic variables.

The proposed software utilizes various repeated algorithms to determine different types of costs associated with the system design, including the initial capital cost, operation and maintenance costs, cost of energy (COE), net present cost (NPC), replacement cost, and the salvage value of the equipment at the end of its working life. The algorithm utilized by the software to assess system performance and to validate the tech-economic performance is presented in Figure 9.

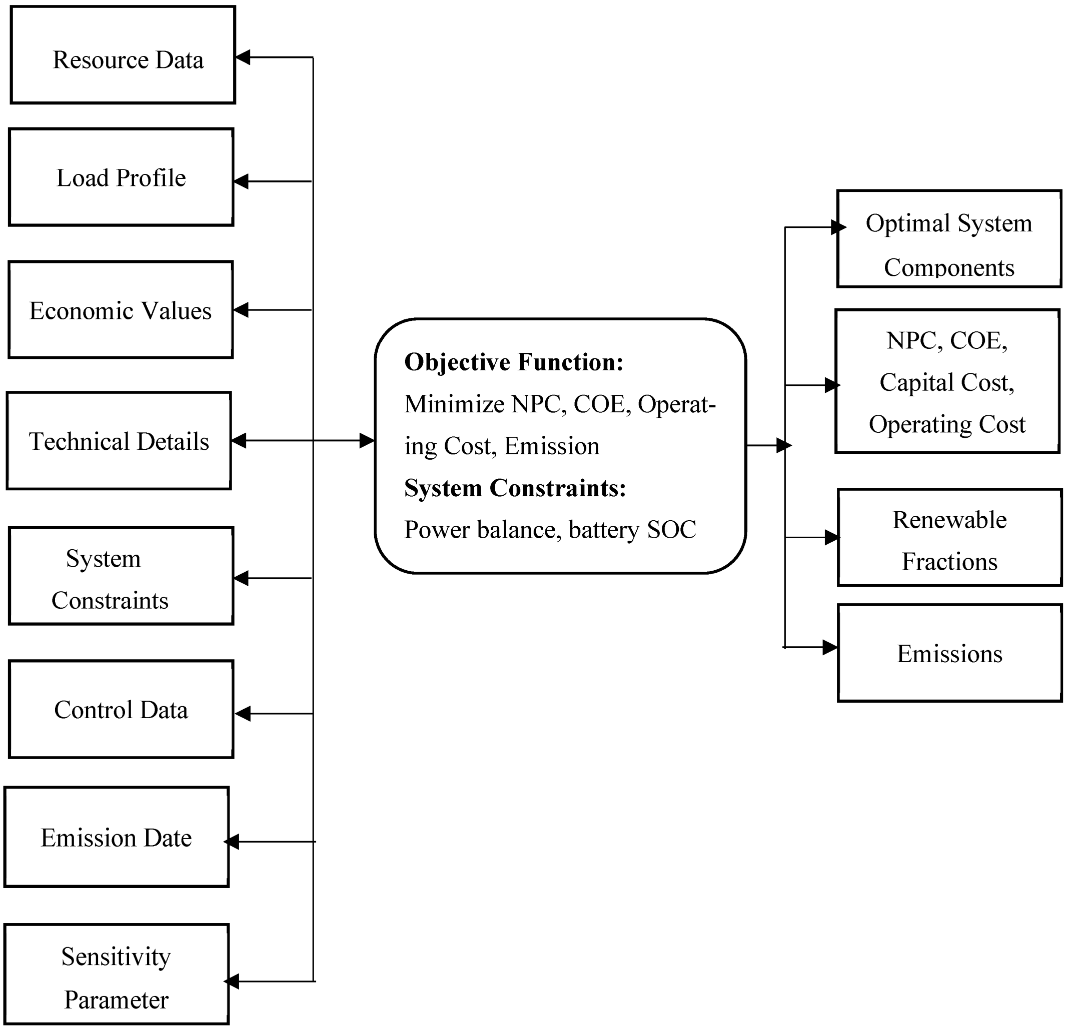


Figure 9. HOMER algorithm.

The primary goal of this research is to design a hybrid microgrid system capable of producing electrical energy while using the least amount of COE, which is the per unit cost of generating electrical energy. The microgrid infrastructure capable of providing optimum values of these economic parameters is considered the optimal system design for supplying the load demand. The COE can be calculated by Equation (3), where C_{TANN}

represents the annual energy generation cost, E_{ts} reflects the electrical energy provided to the load connected directly to the microgrid, and E_{GRIDD} represents any energy sold to the grid [38,40].

$$\text{COE} = \frac{C_{TANN}}{E_{ts} * E_{GRIDD}} \quad (3)$$

The net present cost (NPC) is another important economic factor in this investigation since it represents the total expense of installing and operating the entire system throughout its entire lifespan. For the current microgrid study, these costs include all the costs, such as PV panels, wind turbines, converters, batteries, penalty costs, and the costs of grid integration. Therefore, Equation (4) may be used to compute the NPC [41–43].

$$\text{NPC} = \frac{C_{TANN}}{CRF_{(i,N)}} \quad (4)$$

CRF stands for capital recovery factor: I is the interest rate and "N" is the number of years. Economic concerns include the renewable fraction (RF) and operational costs. The renewable penetration in the total system and the amount of power generated from renewable energy resources are represented by the RF, and the operational cost is the cost that happens yearly due to the operation and maintenance of the system.

The operating cost is another important economic criterion considered in this research for assessing the optimal system configuration of the microgrid. The operating cost is the annualized value of all the costs involved in the continuous operation of the system. This can include the diesel costs and the costs of lubricating oil for the generators, as well as any other costs related to the operation of the energy resources and the equipment connected to the microgrid structure. The operating cost can be determined using Equation (5). Here, $C_{ANN,\ the\ total}$ represents the total annualized costs involved in the operation of the equipment installed in the microgrid, while $C_{ANN,\ capital}$ is the total capital cost per year.

$$Cap\ cost = C_{ANN,total} - C_{ANN,capital} \quad (5)$$

The annual replacement cost (ARC) is the cost of replacing a unit during the entire lifetime of the project. Mathematically, the ARC is defined in Equation (6).

$$ARC = C_{rep}.\ SFF\ (i, n) \quad (6)$$

where C_{rep} is the replacement cost of the unit and SFF is the sinking fund factor. The SFF, defined as the ratio calculating the future value of a series equal to the annual cost, is given by:

$$SFF\ (i, n) = \frac{i}{(1+i)^n - 1} \quad (7)$$

Regarding the annual operating and maintenance costs: there are several models for estimating the AOM system. It is assumed to be a function of both the inflation rate f and the lifetime of the project. In this case, it can be defined as

$$AFC = AOM \cdot (1+f)^n \quad (8)$$

7. Existing Power System

The power-generating infrastructure that is already installed on the university premises is highlighted in Figure 10. It can be seen that the existing system comprises a grid-connected diesel generating system. In their current form, both of these energy resources utilize conventional fossil fuel reserves for generating electricity. The power system under this configuration is highly hazardous to the environment and is causing considerable damage to local as well as global environmental health. The existing system is connected to the grid with a diesel generator as a backup power supply unit for power shortages or any other power shutdown conditions.

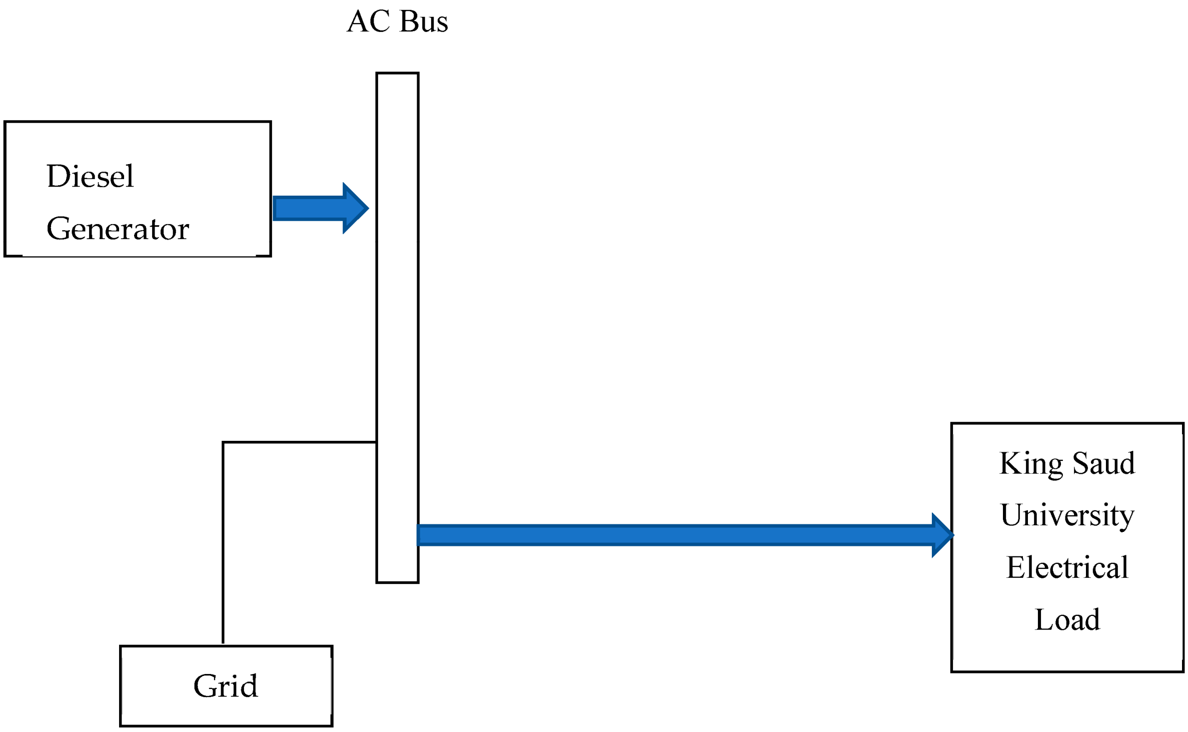


Figure 10. Existing system layout.

The existing power system utilizes grid energy at the price of 0.1 USD/kWh, whereas the diesel price is around USD 1 per liter, comprising the cost involved in its transportation, storage, and handling. A 2000 kW generator is responsible for taking the entire load during any power breakdowns, whereas the grid supply is utilized to compensate for the entire load demand during normal operation.

The existing system was analyzed with respect to the economic parameters considered in this research work, and the results are presented in Table 1. It can be seen that the COE in this system configuration is around 0.115 USD/kWh, while the NPC and operating costs are also much higher. The capital cost is lower in this case as there are no additional infrastructure and equipment connected. The renewable fraction, which is the representation of renewable energy resources in the total power generation, is zero as there are no renewable energy resources attached.

Table 1. Existing system economic values.

Economic Constraint	Value (USD)	Unit
Capital Cost	600,000	$
NPC	12.4	M$
COE/kWh	0.115	$
Operating Cost	909,862	$
Salvage	135,589.74	$
Renewable Fraction	0	%

Table 2 represents the total energy bought and sold to the grid. The annual energy purchased from the grid is around 7,957,534 kWh, while there is no energy sold back to the grid. The existing system structure has a peak load of around 2000 kW, and it requires around USD 795,753.35 for its proper operation.

Table 2. Annual energy purchase and sale under the existing system.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge (USD)	Demand Charge (USD)
January	618,701	0	618,701	1804	61,870.10	$0
February	597,591	0	597,591	2000	59,759.08	$0
March	748,648	0	748,648	2000	74,864.83	$0
April	772,936	0	772,936	2000	77,293.56	$0
May	837,864	0	837,864	2000	83,786.41	$0
June	884,377	0	884,377	2000	88,437.73	$0
July	726,774	0	726,774	2000	72,677.40	$0
August	692,744	0	692,744	2000	69,274.38	$0
September	597,877	0	597,877	2000	59,787.67	$0
October	549,256	0	549,256	1911	54,925.58	$0
November	479,043	0	479,043	1762	47,904.32	$0
December	451,723	0	451,723	1742	45,172.28	$0
Annual	7,957,534	0	7,957,534	2000	795,753.35	$0

The annual energy generation from each energy source under the existing system structure is presented in Figure 11. It can be seen that over the year, most of the energy is provided by the grid, and the diesel generator works only for those periods when the grid power is less than the required power demand.

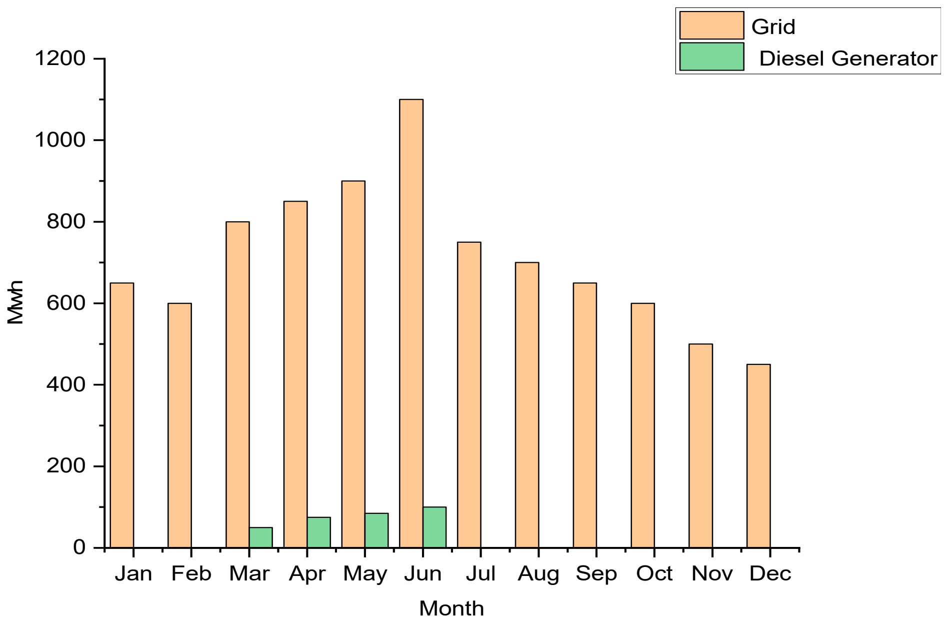


Figure 11. Monthly production of electric energy by each system component.

Figure 12 represents the total cash flow over the complete lifetime of the project. It can be seen that the highest costs are involved in the operation of the existing power system, which involves the costs of operating the grid as well as the diesel generator. These figures refer to 25 years of the system's operation. Due to the rate of inflation, the replacement cost is very high compared to the capital cost. This is followed by the fuel cost and the operating cost in this order.

The total operating hours and other relevant details regarding the operation of the diesel generator are presented in Table 3. It can be observed that the total energy generated by the diesel generator is around 336,726 kWh at a cost of USD 1.29 M, which reflects that in its current configuration, the system is highly inefficient and costly.

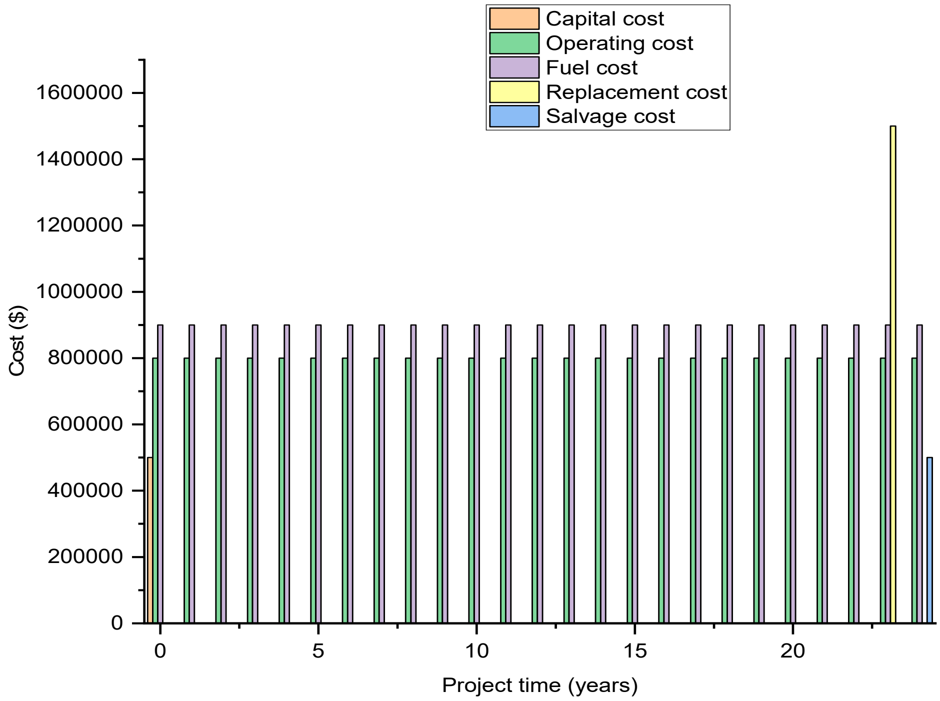


Figure 12. Cost summary of the existing system.

Table 3. Operation, fuel, and summary costs of the diesel generator.

Quantity	Value	Unit
Hours of Operation	634	hrs/yr.
Operational Life	23.7	yr.
Total Fuel Consumed	99,913	L
Average fuel per Day	274	L
Average Fuel per hour	11.4	L
Total Energy Generated	336,726	kWh/yr.
Total Fuel Charges	1.29	M USD

The greenhouse gas (GHG) emissions generated by the current system configuration are presented in Table 4. It can be easily seen that the existing system is very harmful to the environment as it generates a significant amount of GHG emissions. It can be concluded from these assessments that this system configuration is highly inefficient, unreliable, costly, and has the worst effects on the environment.

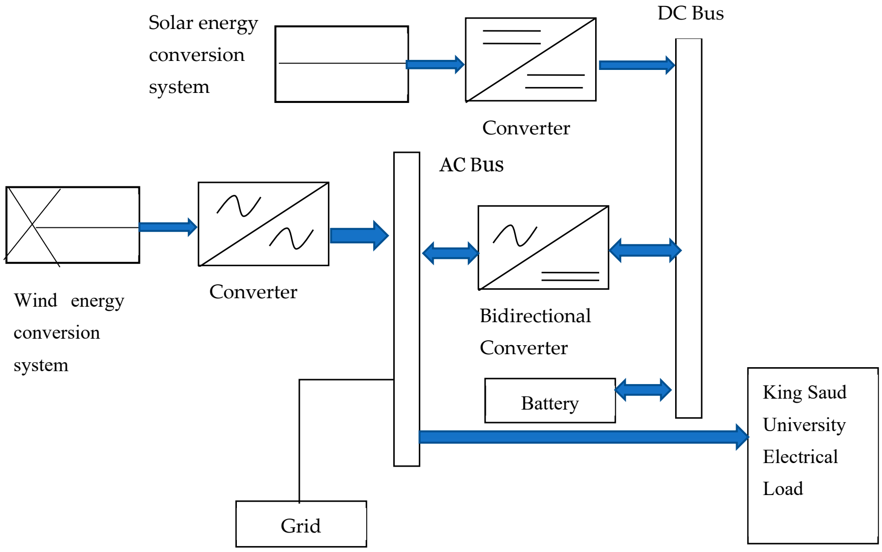
Table 4. Emissions generated by the existing system.

Quantity	Value	Unit
Carbon Dioxide	5,291,156	kg/yr
Carbon Monoxide	1355	kg/yr
Unburned Hydrocarbons	71.9	kg/yr
Particulate Matter	11.6	kg/yr
Sulfur Dioxide	22,444	kg/yr
Nitrogen Oxides	10,923	kg/yr

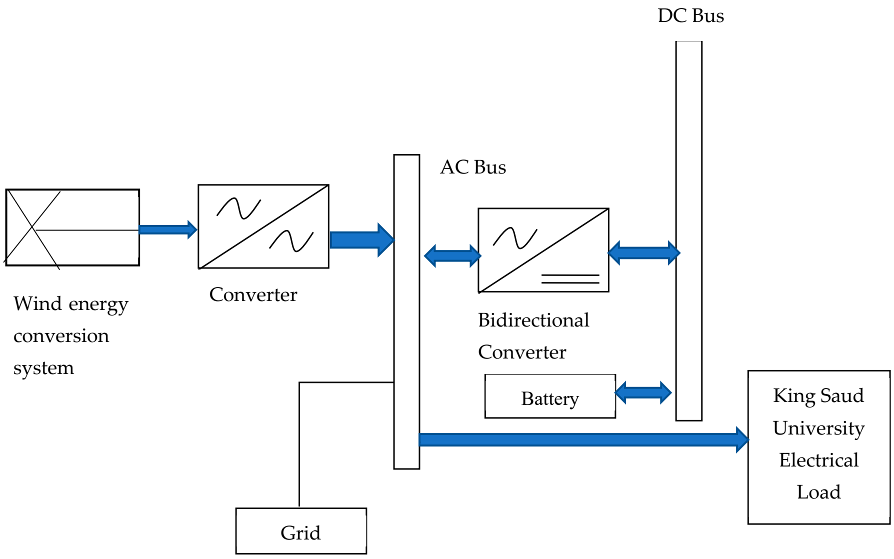
8. Proposed System Model

The problems associated with the existing system can readily be mitigated by utilizing a hybrid microgrid structure. The hybrid microgrid structure consists of locally available renewable energy resources with a medium backup in the form of batteries, and it is connected to the grid to increase the system reliability and to sell any excess energy generated by the designed microgrid.

Several different microgrid configurations were analyzed in this research work to select the most optimal system configuration. The proposed microgrid structures were analyzed using various economic parameters, and the system configuration that provided the optimal values of these parameters was selected as the optimal system design configuration. As the university campus has appropriate potential for both solar and wind energy, both solar and wind energy resources were utilized for the design of optimal hybrid microgrids for the university campus. All the proposed microgrid configurations are integrated with a battery, which is an energy storage system (ESS), as a backup to store excess energy during low-load conditions and then deliver energy back during times of high demand. A bi-directional converter is utilized in the configuration to convert the DC power generated by the solar panels into AC and to store and utilize energy in the battery backup. The different microgrid configurations considered in this study are presented in Figure 13. In all configurations presented herein, it is assumed that power electronics converters/inverters are embedded into the systems. Due to this assumption, these devices are shown in the figures.

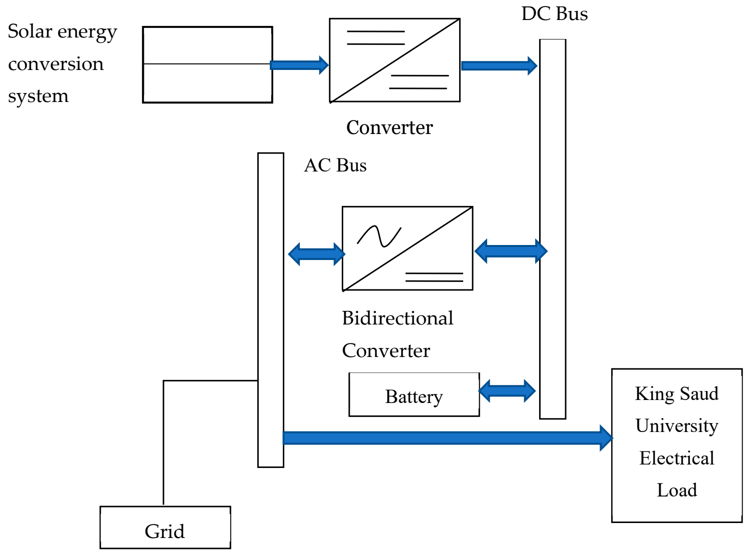


(**a**) PV-WIND-GRID-ESS

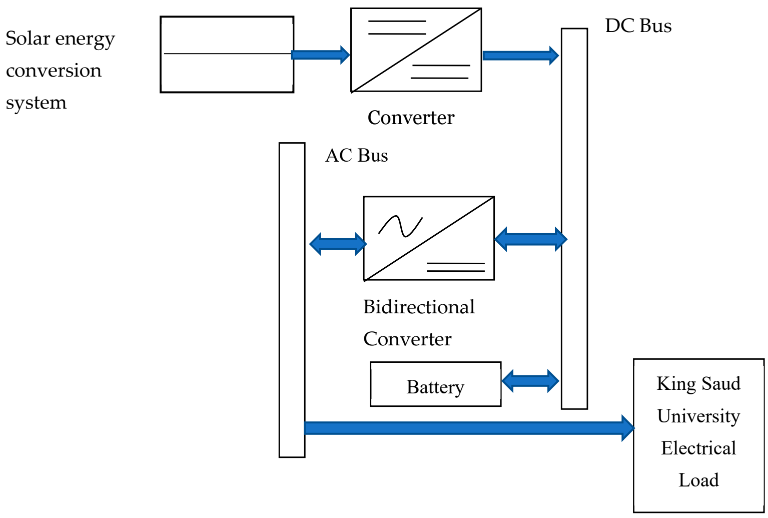


(**b**) WIND-GRID-ESS

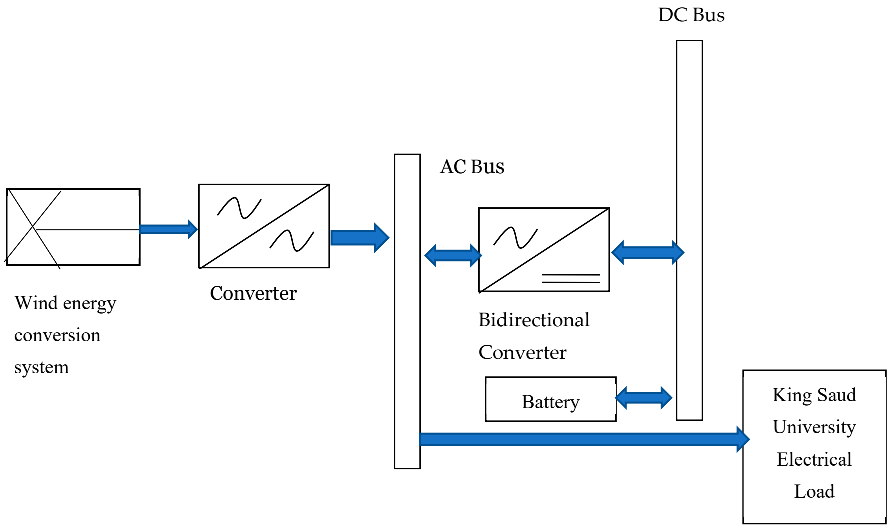
Figure 13. *Cont.*



(**c**) PV-GRID-ESS



(**d**) PV-ESS



(**e**) WIND-ESS

Figure 13. (**a**–**e**) Proposed hybrid microgrid configurations.

The costs and sizes of the system components and their lifetimes are presented in Table 5. The prices of all the system components were determined by a thorough investigation of current market prices. The grid power purchase and sell-back prices considered in this work were 0.1 and 0.05 USD/kWh, respectively. These parameters were eventually used to carry out a techno-economic analysis of the proposed system design, as presented in Sections 9–12. These values were chosen for their software and market availability.

Table 5. Cost of system components.

System Component	Rated Power	Capital Cost ($)	Replacement Cost (USD)	O&M Cost (USD/year)	Lifetime (yr.)
Solar PV Panel	1 kW	1200	1200	5	25
Wind Turbine	10 kW	5000	5000	50	20
Battery	1 MWh	350,000	350,000	5000	15
System Converter	1 kW	600	600	0	10

9. Economical Comparison

An economical comparison of the proposed hybrid microgrid structures is explained in this section to validate the optimal system configuration. The most optimal system configuration would be the one that delivers the required load demand with the lowest COE, NPC, and operating costs while achieving the highest renewable fraction in the hybrid system configuration. The results of the economic analysis are presented in Table 6. It can be seen that the PV-WIND-GRID-ESS system configuration has COE and NPC values of 0.0259 USD/kWh and USD 5.36 M, respectively, whereas the operating cost is USD 17,276. All these economic variables are the lowest in this configuration while achieving the highest energy generation contribution values from the renewable energy resources, and the system assures the highest renewable fraction among the hybrid microgrid configurations.

Table 6. Economic comparison of proposed system architectures.

System Architecture	Capital Cost (M USD)	NPC (M USD)	COE/kWh (S)	Operating Cost (M USD)	Renewable Fraction (%)
PV-WIND-GRID-ESS	5.13	5.36	0.0259	17,276	82.8
WIND-GRID-ESS	5.28	7.75	0.0398	190,975	76.7
PV-GRID-ESS	4.62	15.3	0.143	824,737	20.2
PV-ESS	27.4	36.5	0.341	702,645	100
WIND-ESS	47.1	68.9	0.643	1.69	100

10. Emissions Comparison

A reduction in GHG emissions is one of the most important objectives of this research work as the world is currently dealing with the worst effects of climate change and global warming. Saudi Arabia is a country that produces most of its electric power through oil, which must now be changed for good. With this intention, the Vision 2030 blueprint by the Kingdom of Saudi Arabia is a revolutionary step toward the utilization of renewable energy resources for power generation so that overall GHG emissions may be reduced [42]. A comparison of GHG emissions among the proposed system configurations is presented in Table 7.

It can be observed from the emissions analysis that among the hybrid microgrid structures, the PV-WIND-GRID-ESS system configuration generates the least amount of carbon dioxide, sulfur dioxide, and nitrogen oxides, while all the other hybrid microgrid structures generate higher GHG emissions. This indicates that the PV-WIND-GRID-ESS system is the most environmentally friendly hybrid microgrid system configuration.

Table 7. Emissions comparison among proposed system configurations.

System Architecture	Carbon Dioxide (kg/yr.)	Carbon Monoxide (kg/yr.)	Unburned Hydrocarbons (kg/yr.)	Particulate Matter (kg/yr.)	Sulfur Dioxide (kg/yr.)	Nitrogen Oxides (kg/yr.)
PV-WIND-GRID-ESS	1,736,974	0	0	0	7531	3683
WIND-GRID-ESS	2,222,117	0	0	0	9634	4711
PV-GRID-ESS	4,183,112	0	0	0	18,136	8869
PV-ESS	-	-	-	-	-	-
WIND-ESS	-	-	-	-	-	-

In Table 7, an economic and emissions comparison analysis is presented. It is clear that the PV-WIND-GRID-ESS system configuration is the optimal system configuration for designing a hybrid microgrid structure for the university campus. The selected system configuration is not only economically viable but is also able to generate clean energy when compared to other hybrid configurations. The annual production of energy and its sale back to the grid for this optimal configuration are presented in Table 8. It can be observed that the proposed system is not only receiving energy from the grid but is also able to sell energy back to the grid during the entire year. It can also be seen that the system can sell more energy to the grid than it buys.

Table 8. Annual Energy Production and sale from the Optimal System.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load	Energy Charge (USD)	Demand Charge (USD)
January	192,014	652,651	−460,637	1505	(13,431.12)	0
February	182,254	714,869	−532,615	1600	(17,518.09)	0
March	247,059	750,465	−503,406	1600	(12,817.33)	0
April	296,491	620,320	−323,829	1600	(1366.88)	0
May	358,419	534,776	−176,358	1600	9103.07	0
June	357,457	668,041	−310,585	1600	2343.61	0
July	205,905	847,926	−642,021	1600	(21,805.80)	0
August	228,849	663,089	−434,239	1600	(10,269.48)	0
September	210,045	509,019	−298,974	1600	(4446.43)	0
October	187,592	506,088	−318,496	1311	(6545.22)	0
November	138,839	587,708	−448,869	1348	(15,501.48)	0
December	143,453	676,166	−532,713	1600	(19,463.02)	0
Annual	2,748,377	7,731,118	−4,982,741	1600	(111,718.18)	0

All the above economic and environmental analyses indicate that the PV-WIND-GRID-ESS hybrid system configuration is the most optimal system design to be selected for the installation of a microgrid at the university campus. The reliability of this optimal system is also an important criterion to be considered and can be validated by performing a sensitivity analysis.

11. Sensitivity Analysis

The optimal system configuration, which was selected through a rigorous procedure, was subjected to a sensitivity analysis to validate the system performance with varying different system parameters. The optimal system performance as per the sensitivity analysis will finalize that the selected system configuration is not only economically and environmentally viable but is reliable as well [42,43]. In this research work, four different sensitivity variables, the grid power price, minimum renewable fraction, carbon emission penalty, and battery backup size, were selected as system constraints for analyzing the selected system's reliability.

Grid power prices increase each day as fossil fuel prices rise exponentially. Most of the grid power in Saudi Arabia is generated through oil and other fossil fuels. This shows that the grid prices are expected to increase with time. The grid power prices were selected to be 0.1, 0.2, and 0.3 USD/kWh, and the sensitivity results are presented in Table 9. It can be observed that as the grid power prices increase, the optimal system tends to generate more power from renewable energy resources, and the renewable fraction increases. The COE, NPC, capital, and operating cost also increase because of the utilization of renewable energy resources, which are costlier to operate when compared to the conventional grid structure.

Table 9. Effect of grid power price variation on system economics.

Grid Power Price (USD/kWh)	Capital Cost (M USD)	NPC (M USD)	COE/kWh (S)	Operating Cost (M USD)	Renewable Fraction (%)
0.1	5.13	5.36	0.0259	17,276	82.8
0.2	6.81 M	7.60 M	0.0353	61,514	90.5
0.3	7.78 M	9.51 M	0.0444	133,233	93.0

The second sensitivity variable considered in this research work was the minimum renewable fraction. The renewable fraction indicates how much energy is being generated from renewable energy resources. Here, the minimum renewable fraction variables considered were 82.8, 85, and 90%. The results of this sensitivity analysis can be observed in Table 10, which indicates that as the renewable fraction increases, the capital cost increases while the COE and operating cost decrease. This indicates that the performance of the proposed system configuration is enhanced, as the renewable penetrations are increased.

Table 10. Effect of minimum renewable fraction on system economics.

Renewable Fraction:	Capital Cost (M USD)	NPC (M USD)	COE/kWh (S)	Operating Cost (M USD)
82.8	5.13	5.36	0.0259	17,276
85	5.94	4.12	0.0172	−140,984
90	7.53	4.70	0.0184	−218,573

The third sensitivity parameter considered in this study was the carbon emissions penalty. The carbon emissions penalty refers to a scenario in which the energy generation company is charged some penalty for the generation of carbon emissions to reduce the carbon footprint. This penalty is already being considered in different countries to compel energy-producing sectors to move toward renewable energy resources. The emissions penalties considered in this work were 2, 5, and 10 USD/ton, and the results are presented in Figure 14. It can be seen that as the emission penalty increases, the renewable fraction increases, and the carbon emissions generated during the process decrease, reflecting that the proposed system is moving toward the use of renewable energy resources. The increase in the renewable fraction is nominal because of the limited space for renewable energy resources to be installed on the university premises.

The fourth sensitivity variable considered in this research was the battery backup, which was considered to be either small, medium, or large. The results of this analysis are presented in Table 11. It can be observed that the medium-size backup with a size of 1000 kWh is the most optimal backup configuration and can provide the system with the required backup energy by utilizing lesser COE, NPC, and operating costs.

From the above sensitivity analyses, it can be determined that the proposed PV-WIND-GRID-ESS system configuration is the most optimal system configuration to be selected for the hybrid microgrid design. The economic and emissions comparison indicates that this system configuration is cost-effective, efficient, and environmentally friendly, and the sensitivity analysis proved the reliability of the optimal system configuration.

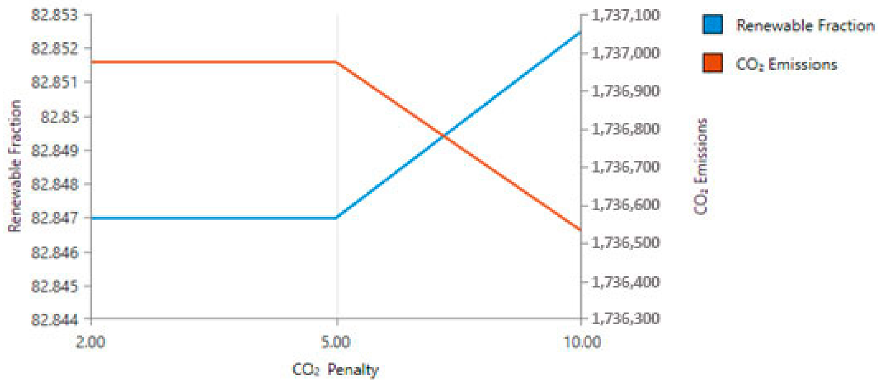


Figure 14. Effect of emissions penalty variation on system variables.

Table 11. Effect of battery backup variation on system economics.

Battery Backup Type	Size (kWh)	Capital Cost (M USD)	NPC (M USD)	COE/kWh (S)	Operating Cost (M USD)
Small	100	5.64	6.16	0.0298	39,761
Medium	1000	5.13	5.36	0.0259	17,276
Large	4216	3.59	9.32 M	0.0759	442,916

12. Comparison with Previous Works

Table 12 presents a general comparison between this research and previously published works in the literature. Here, the comparison was based on five variables, and the variables used in the analysis were the COE, NPV, capital cost, operating cost, and renewable energy fraction of each design It can be observed that the proposed microgrid structure is the best, with a clear margin in all the variables except the cost of energy.

Table 12. General comparison.

Criteria	Capital Cost (M USD)	NPC (M USD)	COE/kWh (S)	Operating Cost (M USD)	Renewable Fraction (%)
[10]	7.31	10.6	0.155	256	83.7
[43]	108	10.4	0.00257	7.58	88.6
Proposed	5.13	5.36	0.0259	17,276	82.8

13. Conclusions

This research work investigated the techno-economic and environmental feasibility of a hybrid microgrid infrastructure for King Saud University, Riyadh. Several different microgrid architectures were investigated based on their economic and environmental footprints. In this paper, all simulations of the various microgrid architectures were carried out using HOMER software. The microgrid infrastructure containing a solar PV array, wind turbines, a grid, and a battery was identified as the most optimal solution for the respective electrical load demand. The COE of the optimal system is 0.0259 USD/kWh, which is even lower than the grid price. The system is environmentally friendly and can generate around 82.8% of the total required energy through renewable energy resources. The GHG emissions in the proposed system structure are also 32% lower than in the existing system. A sensitivity study of the optimal system configuration was also undertaken to test its robustness with respect to various system parameters. Future research may be performed to integrate net metering with the present system to evaluate its revenue-generating potential when surplus renewable energy generation competence is obtained, and a business model can be suggested to ensure its business-related feasibility. The suggested system not only accounted for the required load demand while incurring the lowest COE, NPC, GHG emissions, and operational costs but also established its durability and efficiency by performing well across all sensitivity variables. The research contributions of this work can be summarized as follows.

- Analyses of the solar and wind energy resources of King Saud University have shown the potential for the renewable energy sources to supply the electricity requirements of the University.
- Based on the results of the optimization from the HOMER software, a microgrid consisting of wind turbines, a solar array, a battery storage system, and external grid shows better performance than any other possible combinations in term of cost of energy and emissions.
- A sensitivity analysis was performed to assure the economic viability of the optimal system configuration by varying different system design parameters.

The limitations of this work include the inability of the proposed method to analyze the reliability of the proposed design. Some of the possible reliability variables that could be analyzed include the expected energy supply and energy index reliability, to mention a few. This limitation also makes it impossible to evaluate a component importance analysis for each building block comprising the entire microgrid structure throughout the design. Furthermore, the synchronization of the HOMER software and the NASA weather data for the site used in the design makes it too difficult to carry out a renewable energy data analysis.

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