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Techno-Environmental Analysis of a Microgrid Energy System in a University Office Complex

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Abstract: The world is undergoing an irreversible shift towards clean energy. Microgrids are recognized as a key technology that holds significant potential to make a substantial difference in this regard. The paper provides a comprehensive overview of how microgrids work and their impact on climate. The research presented in this paper focuses on reducing carbon dioxide (CO^2) in the main campus of Qassim University, Saudi Arabia, through the development and implementation of an engineering model that facilitates the installation of a microgrid system designed to meet the university's sustainability goals. The study aims to explore possible solutions that can reduce emissions in the administrative building (A7) at Qassim University and meet the university environmental plan. Therefore, a comprehensive study is conducted to investigate the potential reduction in emissions associated with the installation of a microgrid system. This microgrid system operates in a grid-connected mode and comprises three main components: the load, a photovoltaic (PV) system, and batteries. The results of the study indicate that the microgrid reveals a notable transition in the primary sources of electricity. Moreover, the microgrid system proves its capability to meet a substantial portion of the daily energy requirements, highlighting its efficiency and effectiveness in addressing energy needs. The findings of this study highlight the significant potential of the proposed model in curbing carbon emissions, as it demonstrates a reduction from 615.8 to 147.4 Mt of CO^2. This reduction aligns with the university's commitment to sustainability and green initiatives. The computed decrease in carbon footprint emphasizes the possibility of the suggested model to encourage sustainable practices among the university community and mitigate the environmental consequences of energy usage.

Keywords: carbon emission; design; energy consumption; modeling; photovoltaic cells; power generation; solar energy; solar power generation

Citation: Almohaimeed, S.A. Techno-Environmental Analysis of a Microgrid Energy System in a University Office Complex. *Sustainability* **2023**, *15*, 12506. https://doi.org/10.3390/su151612506

Academic Editor: Luis Hernández-Callejo

Received: 30 June 2023
Revised: 29 July 2023
Accepted: 11 August 2023
Published: 17 August 2023

1. Introduction

Electric generation is one of the major contributors to greenhouse gas emissions (GHGs) that cause global warming and climate change [1]. The demand for electricity is set to increase due to rising living standards in developing countries [2]. Therefore, several countries produce power from traditional generating resources to meet global energy needs. Hence, power grids will become more complex as they attempt to balance supply and demand across larger areas [3]. A microgrid is a small-scale electricity grid with distributed energy sources and loads, optimizes the supply and demand of electric power, thereby allowing for greater flexibility and reliability [4]. Microgrids are increasingly being used around the world to supply local and small-scale electricity as an alternative/supplement to large central power systems [5]. If fact, several studies investigate the positive impact of applying a microgrid system [6–9]. Microgrids are developed by transmission and distribution grids. Microgrids helps to reduce or eliminate intermittencies, voltage and frequency drops, blackouts, and power surges that are increasingly becoming worse in many regions of the world due to population increase and urbanization [10,11].

Microgrids can play an important role in diminishing the impact of climate change by reducing CO^2 associated with fossil fuels used by conventional generation, and by adopting renewable energy sources [12]. Microgrids continue to provide benefits to the environment and utility operators [13–15]:

- Microgrids have the potential to help mitigate climate change by integrating more zero-emission electricity sources into the grid.
- Microgrids can improve energy management, reduce costs, and defer investments in new energy generation.
- Microgrids can operate in a more resilient manner than traditional grids during severe weather events and climate change.
- Microgrids are installed near the point of use, which minimizes power losses and makes it possible to meet the demands using less energy.

In fact, microgrids are a potential solution in many developing countries as they can be rapidly deployed, they do not require large subsidies, they can be tailored to local needs, and allow electricity customers to actively participate in the operation of their electricity systems [16,17]. However, there are several important implementation challenges with microgrids that must first be overcome before their widespread adoption. The work in [8] illustrates the three primary objectives of microgrids, such as providing power, quality, and reliability, using assets that are unlikely to be operated by a traditional grid and presenting a controlled profile in a wide area. In addition to this, functionality and the techniques of microgrids are explained, such as generation and storage technologies, control and protection philosophies, and communication technologies. Further, this paper shows that microgrid stakeholders and ownership entities can benefit from microgrids in several ways. Indeed, a microgrid can deliver direct benefits, such as the benefits previously explained, and indirect benefits related to emissions mitigation and dependency on external fuel. Furthermore, the work in [18] illustrates lessons learnt from the Fort Collins project, Fort Collins, Colorado, USA. It shows that there are some differences between the dispatch in microgrids and the interconnected grids where microgrids are more complicated and associated with challenges. The interconnected grids are guided by the principles of economic dispatch and unit commitment. On the other hand, microgrids incorporate more goals or constraints that might influence the dispatch. Furthermore, microgrids include combined heat and power systems and renewable energy generation, which make the dispatch more complicated due to the variation in heat loads and stochastic variation in clean energy output. However, chance-constrained programming is used to model the randomness in the system. Additionally, the paper illustrates that individual resources within the microgrid must cooperate, such as using hierarchical control, to achieve a common objective. The process of dispatch in the Fort Collins project includes:

- Selecting the feeder load set point;
- Picking the assets;
- Choosing the scheduling order.

The work in [19] demonstrates the functions of microgrids. It describes the required functionality of the microgrid central controller for optimizing the operation of a microgrid. The author explains that a microgrid can be considered as a controlled system that can operate as a single aggregated load. In another way, customers consider microgrids as a conventional distribution system, which enhances reliability, CO^2 reduction, and power quality improvement. The paper explains some functions required for a microgrid operation in the traditional mode, such as economic scheduling, electrical load forecasting, security assessment, and the functions of demand side management. Additionally, it demonstrates that two functions are required to optimize the operation of the power system, economic dispatch, and unit commitment. However, some techniques have been used to solve operational problems in microgrids, such as:

- Priority list;
- Sequential quadratic programming;

- Ant-colony optimization.

1.1. Case Studies and Microgrid Projects

Dynamic economic dispatch for microgrids is explained in [20]. It includes a flexible and powerful distributed algorithm that manages dynamic economic dispatch problems for microgrids, either in the modes of interconnected or islanded. In such a scheme, a microgrid can solve its issues locally without requiring central control. The authors used the distributed algorithm based on the alternating direction method of multipliers to appoint security and privacy concerns. A case study compromising five microgrids is conducted using an algorithm based on the decomposition–coordination scheme. The obtained results show that all microgrids can cooperate to achieve the global optimum solution without requiring central coordination. Fort Carson is a US Army microgrid in Colorado Spring, CO, USA, and represents a smart power infrastructure for energy reliability and security. The base accommodates 14,000 residents and covers 550 sq. Km. Fort Carson base aims to become a net zero emissions facility and protect critical assets from losing power. The project consists of RES and distributed generation: 1 MW solar generation, 3 MW diesel generators, and five electric vehicles (EVs) as a V2G operation. However, the project faced some challenges related to system ownership and communication during the implementation [21].

The capacity optimization of a community microgrid for rural electrification is presented in [22]. The paper explains the developed algorithm for the optimization of solar generation and the energy storage capacity of small community microgrids. The optimization problem aims to maximize the operational profit and minimize the installation cost. The project aims to provide reliable and affordable electricity for rural communities with high energy efficiency and reduced energy costs. Such types of projects will facilitate the basic and essential needs of rural communities. The project is applied to determine the optimum configuration of the Madan Microgrid in Jiwaka, Papua New Guinea, where about 90% of the population lack electricity. The microgrid includes three community centers, eight primary schools, and the Madan Medical center. Another study by [23] discusses several techniques for data reduction, reliability quantification, and metrics for a performance analysis associated with the FortZED RDSI microgrid. The goal of the program is to diminish the peak load by 15% while the project goal is to achieve a 20–30% peak feeder load reduction. Some performance metrics specified by the North American Electric Reliability Corporation are used to calculate the assets and operations, such as starting reliability, average run time, availability factor, service factor, net capacity factor, net output factor, weighted availability factor, and weighted service factor. Furthermore, the paper presents new metrics based on a yearly load curve; the traditional approach of peak load reduction considers the maximum microgrid output to maximum total feeder load. Time congruent approaches include the actual peak load reduction while considering time congruent values, and there are five proposed approaches presented in comparison with the traditional approach.

The Huatacondo Microgrid is the first project in Chile developed by the University of Chile. Prior to this project, the Andes Mountain community had a diesel generator that only operated 10 h per day. Therefore, building a microgrid would facilitate an electricity service for 24 h a day. The microgrid includes the existing 150 kW diesel generator, 22 kW PV system, 3 kW wind turbine, and 170 kW storage bank. Moreover, energy management systems are incorporated to analyze the real-time data, such as providing a set-point generation while minimizing costs. The results show that a 50% consumption reduction in the diesel generator is achieved. Additionally, solar generation from the PV system achieved a capacity factor of 28% [24].

1.2. Role of Universities in Climate Change Mitigation

In recent decades, climate change has become a major issue as it will eventually lead to global warming, an increase in the sea level, or changes in weather patterns. In the context of climate change mitigation and the reduction in CO^2, a microgrid is especially advantageous because it provides access to cheap solar power for remote island communities, military bases, or fishermen [25,26]. The electric grid is mostly connected to fossil fuel power plants as the emissions increased in 2021 to reach 700 Mt CO^2. However, adopting a decentralized system reduces this figure considerably and makes it more efficient to use energy [27,28]. In Saudi Arabia, the CO^2 emissions increased from 200 to 600 million tons during the period spanning from 1996 to 2014, in which heat and electricity generation contributed to 40% of the overall CO^2 emissions [29,30]. Hence, the Green Saudi Initiative is an ambitious national initiative that was setup in 2021. The initiative aims to increase the country's reliance on clean energy production, thereby contributing to the reduction in carbon emissions and the fight against climate change. One of its goals is to reduce carbon emissions by more than 4% of global contributions [31]. In addressing the challenges posed by climate change, universities are assuming critical responsibility via their educational, research, and community outreach endeavors. However, as substantial entities, universities are themselves substantial sources of greenhouse gas emissions [32]. On the other hand, universities are recognized as academic institutions that take responsibility for addressing climate challenges, including CO^2 emissions, implementing sustainable plans. Different university campuses in the world have taken intensive actions and launched aggressive plans to ensure sustainable campuses. Princeton University intends to establish a new solar initiative that will be integrated with the Princeton University microgrid. The project is expected to expand the university's present PV-generating capacity from roughly 5.5% to 19% of its present electrical energy consumption [33]. The initiative aligns with the university's objective of transitioning to more sustainable energy production practices and is a pivotal component of its overarching goal to achieve net carbon neutrality by 2046 [34].

The Illinois Institute of Technology Microgrid is one of the interesting projects. There are several motivations behind building this microgrid. One of the drivers is the number of outages that reach three power blackouts per year disrupting teaching and research programs. A 14 MW load is the maximum load allocated to the university campus, which would lead to improving the infrastructure to accommodate the load growth as well as increasing the energy efficiency. The project is a collaboration between the Illinois Institute of Technology and DOE that is providing a fund of USD 7 million. The project aims to provide reliable and accommodating electric power systems, load reduction, and an economic operation. In fact, this microgrid is the first system that offers a full isolated campus load. Furthermore, the project includes some innovative applications, such as an intelligent controller, high-reliability system, and advanced recovery system. The total DER capacity allows the campus to operate in an isolated mode, most of the time, without importing power from the main electric grid [28].

The third microgrid project is the University of California San Diego microgrid. The project serves a 450 hectare campus and 45,000 people per day by providing them with electricity, heating, and cooling. The microgrid consists of a 13.5 MW gas generator, 3 MW steam engine, 1.2 MW solar system, in addition to a distributed storage system. The generators can emit a 75% lower emission than traditional turbines as one of the environmental benefits. The microgrid is connected to the electric power system through a single 69 kV substation using a complex SCADA system to manage the energy operation and supply. Furthermore, the developers are installing a master controller to control all the generation, storage, and demands with hourly computing to optimize the operation [35].

A study by [36] shows that the purchased electricity contributes to more than 64% of the carbon footprint value of Qassim University with about 79,808 Mt of CO^2. Furthermore, the King Abdullah University of Science and Technology has conducted a study to estimate the emissions of its campus. The results show that the overall estimated CO^2 emissions is 127.7 MT CO^2 [37].

1.3. Qassim University's Sustainability Initiatives

In this regard, Qassim University has an ambitious plan for sustainable development to align with the Kingdom's vision for 2030 [38–40]. Qassim University has released its strategic plan 2020–2025 where sustainability assurance is at the top of the strategic outcomes [41]. Strategic plan 2020–2025 of Qassim University incorporates a range of strategic initiatives aimed at promoting sustainability. According to the university's strategy for climate change [42], reducing CO^2 emissions constitutes a significant priority, which can be realized through several strategic projects. These projects include increasing the area of green plantations within the university's premises and lowering CO^2 emissions from vehicles on campus. Additionally, reducing energy consumption constitutes another strategic initiative. This can be achieved by adopting more renewable energy sources on campus and minimizing the energy purchased by the university from the public provider. Furthermore, the strategic plan emphasizes the importance of measuring the ratio of renewable energy production to the total energy usage per year to assess the effectiveness of these initiatives. These strategic initiatives reflect Qassim University's commitment to sustainable practices and its contribution to the global efforts to address climate change. In fact, there are several solutions to help the university to achieve its plan, such as [43,44]:

- Sunshine harvesting;
- Smart energy management;
- Highly efficient appliances;
- Smart meters;
- Energy conservation;
- EV charging stations;
- Solar energy system.

University microgrids are considered one of the promoted solutions to provide both reliable and environmentally friendly electricity systems [43,45]. Hence, the university has different options to achieve its sustainability objectives [46]. One proposed option is the minimization of energy consumption. The university launched two initiatives in that regard: the energy conservation program and the on-site renewable energy program [47]. The accomplishment of these programs can be measured by tracking the number of RES installations, the annual energy consumption (kWh/year), and the RES generation/total energy consumption.

In fact, university microgrid systems have attracted the attention of academic institutions worldwide, with numerous research studies investigating various aspects, such as energy cost reductions, increased use of distributed energy resources (DERs), or demand–supply balance. However, there remains an important research gap concerning the investigation of emissions reduction within microgrid systems in academic institutions. Furthermore, while many universities in Saudi Arabia have launched their sustainable plans, the investigation of engineering-based solutions is limited. Thus, this study aims to study the potential of microgrid technology as a solution from an engineering perspective specifically focusing on mitigating CO^2 emissions within Qassim University. The findings of this work are expected to obtain valuable outcomes that can help Saudi universities to effectively achieve their environmental goals. Additionally, this research aligns with the broader objectives of the Green Saudi Initiative, as it seeks to contribute to the Kingdom's efforts in combatting climate change and reducing carbon emissions.

1.4. Structure of the Paper

The rest of this paper is structured as follows: Section 2 offers an overview of the concept of microgrids and the IEEE 1547 standards [48]. Section 3 focuses on the methodology and approach used for designing and modeling the microgrid system. Section 4 presents the results and discussions obtained from the implementation and analysis of the microgrid system. In Section 5, the paper concludes by summarizing the key findings and implications of the research and considering future directions for the research.

2. Microgrid Concept

This section presents a comprehensive overview of microgrids and their several types. It also provides an explanation of the IEEE 1547 family of standards, as well as highlights some of the valuable insights that were obtained from the microgrid dispatch.

2.1. Defenition

The Department of Energy (DOE) is taking microgrids into consideration as a was to shift to using a smart grid. Microgrids play an essential role in improving reliability, quality, and efficiency, as well as enabling grid independence on individual end-user sites. The DOE defines a microgrid as a group of connected loads and DERs that clearly functions as a unified and manageable entity in relation to the main power grid. A microgrid can connect or disconnect from the main grid, allowing it to operate either in conjunction with the grid or independently as an isolated system. A microgrid is defined in a similar way by others considering multiple generations and loads in addition to the ability to disconnect from the grid [49]. The paper shows some benefits of microgrids, such as enabling several smart grid technologies, integrating renewable energy resources (RESs), meeting the demands, and providing support for the microgrid. Therefore, microgrid workshops were held to identify the areas of R&D in the field of microgrids. The outcomes show technical, social, economic, and environmental benefits can be achieved from the deployment of microgrids [50]. Source [51] delivered an overview of microgrids, which are a group of interconnected energy resources and loads. They usually operate connected to the grid or work autonomously. There is no preferred generation or distributed energy resource (DER) technologies. A microgrid can involve a combination of resources and technologies [52]. There is no guidance on the size of microgrids, while the two features are:

- A microgrid is a locally controlled system.
- Microgrids function in islanded or interconnected modes.

The grid-connected mode means that the microgrid is connected to the distribution system at the point of common coupling (PCC). Figure 1 shows the architecture of the interconnected mode. However, the islanded mode can be used when the microgrid operates isolated from an infinite source, such as the distribution system, as shown in Figure 2.

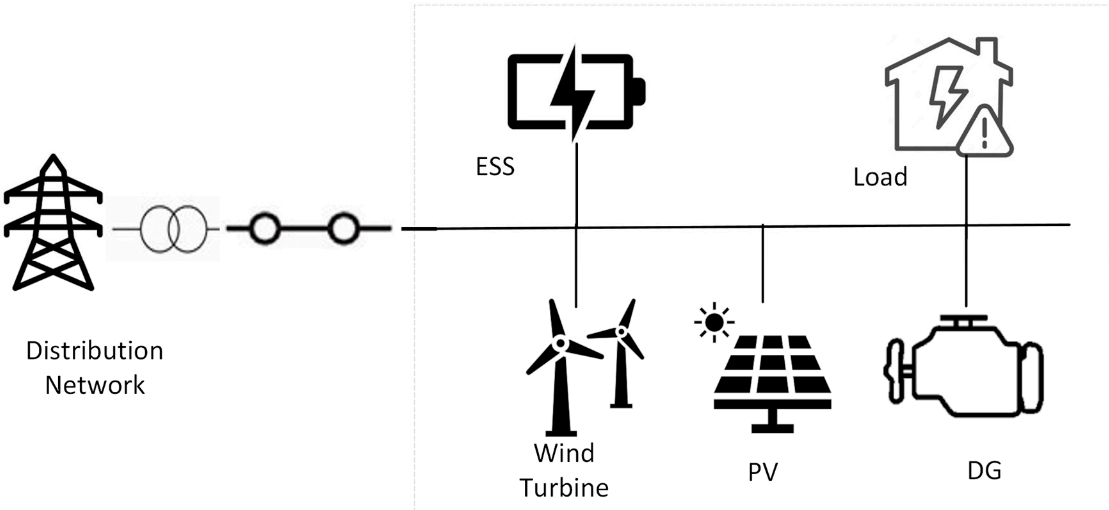

Figure 1. Architecture of an interconnected microgrid regenerated from [53].

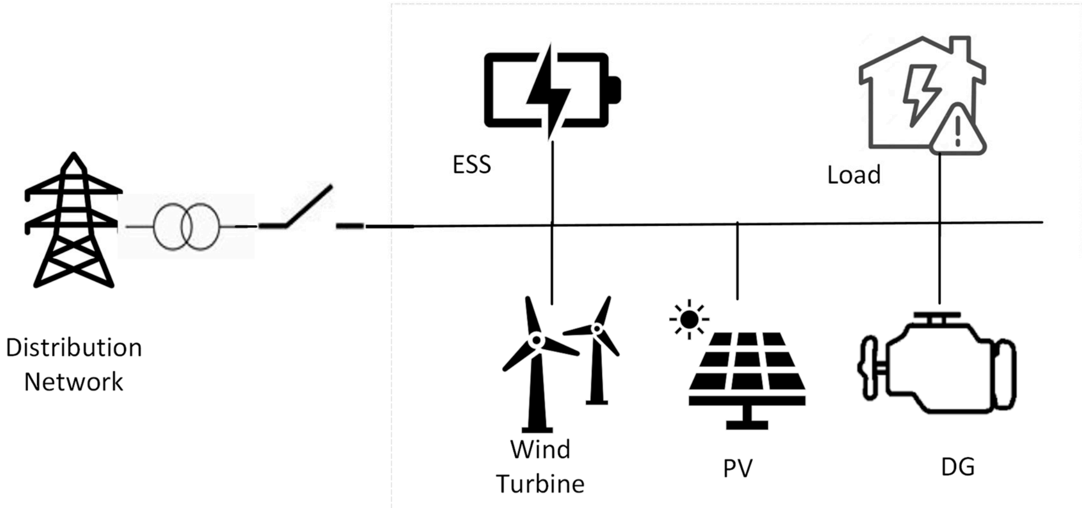

Figure 2. Architecture of an islanded microgrid regenerated from [54].

In addition to the microgrid benefits presented in the previous reference, there are many operational benefits, such as reducing energy loss, relieving congestion, and controlling the voltage. Furthermore, a locally managed grid can provide balanced choices, such as balancing efficiency and supply technologies investments. Moreover, the reference mentions that microgrids are proposed as a novel distribution network within smart grids. A roadmap for microgrid evolution is presented in [8] from engineering, economic, and experience perspectives. The CIGRE C6.22 working group defines microgrids and provides the necessary functions and techniques for microgrid deployment. Working group shows that microgrids have two fundamental requirements:

- Microgrids include sources and sinks under local control.
- Microgrids can operate in islanded or interconnected modes.

2.2. Types of Microgrids

A. Customer Microgrids:

This type is also called the true microgrid and it is popular due to its relaxed restrictions. It is also autonomous (self-governed) and usually downstream of a point of common coupling. An example of a customer microgrid is the Sendai Microgrid in Tohoku Fukushima University. The project comprises multiple generation sources, including 700 kW natural gas fired gensets, 50 kW PV systems, and a 200 kW fuel cell. The microgrid system is designed based on the concept of multi-power quality to ensure the reliable and efficient supply of electricity within the microgrid system [17,55].

B. Utility/community microgrids:

Community microgrids include a portion of the regulated distribution grid and must comply with the existing utility codes. It is important to mention that it has different regulatory and business models compared to the customer-owned microgrid. The Mannheim–Wallstadt microgrid in Germany is one of the most common community microgrids. The project caters to both residential and commercial units, encompassing diverse loads. It is designed with multiple on-site distributed generation technologies, including a 4.7 kW fuel cell, a 33.8 kW PV system, a 1.2 kW flywheel storage unit, and 14.5 kW gas and diesel generators [56].

C. Virtual microgrids:

This type of microgrid includes distributed energy recourses from multiple locations collectively presented to the grid as a single controllable entity, such as the Kyotango Microgrid, Japan [57].

D. *Remote microgrids:*

This type is gaining popularity in remote parts of the world. It can be defined as an isolated microgrid without access to larger grids, such as the Huatacando Microgrid in Chile, which we previously addressed [58].

2.3. International Standards

There are several issues associated with the integration of distributed generation with the electric grid. Hence, the authorities established different standards and guidelines related to microgrids and DER interconnection. These standards provide a comprehensive framework for understanding and implementing the necessary requirements and specifications to ensure optimal and reliable operations [59]. The IEEE Standard 1547-2003 is a guideline for interconnecting distributed resources with electric power systems [60]. This standard covers technical specifications and requirements for the interconnection as well as testing specifications and requirements. In fact, IEEE Std. 1547 provides criteria related to the performance, operation, testing, safety considerations, and maintenance of the interconnection of distributed resources to the electric grid. Additionally, the standard does not specify the particular equipment; the mentioned requirements for the standard type are universally needed to apply to the PCC. According to the standard, the requirements are applicable to all distributed resource technologies with a total capacity less than or equal to 10 MVA. The standard set general requirements are met at the point of common coupling. These requirements include voltage regulation, disconnections, grounding, monitoring, synchronization, and isolation. Additionally, it requires a response to abnormal grid conditions, such as faults, abnormal voltage, and abnormal frequency. In addition, the standard considers some power quality and islanding requirements. On the other hand, the standard requires some tests to ensure that the interconnection at the point of common coupling meets the requirements. The test allows us to design, produce, commission, and conduct periodic checks.

The IEEE standard for interconnecting distributed resources with electric power system amendment 1 is an updated standard approved in 2014 to change the IEEE Standard 1547-2003 [48]. The changes include some modifications to the interconnection technical specifications and requirements. Voltage regulation, under general requirements, was changed to force distributed resources to participate in regulating the voltage by varying the real and reactive power levels. Furthermore, the updated standard includes modifying some default responses to abnormal conditions in the electric power system. The default response of the clearing time to abnormal voltages was also changed. Furthermore, the default response to an abnormal frequency was modified based on under-frequency and over-frequency settings. This amendment ensured the distribution system accommodated the integration of distributed resources. It presents the best performance, operation, and maintenance of the interconnection. This is why the Energy Policy Act and Energy Independence and Security Act use such types of standards.

To understand the effectiveness of the previous standard, the setup of a real-time controller depending on IEEE Std. 1547-2003 was described to study the connection distributed generation to the electric grid. A case study was performed based on the concept of real-time hardware in the loop simulation. In fact, using real-time hardware in the loop simulation allowed us to evaluate the electric distribution system's performance with distributed generation and an industrial controller. Additionally, the real-time simulation was used as IEEE Std. 1547-2003 refers to the connecting and disconnecting of distributed generation during and after a fault. Therefore, a real-time digital simulator was employed to communicate between real-time and external hardware. In addition to the hardware in the loop component, the simulation setup for the distributed generation interconnection included actual system data in the southwest US and a fast-switching-inverter bridge that provided power quality control, voltage control, and phase angle controls. The case study was implemented under three conditions: the system operated with distributed generation under no faults, line-ground faults close to the distributed generation, and a distributed generation reconnection after five minutes [61]. Furthermore, the standard entitled "Testing of Microgrid Controllers" was another standard launched in 2018 under Std ID: IEEE P2030.8. This standard specifically focuses on the evaluation and assessment of the control functionalities associated with microgrid systems [62].

IEC 62898-1 is another international standard that offers comprehensive guidelines for the planning and specification of microgrid projects. The scope of this standard is to serve AC electrical systems and distributed energy resources (DERs) operating at low- or medium-voltage levels. However, DC-operated microgrids are not addressed in this standard. The first part of the standard focuses on various aspects of microgrid implementations, including microgrid application, resource analysis, generation, and load forecasting [63].

Furthermore, it covers power system planning in the microgrid system. The standard also outlines the requirements for DER integrations into microgrids, such as the control of, protection of, and connection to the distribution system. Additionally, the standard provides guidance on the evaluation of microgrid projects. The second part of the standard, IEC 62898-2, covers the regulations and guidelines relevant to the operational aspects and control mechanisms of microgrids. Hence, the scope of this standard includes the operation and transfer of modes within a microgrid. Furthermore, areas, such as the Energy Management System, communication protocols, and ESS, are also addressed [64]. The joint standard IEC/IEEE/PAS 63547 presents technical specifications and requirements for the interconnection, as well as test specifications and requirements. This standard serves as a framework for defining the criteria and prerequisites governing the interconnection of DERs below or equal to 10 MVA for electric power systems [65].

In Saudi Arabia, the Water and Electricity Regulatory Authority (WERA) provided an important update to the ERD-TA-004 regulatory system. This new version outlines the requirements for generating electricity, whether you are connected to the main power grid or not. One key point is that it sets a maximum limit of 30 MW for DER generation. This framework is designed to establish specific requirements for self-generation systems and provides a billing framework for grid-connected interconnections. Additionally, the regulations provide guidelines for the safety and reliability of DER installations. This includes proper construction, installation, maintenance, and operation practices. The standard includes a set of conditions that aim to ensure compliance with the grid codes in Saudi Arabia, such as the establishment of a connection point between the end-user and electricity grid through the PCC. Furthermore, it ensures meeting the regulatory requirements in the distribution and transmission codes, such as the technical design and operational criteria and boundaries. The framework also ensures all devices and equipment must comply with the laws and regulations of the approved standards and technical codes as provided by the Saudi Standards, Metrology, and Quality Organization [66,67].

3. Design and Modeling

In order to meet the university's strategic plan 2020–2025, microgrids are set to be a promoted solution. A microgrid system can provide a sustainable and reliable source of energy while reducing emissions. In this section, one building was selected to install a microgrid energy system. The Deanships building is an administrative building that plays a crucial role in serving students and beneficiaries. It includes several offices, each serving a different purpose. The Register Office is responsible for registering and maintaining students' academic records, while the Students Affairs Office provides support to students during their studies. The Grad School Office manages the graduate programs and supports students pursuing advanced degrees. The E-Learning Office provides students and faculty members with access to online learning resources and supports the use of technology in education. These offices work together to ensure the smooth operation of the administrative tasks required for students to succeed in their academic life. The Deanships building is an essential part of the university's infrastructure and serves as a hub for administrative activities that support students and beneficiaries. Table 1 provides an insight into the building.

Table 1. The building layout.

Facility	Number
Corridor	117
Elevator	51
Stairs	50
Stores	12
Maintenance room	61
Lobby	25
Mosque	4
Office	275
Market	2
Restaurant	1
Classroom	8
Services room	10
Sports room	5
Meeting rooms	6
Meeting hall	11
Toilet	18
Shop	2
Courtyard	2
Control room	1
Kitchen	26
Cafeteria	1
Theater	1
Training room	8

Accurately calculating the load demand is crucial for designing an appropriate energy system that can meet the energy requirements of the building. Google Earth was used to measure the building's total area. Figure 3 shows a Google Earth map that presents the dimensions of the building [68].

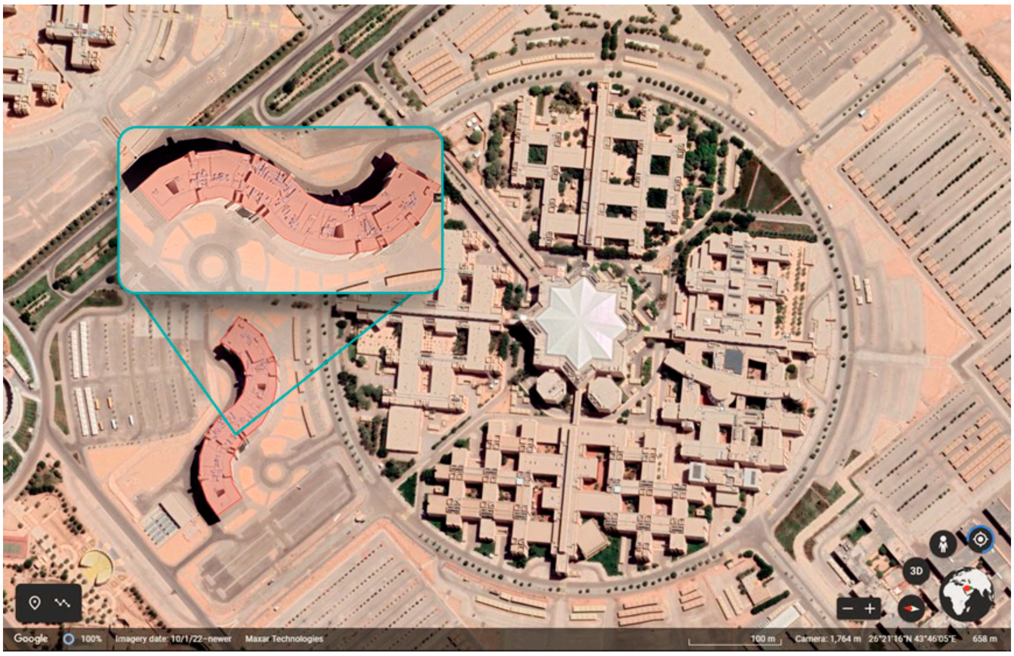

Figure 3. View of Qassim University.

3.1. Energy Consumption

The Saudi Electricity Company (SEC), the main electricity provider, launched a standard for the distribution plan. The standard provides an equation to estimate the total constructed area of the buildings. The built-up area (A) requires several inputs, such as land area (α), construction on the land (β), and the number of floors in the building (γ), as shown in the following equation [69]:

$$A = \alpha \times \beta \times \gamma \tag{1}$$

To calculate the total load for the building, we can refer to the distribution planning standard in [70,71], which provides guidelines for estimating the electrical loads connected to a building's power supply. In this case, the standard estimates the average load density to calculate the customer loads. The following equation shows the required information to calculate the total load (TL), where δ is the load density:

$$TL\ (KVA) = \frac{\left[A\ \left(\mathrm{m}^2\right) \times\ \delta\ \left(\frac{VA}{\mathrm{m}^2}\right)\right]}{1000} \tag{2}$$

Given the primary use of the building, it is appropriate to apply the optimal classification from the standard in [70] for the purpose of calculating the electrical loads. Thus, Table 2 shows the load densities of different load categories provided by SEC [70]. This approach solely considers the electrical loads associated with lighting and power sockets within the building. In this estimation, heating and air conditioning loads were not considered, as the emphasis of the analysis was on critical loads.

Table 2. Load densities of different loads.

Category	**Loads**	**VA/m²**
Furnished flats	Lights + Power Sockets	80
Hotels	Lights + Power Sockets	95
Malls	Lights + Power Sockets	75
Medical clinics	Lights + Power Sockets	100
Offices	Lights + Power Sockets	90
Public services facilities	Lights + Power Sockets	50
Indoor parking	Lights + Vans + Gates + Safety Systems	30
Outdoor parking	Lights	5
Parks and garden	Lights + Water Distributor	4
Light industries	Lights + Motors + Power Sockets	240
Recreational facilities	Lights + Power Sockets	90
Hospitals\medical facilities	Lights + Power Sockets	115

To obtain the annual energy consumption, we need to sum up the energy consumption for each hour. Equation (3) shows the formula for calculating the energy consumption for per year.

$$E_{kWh} = \frac{P_{Wh} * t\ (hrs)}{1000} \tag{3}$$

3.2. Hybrid Microgrid

In this subsection, we studies the development and design of the hybrid microgrid for the building. Figure 4 shows the structure of the microgrid. The connected loads were linked to the AC bus, while a PV solar system and an energy storage unit were connected to the grid using bidirectional inverters. The storage system played a key role in the microgrid operation, especially during high-demand scenarios and unexpected power outages. Therefore, the system provided an energy supply from batteries or uninterruptable power supply systems.

Since the building had a critical load, such as servers and emergency exit lights, a storage system was considered to harness the surplus energy generated by the PV system. This strategic design allowed the storage system to efficiently charge during periods of excess energy production. Therefore, the building could ensure a reliable power supply to the critical load during outages.

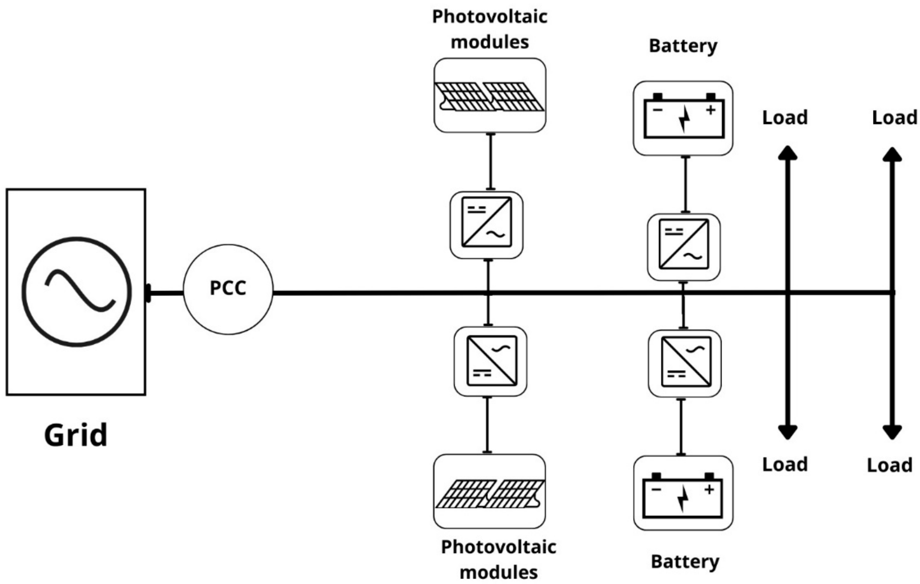

Figure 4. Microgrid configuration.

In our case, a mathematical model was used to calculate the produced electricity power from the PV system, based on several parameters. This model was provided by the National Renewable Energy Laboratory (NREL) [72,73]. The model used different factors, such as sunlight, temperature, and metrological inputs. However, the model showed its simplicity as there were two primary input variables: effective irradiance (E_e) and PV cell temperature (T_c). Therefore, depending on the above, the maximum power point (P_{mp}) using Equation (4) is:

$$P_{mp} = \frac{E_e}{E_0} P_{mp0}[1 + \gamma(T_c - T_0)] \tag{4}$$

where

E_0: reference irradiance $(1000\ \frac{\text{W}}{\text{m}^2})$;
T_0: reference temperature $(25\ ^\circ\text{C})$;
γ: temperature correction.

Several studies suggest equations to calculate the total radiance depending on different inputs. According to [74], the cell radiation received on the module plane (E_e) is defined as:

$$E_e = \frac{I_{sc}}{I_{sc0}\{1 + \alpha_{Isc}(T_c - T_0)\}} \tag{5}$$

where

I_{sc}: the short circuit current;
α_{Isc}: the normalized temperature coefficient for the short circuit current.

The microgrid was operated in a grid-connected mode, where the microgrid consisted of a PV solar system, batteries, and loads. The operation of the microgrid can be presented by a flowchart with several steps, as shown in Figure 5. The PV output is compared to the load demand. If the PV output is greater than or equal to the load, the microgrid supplies the load while charging the battery. When the PV output is insufficient, the microgrid supplies the load directly from the battery and then checks the SOC against the minimum SOC threshold. If the SOC is below the threshold, the flow returns to the supply from the battery; otherwise, the microgrid sources power from the main grid to supply the load. This flowchart process ensures the smooth operation of the microgrid, adapting to varying

PV outputs and load demands while maintaining the battery's SOC within the specified limits [75,76].

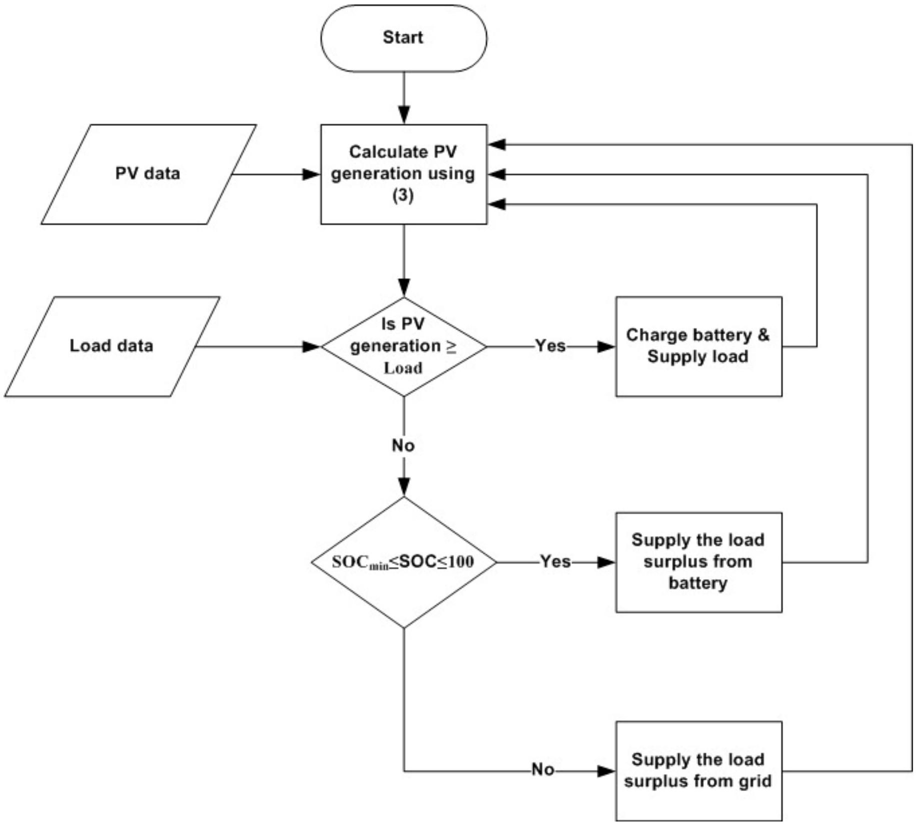

Figure 5. Microgrid simulation process.

In the A7 building, the implementation of a microgrid was planned to operate in a mode that remained connected to the main electrical grid. This microgrid system comprised various components, such as PV panels, an inverter, batteries, and associated cables. To determine the ideal PV panel size, the Saudi Water and Electricity Regulatory Authority proposed considering the available rooftop space on the A7 building [77]. This recommendation assisted in estimating the anticipated energy output achievable from a specific area or system size, taking into account the geographical location of the building [78]. Key inputs for the microgrid specification are outlined in Table 3 [79,80].

Table 3. Microgrid specifications.

Component	Parameter Descriptions
Size	785 kWdc
Array type	Fixed open track
Module type	Standard
Cell material	mono-crystalline silicon
Tilt	26.34°
Azimuth	180°
DC to AC ratio	1.2
Rated inverter size	654.17 kW
Inverter efficiency	96%
Ground coverage ratio	0.4
Battery type	Lithium ion
Battery capacity	2774 kWah
Battery power	412.33 kW

This section introduces a proposed model aimed at aligning with Qassim University's environmental strategy, which involves utilizing a microgrid in one of the campus buildings. The proposed model involved several steps, including measuring the building, determining the average daily energy consumption, and designing the appropriate solar system size to meet the building's load demand.

4. Results and Discussion

This section provides an analysis of the performance of the microgrid operation. It quantifies the energy generation capacity of the microgrid, considering the contributions from various sources, such as solar panels, battery system, and the main grid.

4.1. Load Calculations

The information in Figure 3 estimates the building's energy requirements. According to Figure 3, the building includes four floors that are built on an area of 7700 m^2. Furthermore, the basement was constructed to cover an area of approximately 13% of the land area. This meant that most of the estimated emissions were caused by operations conducted using the four floors. In terms of the building's electrical connectivity, it was connected to the main electricity provider through two primary feeders. The first feeder was dedicated to supplying power specifically to the central air conditioning system, ensuring a comfortable and regulated indoor climate. On the other hand, the second feeder served multiple purposes. It supplied electricity to smaller air conditioning units that were responsible for cooling the servers, networking equipment, and storage devices. Additionally, this feeder supplied other electrical sources within the building, including lighting systems, computers, servers, printers, photocopiers, plug loads, and other office equipment. It also supported the essential communication infrastructures, such as telephone lines, routers, and wireless access points. In our scenario, our focus was directed towards analyzing the power supply sourced from the second feeder. However, it was important to note that the load associated with the small AC units connected to this feeder was excluded from our study. Therefore, our analysis considered the energy delivered to fulfill the electrical requirements. Figure 6 illustrates the typical daily load curve observed in this context.

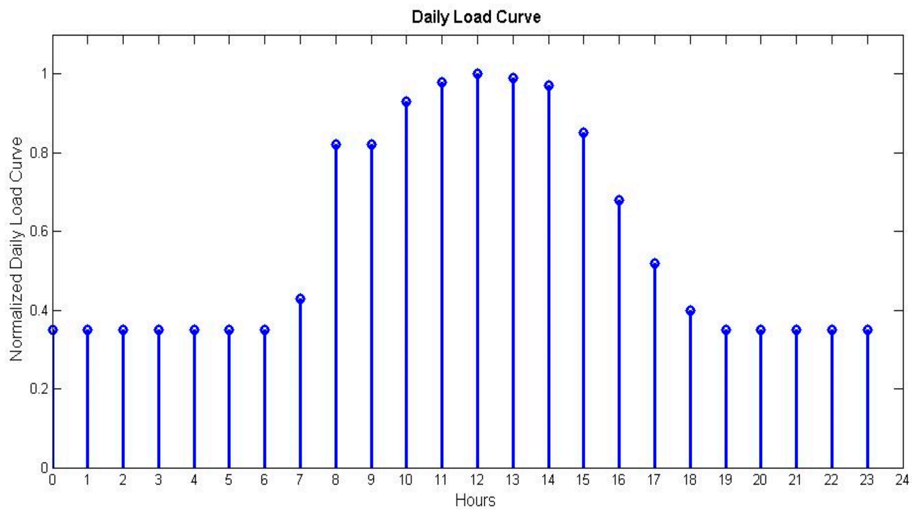

Figure 6. A typical daily load curve in the administrative building.

In Saudi Arabia, business operations typically commence at 8:00 a.m. and conclude at 2:00 p.m. from Sunday to Thursday. In Figure 6, we notice that the load profile experiences minimal variations throughout the day and remains consistent across different seasons. This was primarily attributed to the predominant demand stemming from administrative requirements. Outside of the designated business hours, the demand remained stable. This was due to the necessity of providing a continuous power supply to critical loads, including security systems, communication and data access systems, fire protection systems, and alarms.

It should be noted that the energy load can vary based on the day. As a result, we could categorize the days in each month into three specific groups. Firstly, there were business days, when the building was operational and provided services to beneficiaries. Secondly, there were student holidays, which encompassed days when students were on vacation, such as extended weekends or winter breaks, while employees still occupied the office. Lastly, there were weekends and public holidays, when the building remained closed. Therefore, the monthly energy demand was influenced by the number of days falling into each of these three categories within a given month. Table 4 presents the number of days for each month during 2022 [81].

Table 4. Days for each category in 2022.

Days	January	February	March	April	May	June	July	August	September	October	November	December
Days/months	31	28	31	30	31	30	31	31	30	31	30	31
Weekends	9	8	8	10	8	8	10	8	9	9	8	10
Student holidays	5	4	5	0	2	2	21	20	0	2	5	2
Official holidays	0	1	0	5	5	0	0	0	2	0	0	0
Business Days	17	15	18	15	16	20	0	3	19	20	17	19

Based on the information in Table 4, it is obvious that the monthly electricity demand varies in accordance with the type of days in each month. Figure 7 presents the monthly energy demand for the year 2022, which reflects the relationship between the type of days and the energy demand.

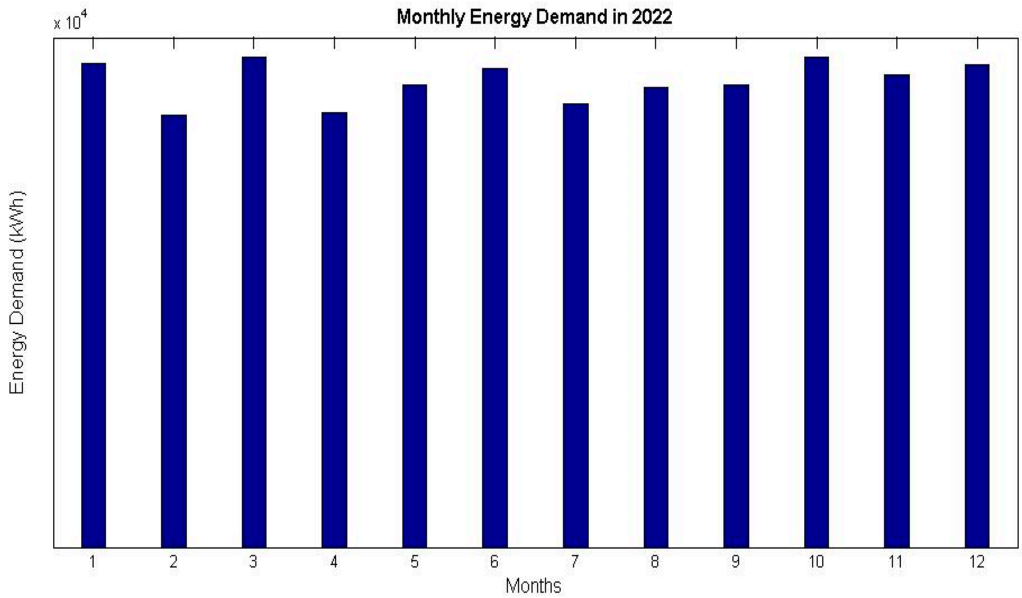

Figure 7. Energy demand in the building in 2022.

The provided dataset illustrates the monthly electricity demand observed during 2022. Throughout the months, the demand values exhibit fluctuations, with the highest peak occurring in March. This can be attributed to the presence of 18 business days and 5 days designated as holidays for students. However, February represents the month with the lowest demand. Despite June having 20 business days, its power demand ranks lower than that of March. This observation highlights the influence of student vacation days on the overall demand pattern. Even during the summer break, June still exhibits a high electricity demand, indicating minimal disparity between business days and days when students are on a break. The results show the seasonal variations in 2022 do not significantly impact the demand patterns.

4.2. Weather Data

The Qassim region exhibits weather conditions that contribute to the generation of electricity from solar sources. The region experiences abundant sunshine throughout the year, with a high number of clear and cloudless days. The intense and consistent solar irradiance provides a conducive environment for solar energy systems to harness and convert sunlight into electricity. This makes Qassim province an ideal location for the deployment of solar power projects, as it maximizes the potential for generating clean and sustainable energy. Based on the measured data, the average solar radiation and plane of array irradiance levels are presented in Figures 8 and 9, respectively.

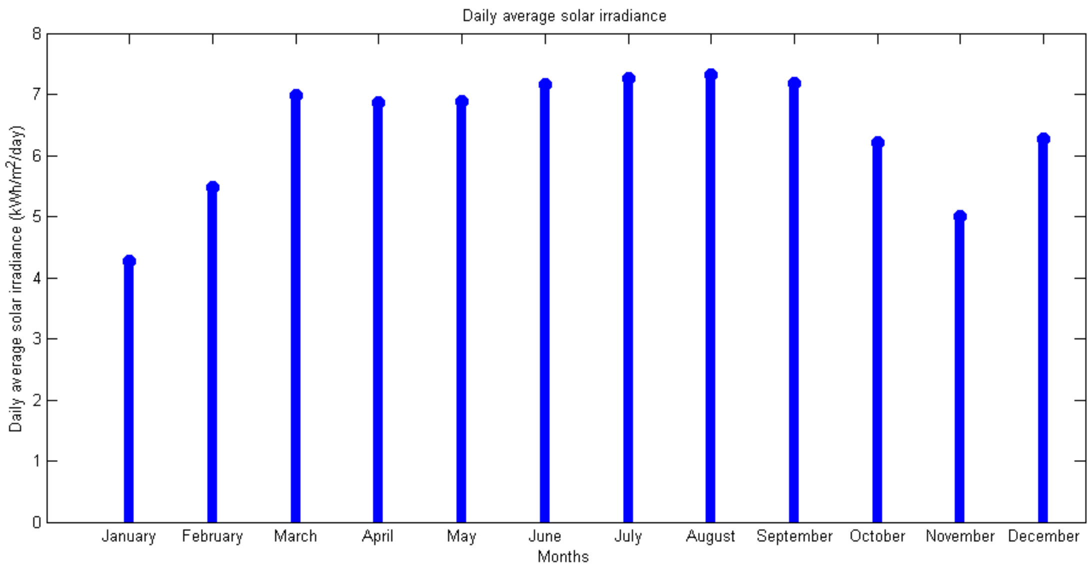

Figure 8. Daily average solar radiation levels in the Qassim region.

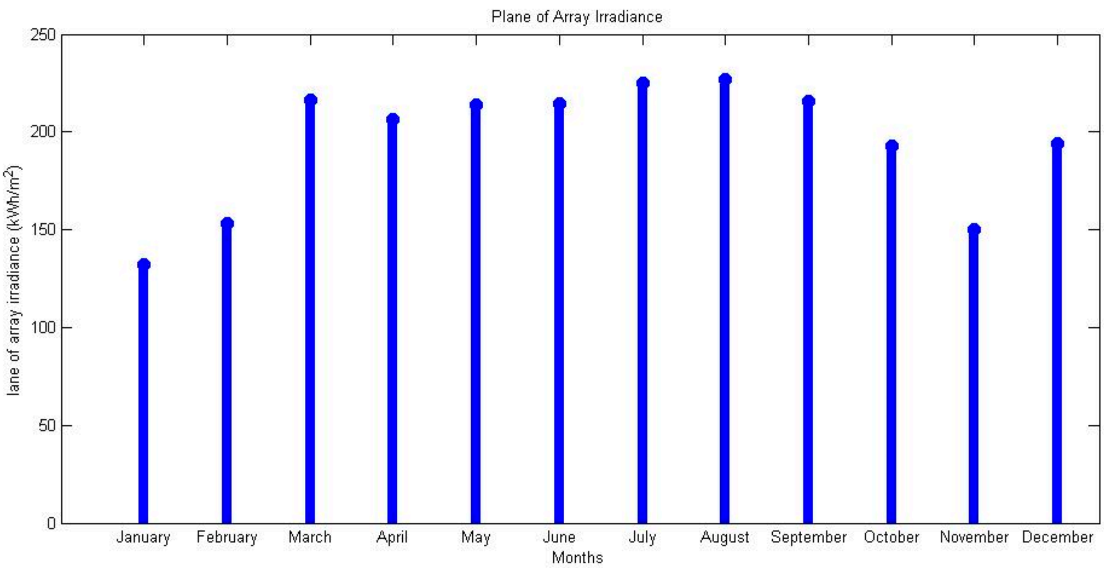

Figure 9. Plane of array irradiance levels in the Qassim region.

According to the findings in Figure 8, the average solar radiation exhibits a range of values throughout the year. In January, the solar radiation stands at its lowest. The average solar irradiance continues increasing in the first quarter of the year. Furthermore, the solar irradiance remains relatively high from April to June. The data also show an increase in solar radiation levels from July until reaching the peak in August. However, solar irradiance begins to decline from September, before experiencing a slight increase in December.

From Figure 9, it is obvious that there are variations throughout the year. The highest irradiance levels occur in the summer months. This indicates that the solar panels receive ample sunlight and have the potential to generate significant energy during this period. On the other hand, the lowest irradiance values are observed during the winter months, with January having the lowest value. These fluctuations in irradiance levels highlight the seasonal nature of solar energy availability in the region [72].

4.3. Microgrid Operation

The simulation process involved defining the necessary data for the A7 building, as shown in Figure 3. These data encompass various aspects, such as the energy demand profile, geographical location, meteorological data, and the specific design of the system. The simulation tool employed for this purpose was the system advisor model (SAM), a powerful tool developed by NERL. SAM allowed for a comprehensive analysis to be conducted to evaluate the performance of the proposed system in the A7 building [78,82]. The simulation outcomes demonstrate the efficacy of the proposed model in effectively fulfilling the load requirements while concurrently achieving a notable reduction in CO^2 emissions linked to electricity generation within the university campus. The results show that the model serves as a viable solution to meet the energy demands in the A7 building while prioritizing environmental sustainability. Furthermore, the proposed approach significantly contributed towards minimizing the campus's carbon footprint, aligning with the university's commitment toward environmental stewardship and sustainable practices.

The data in Figure 10 show a clear relationship between time, electricity load, and solar panel output. During daylight hours, both the electricity load and solar panel output steadily increased. This indicates that the solar panels are effectively generating electricity and helping to meet the demands. However, both the electricity load and solar panel output gradually decreased as the evening approached, with minimal to no solar panel outputs during nighttime hours.

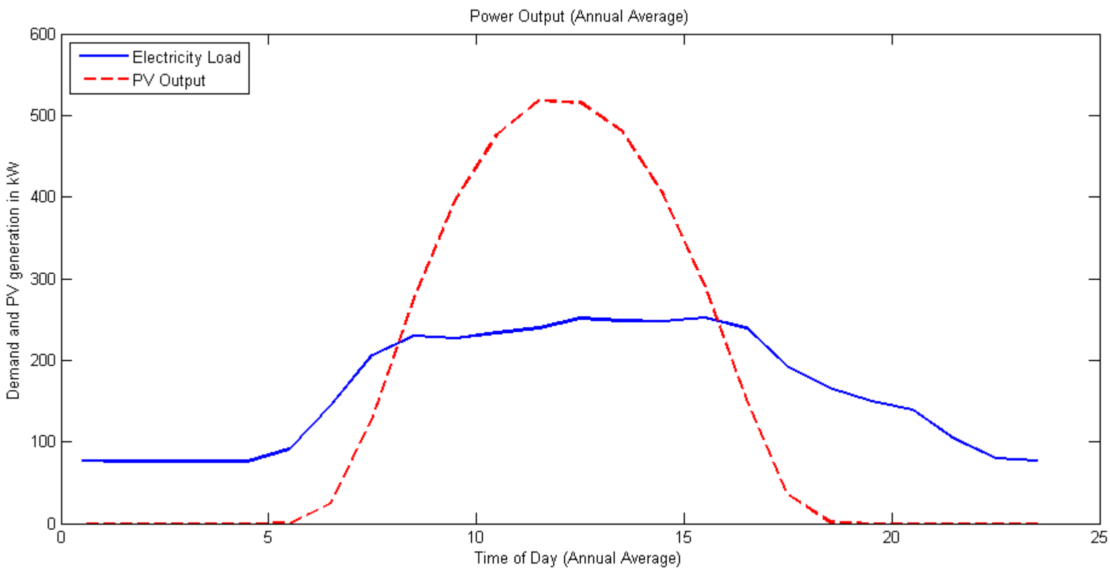

Figure 10. Electricity load and PV output.

The data presented in Figure 11 illustrate the relationship between the battery SOC and solar panel output. The battery capacity is influenced by the energy produced by the solar panels, which is stored in the battery during periods of high solar output. However, the battery discharges its stored energy to meet the electricity demand during the night. This dynamic operation allows for efficient energy management and utilization within the microgrid. Moreover, Figure 12 illustrates that more energy is drawn from the battery to meet the load demand during the winter season. As a result, the highest energy consumption levels from the battery are observed in December and March, while the lowest consumption activities occur in June and July. Furthermore, the PV generation shows a clear seasonal pattern, with a peak output during spring and reduced output during summer. Therefore, the microgrid system utilizes the stored energy in the battery and optimizes solar energy utilization during the year.

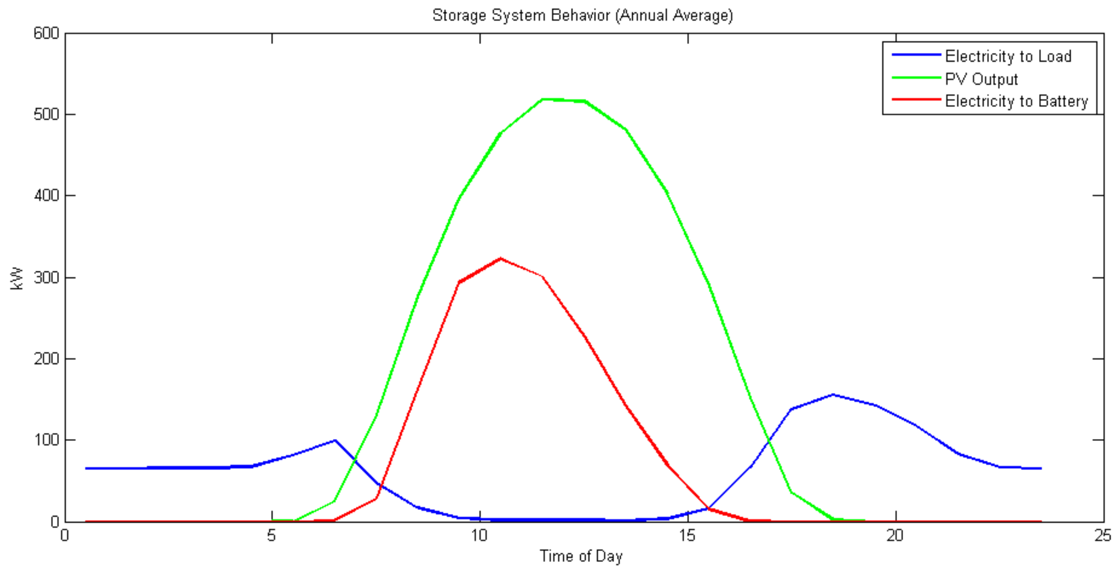

Figure 11. Battery behavior.

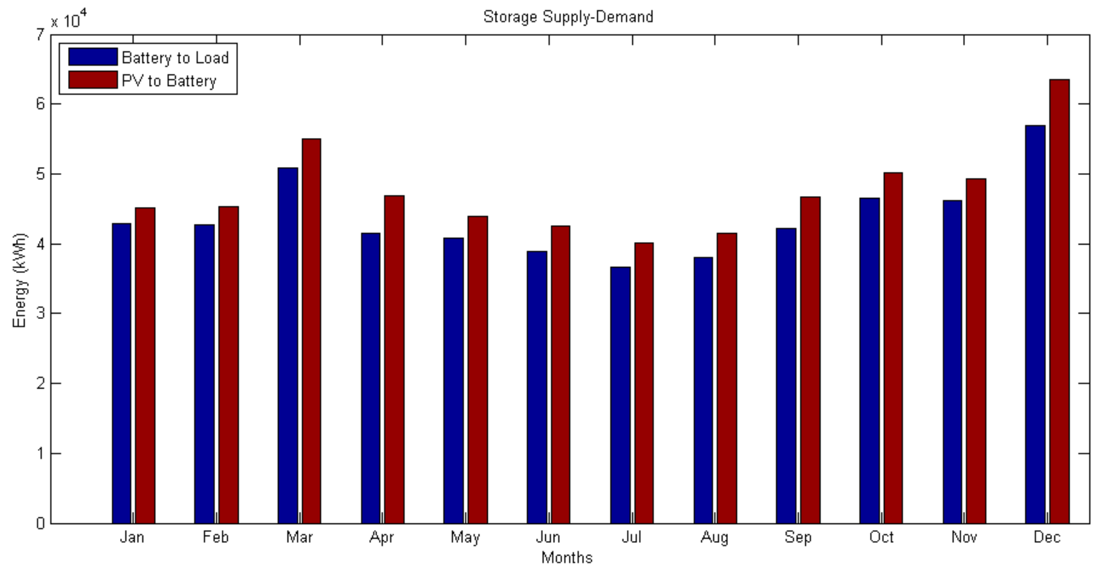

Figure 12. Battery supply and demand.

The data presented in Figure 13 illustrate the supply–demand balance during the operation of a microgrid. In the early hours of the day, the primary source of electricity comes from the battery, while the main grid plays a minor role. As daylight gradually increases, the significance of the PV output grows, reducing the reliance of the battery for the electricity supply. In the mid-morning to early afternoon, the PV system reaches its peak output, supplying a significant level of electricity. The surplus energy is stored in the battery for later use. However, as the evening approaches, the PV output declines, leading to an increased gap between demand and supply. During this time, electricity is sourced from the battery, with minimal contribution from the grid. Overall, these observations highlight the dynamic interplay between electricity supply and demand within the microgrid, emphasizing the vital role played by the microgrid to displace the supply from the conventional generation.

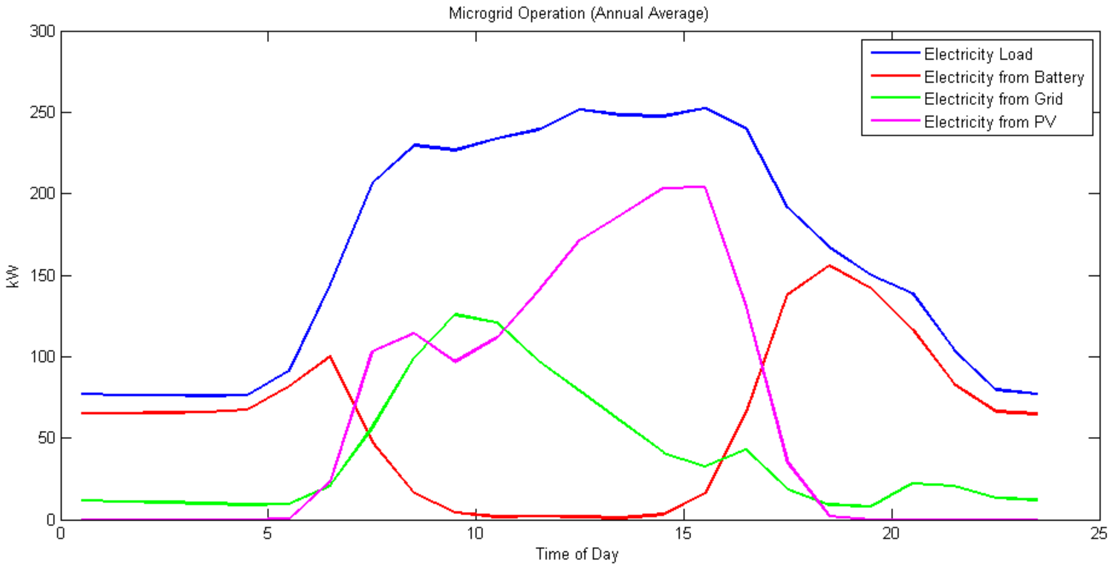

Figure 13. Microgrid operation based on the load profile.

The monthly energy supply sources for the electricity load can be observed in Figure 14. The PV system contributes to the energy to the load, with varying amounts throughout the year. Hence, the highest monthly supply from PV sources is observed in June, while the lowest supply from PV sources is observed in January. The previous results highlight the importance of considering seasonal variations in solar energy production. The grid also supplied energy to meet the load demand, where the highest value was recorded in January with [supply value], while the lowest supply from the grid was observed in July. Additionally, the battery system plays a role in providing additional energy when needed. The highest supply from the battery was observed in December, while the lowest supply from the battery was observed in July.

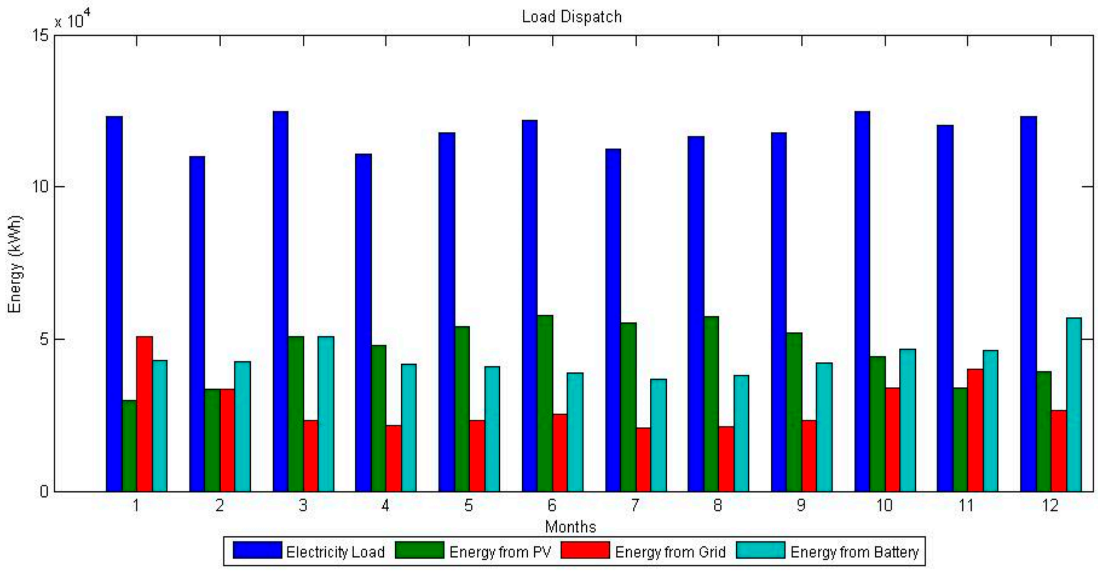

Figure 14. Load dispatch from each source.

Figure 15 presents the monthly energy requested from the main grid to meet the demands. The findings demonstrate the significant potential of microgrids to reduce energy reliance on the main grid. So, we notice reductions in energy consumption levels from the main grid in both the PV-only and PV and storage scenarios, particularly during the summer season. The PV-only scenario presents a decrease in the main grid supply from approximately 24% in January to a peak reduction of up to 49% in July and August. However, the PV and storage scenario reduces the dependency on the main grid supply from 58% in January to an impressive 82% reduction in August.

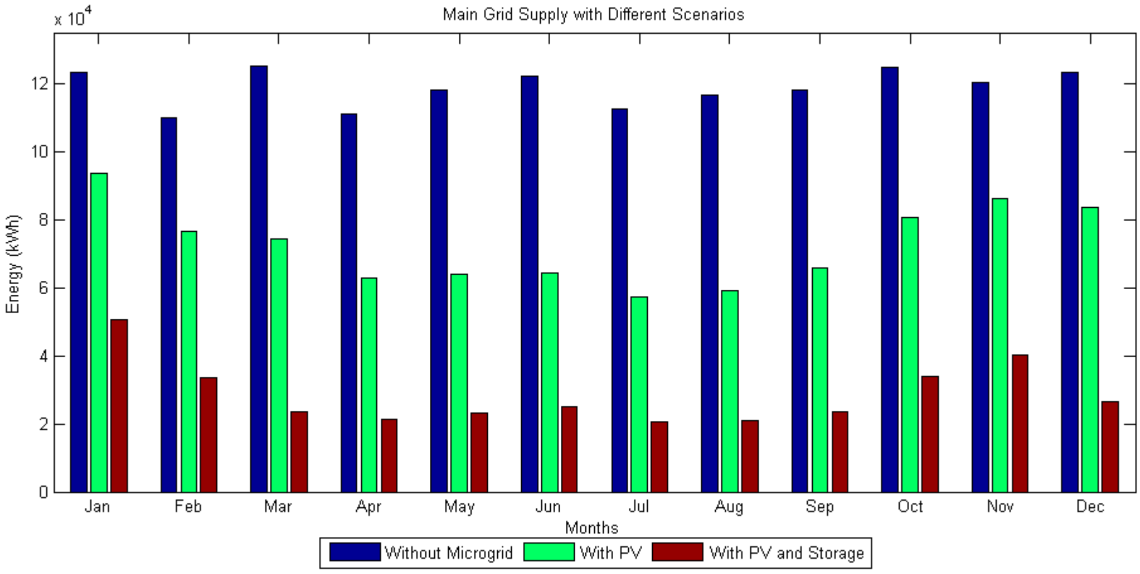

Figure 15. Main grid supply before and after microgrid use.

Based on the outcomes derived from the operation of the microgrid, the subsequent section presents a comprehensive analysis that quantifies the environmental implications of implementing such a microgrid system. Specifically, the calculation focuses on evaluating the potential reduction in emissions linked to electricity generation and examines the alignment of the microgrid with the broader goals outlined in the university's strategic plan. By assessing the impact of this energy solution, valuable insights can be gained regarding its contribution towards achieving sustainability objectives and minimizing the emissions footprint associated with campus electricity consumption.

4.4. Environmental Considerations

The integration of the microgrid presents an opportunity for the university to both reduce its energy consumption and achieve other strategic initiatives, such as the green campus program, total carbon footprint, and indoor environmental quality. Based on the previous results, the microgrid demonstrates its positive environmental impact on minimizing emissions and promoting sustainable energy practices. To evaluate the benefits of the PV system microgrid in terms of CO^2, the GHG equivalencies calculator can be employed to convert energy data into an equivalent amount of CO^2 [83]. This method allows for an assessment of the impact of the PV storage system microgrid on the university's sustainability efforts. Figure 16 highlights the CO^2 reduction for each month during the year. Such a reduction is affected by the microgrid load dispatch and monthly demand, as explained in Table 4.

The results provide data on CO^2 emissions before and after the implementation of the microgrid; it is obvious that significant reductions are achieved. The greatest reduction in emissions was observed in December. Furthermore, the microgrid also demonstrated its effectiveness in minimizing emissions during the remaining months. The lowest reduction was seen in January, with a decrease from 53.2 to 21.9 CO^2e units. This highlights the consistent impact of the microgrid on reducing emissions throughout the year. Therefore, the implementation of the microgrid led to notable reductions in CO^2e emissions across all months. Such a significant reduction in the dependance on traditional sources of electricity generation presented several benefits, including contributing to the achievement of the university's sustainable projects and goals. This reduction might have a positive impact on the environment and economy, as the demonstration of microgrid technologies can help diminish CO^2 emission levels, increase energy independence, and reduce the cost of electricity generation.

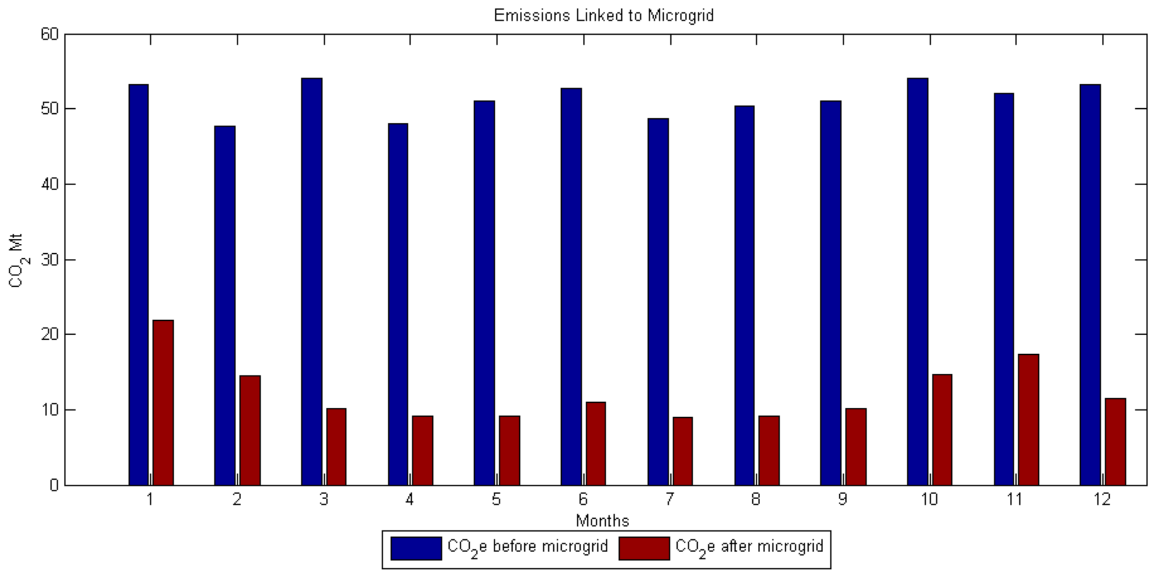

Figure 16. Emissions per month before and after microgrid use.

From the results, the energy generated through the operation of the microgrid led to a significant reduction in emissions. Specifically, we observed a remarkable decrease from 615.8 to 147.4 Mt of CO^2. The avoided CO^2 were converted into different types of equivalent units, as shown in Table 5 [83]:

Table 5. Equivalencies of avoided CO^2.

Number	Type
524,680	Pounds of coal burned
1083	Barrels of oil consumed
91	Homes' electricity use for one year
17,753	Incandescent lamps switched to LEDs
7745	Tree seedlings grown for 10 years

The findings of the study suggest that implementing the proposed model has a notable ability to mitigate the carbon footprint level, contributing to the achievement of the university's green initiatives. The calculated reduction in the carbon footprint highlights the potential of the proposed model to promote sustainable practices within the university community and help mitigate the environmental impact of energy consumption.

4.5. Validation Analysis

To validate the results, our findings were compared to the Shamsi calculator, developed by WERA. This tool is designed to assist users in evaluating the potential benefits of installing solar panels in Saudi Arabia [77]. Shamsi customizes solar resource data obtained from the King Abdullah City for Atomic and Renewable Energy. The utilization of these tools yields numerous benefits to compute a wide range of PV system design parameters, such as module orientation, tracking, sun position and atmospheric conditions, module temperature, shading, as well as inverter efficiency and clipping. In our work, we used the data provided in Table 4 to investigate the system's performance. Hence, the Shamsi tool predicted an annual generation of 1.40 GWh for the A7 building. However, the PV generation analysis in Section 4.3 presented an annual generation of 1.35 GWh at the same location. By comparing these results, we can observe a difference of approximately 3.70% between the two sets of findings. Another factor is the capacity factor. Our results for the system in the specified location show a capacity factor of 23.5%. It is important to mention that other studies investigating the installation of PV systems in different locations in Saudi Arabia, specifically Jeddah and Madinah, reported capacity factors of 22% and 20.2%, respectively [84,85].

From the environmental perspective, the analysis indicated a significant 76% reduction in CO^2 emissions achieved through the implementation of a microgrid relying on environmentally friendly green technology sources. This represents a minor 1% difference when compared to a similar study cited in the literature, which reported a 75% decrease in emissions [35]. Additionally, another study presented different scenarios concerning a campus microgrid. Their outcomes showed a 78% reduction in CO^2 emissions by using the PV storage scenario, which was a 2% difference. Table 6 illustrates a comparison between our simulation outcomes and other research studies from different locations.

Table 6. A comparison between the outcomes and other research studies.

Source	Energy Production (GWh/Y)
Research findings	1.35
Shamsi calculator	1.40
Source	**Capacity Factor (%)**
Simulation findings	23.5
[85]	22
[84]	20.2
Source	**CO^2 Reduction (%)**
Simulation findings	76
[35]	75
[86]	78

5. Conclusions

This paper thoroughly investigated the potential of microgrid technology in mitigating the impact of climate change. It can be observed that microgrids are a key technology with significant potential to reduce the environmental impact of energy consumption. The study provided a comprehensive overview of microgrid technology, including its impact on the climate and future prospects. Additionally, the paper outlined the technical specifications and requirements for interconnections used in the international and national standards. Moreover, several types of microgrids and successful examples of microgrid system implementations were explained in this work.

The aim of this study was to explore the potential solutions for reducing emissions from the main campus of Qassim University in Saudi Arabia. The proposed model in this study was in line with Qassim University's environmental strategy, which included the installation of a microgrid system on the rooftop of the A7 building. The model comprised various steps, such as determining the built-up area, observing the average daily energy consumption, and designing the appropriate microgrid system to meet the building's load demands. The findings of this study demonstrate the effectiveness of the microgrid system in achieving a supply–demand balance, as well as reducing CO^2 emissions. The results show that microgrid technologies can help in achieving the university's strategic plan in terms of sustainability. The dynamic operation of the microgrid highlighted a shift in primary electricity sources, with the battery and solar panels supplying electricity during different periods of the day. Furthermore, the results demonstrate that the proposed model has the potential to reduce the carbon footprint, 615.8 to 147.4 Mt of CO^2, thereby contributing to the university's green initiatives. The microgrid approach promotes energy independence and resilience, offering a sustainable solution for the university to mitigate the environmental impact of its energy consumption levels. The utilization of such an engineering solution presents an opportunity for the university to not only reduce its energy consumption levels, but also achieve other strategic initiatives, such as the green campus program and more environmentally friendly buildings.

While our research focused on assessing the emissions reduction potential associated with microgrid installations, the economic analysis of such an undertaking holds significant importance. Therefore, a separate paper is presently being written to evaluate the economic perspective of implementing a microgrid. This forthcoming paper aims to study the financial parameters, including investment costs, operational expenses, and potential savings. Moreover, it will quantify the impact of financial incentives on the feasibility and cost-effectiveness of adopting microgrid systems. In line with this, the university is actively exploring ways to diversify its funding resources to support the deployment of microgrid systems and further contribute to a greener and more sustainable future. Additionally, the evaluation will consider the environmental cost, providing a comprehensive understanding of the economic viability of microgrid installations.

Our future path aims to expand the scope of our research to explore the integration of EVs into the microgrid system at Qassim University. Specifically, the plan is to investigate the feasibility of installing EV charging stations in the parking lots and integrating them into the microgrid system. This will not only facilitate the transition to sustainable transportation, but also provide an additional source of energy storage for the microgrid. Such additions will further enhance the sustainability of the university campus and contribute to the achievement of the university's strategic plan for sustainability.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: Researchers would like to thank the Deanship of Scientific Research, Qassim University, for funding publication of this project.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviation

CO^2	Carbon Dioxide
DOE	Department of Energy
DERs	Distributed Energy Resources
EVs	Electric Vehicles
GHGs	Greenhouse Gas Emissions
IEEE	Institute of Electrical and Electronics Engineers
NREL	National Renewable Energy Lab
PCC	Point of Common Coupling
RESs	Renewable Energy Sources
SAM	System Advisory Model
SEC	Saudi Electricity Company
PV	Photovoltaic
SOS	State of Charge
WERA	Water and Electricity Regulatory Authority
List of symbols	
A	Built-up area
α	Land area
β	Construction on the land
γ	Number of floors in the building
TL	Total load

δ	Load density
E_e	Effective irradiance
E_0	Reference irradiance
T_c	PV cell temperature
T_0	Reference temperature
γ	Temperature correction
P_{mp}	Maximum power point
I_{sc}	Short circuit current
α_{Isc}	Normalized temperature coefficient for short circuit current

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