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Review

A Comprehensive Review of Existing and Pending University Campus Microgrids

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Abstract: Over the past few decades, many universities have turned to using microgrid systems because of their dependability, security, flexibility, and less reliance on the primary grid. Microgrids on campuses face challenges in the instability of power production due to meteorological conditions, as the output of renewable sources such as solar and wind power relies entirely on the weather and determining the optimal size of microgrids. Therefore, this paper comprehensively reviews the university campuses' microgrids. Some renewable energy sources, such as geothermal (GE), wind turbine (WT), and photovoltaic (PV), are compared in terms of installation costs, availability, weather conditions, efficiency, environmental impact, and maintenance. Furthermore, a description of microgrid systems and their components, including distributed generation (DG), energy storage system (ESS), and microgrid load, is presented. As a result, the most common optimization models for analyzing the performance of campus microgrids are discussed. Hybrid microgrid system configurations are introduced and compared to find the optimal configuration in terms of energy production and flexibility. Therefore, configuration A (Hybrid PV- grid-connected) is the most common configuration compared to the others due to its simplicity and free-charge operation.

Keywords: renewable–nonrenewable energy; microgrid; campus microgrid

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1. Introduction

Adopting a utility power source is not an optimal solution due to its reliance on fossil fuels, which are both costly and detrimental to the environment. Hence, switching to renewable energy sources (RESs) is essential owing to their significant benefits [1]. RESs such as wind, solar, geothermal systems, biomass, tidal, and hydroelectricity are more effective, reliable, low maintenance, and offer efficiently lower carbon dioxide (CO_2) emissions and a quieter atmosphere [1–3]. In addition, RESs are cheaper than traditional resources in the long run, reducing energy costs while providing loads with dependable and sustainable energy. Furthermore, RESs can be integrated with nonrenewable energy sources, such as combined heat and power (CHP) and diesel generators (DGs), to fulfill the electricity demands and maximize power efficiency [4,5]. The advantages of RESs vary according to each source's conditions. For instance, geothermal energy (GE) is considered one of the most promising clean, renewable sources because it depends entirely on the Earth's heat to drive steam turbines that produce electricity. GE is available year-round and unaffected by weather and consequently stabilizes energy output, unlike other renewable energy sources, including wind, hydro, and solar panels [3,6]. Moreover, GE can be installed vertically almost everywhere, requiring less space than wind and solar. Accordingly, GE, wind, and solar panels each require approximately 404, 1335, and 2340 square miles of land surface to generate 1 gigawatt-hour (GWh) of electricity [7]. It is preferable for GE to be installed in an easily accessible area since it goes hundreds of meters below the surface of the Earth. The costs of producing 1 kilowatt (KW) utilizing geothermal, wind, and solar power are USD 3478, USD 1274, and USD 3.025, respectively [8–10]. In 2022, the worldwide installed capacity of wind, solar, and geothermal power reached 906 GWh, 710 GWh, and 14.9 GWh, respectively [8,10,11]. Due to the high cost of drilling boreholes and the high initial costs of facility construction, GE is a more costly power source compared to wind and solar [3,12,13]. Table 1 presents a comparison of renewable energy sources [14–24]. In summary, geothermal, wind, and solar power have similar characteristics, such as clean, sustainable energy sources and low environmental impact. Nevertheless, there are differences in terms of their availability, effectiveness, and installation expenses. Additionally, choosing renewable energy sources relies on such factors such as geographical location and energy demands.

Table 1. Comparison of renewable energy sources.

Aspect	Solar Energy	Wind Turbines	Geothermal Energy
Availability	Depending on the location	Depending on the location	Worldwide
Efficiency	22%	20–40%	32%
Maintenance	Regular	Regular	Low
Installation cost	High	Low	High
Environmental impact (Greenhouse gas)	Low impact	Low impact	No impact
Weather conditions	Affected	Affected	Unaffected

Hybrid power systems (HPSs) can produce electricity by combining two or more renewable and nonrenewable energy sources [25]. A hybrid energy source consists primarily of renewable energy sources, such as photovoltaic (PV), wind turbines (WT), and GE, and conventional energy sources, such as CHP, DG, and storage systems. Figure 1 shows the hybrid power systems. The HPS depends only on one power source to minimize costs and improve system efficiency. Hence, HPS is the most popular option used. There are some advantages of HPSs, such as providing energy to remote areas with high efficiency without the fixed source vulnerability associated with large-scale networks, which can lead to power grid failure [26,27]. In addition, the HPS reduces fuel costs while minimizing line losses and interruptions for consumers [28]. The HPS lowers emissions of pollutants and greenhouse gases [29].

A microgrid is a self-sufficient power grid that can operate either connected to the power grid or independently to provide electricity to various facilities, such as university campuses, commercial buildings, and hospital complexes. The islanded system is not connected to the primary grid. However, the grid-connected system is connected to the primary grid. Figure 2 shows a microgrid architecture. Lubna et al. [5] concluded that a microgrid system would be suitable for areas with inadequate transmission infrastructure, like isolated villages where an islanded microgrid would be the most beneficial type of power network. It is important to note that microgrids provide more dependable and secure energy sources as energy availability becomes increasingly subject to natural disasters and cyber-attacks [30–33]. Furthermore, microgrids are like traditional power grids regarding control, distribution, transmission, and power generation characteristics. The microgrid system, on the other hand, differs from conventional grids that can be installed near the load sites, thereby lowering the initial capital cost associated with the transmission lines between power generation and consumption cycles.

Microgrid systems have emerged as a sustainable and cost-effective solution for several university campuses. These systems are designed to make universities self-sufficient during load shedding and power outages [22]. Stephanus et al. [23] have highlighted the potential of microgrids in meeting the growing power needs of campuses while reducing operational utility expenses. The effectiveness of microgrid technology varies among universities, influenced by factors such as campus size, weather conditions, and geographical location. Numerous studies have been conducted to enhance the overall campus microgrid's performance [34–36].

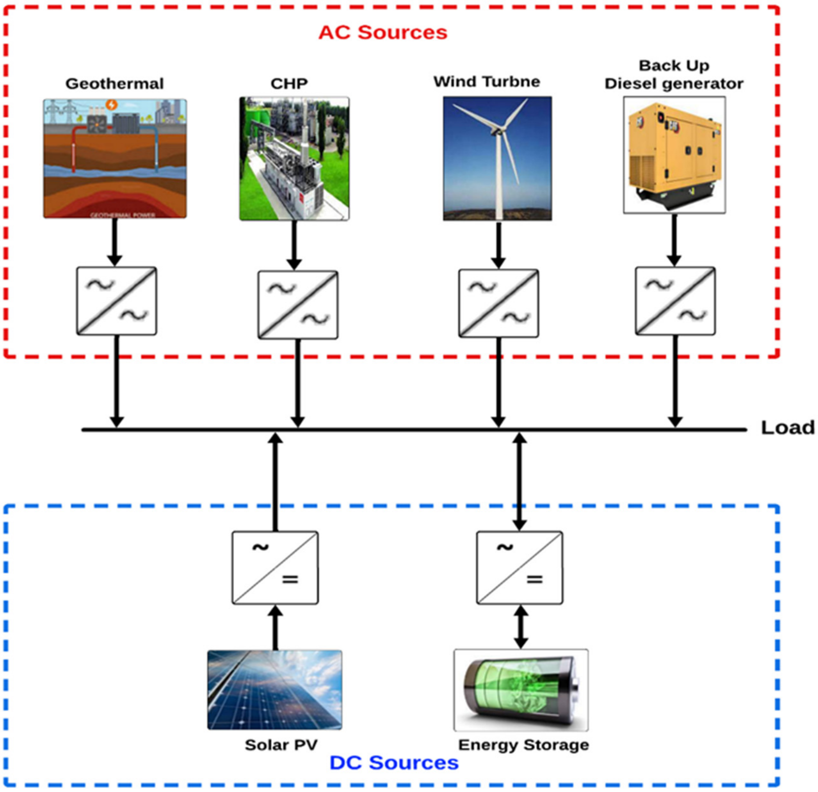

Figure 1. Hybrid power system.

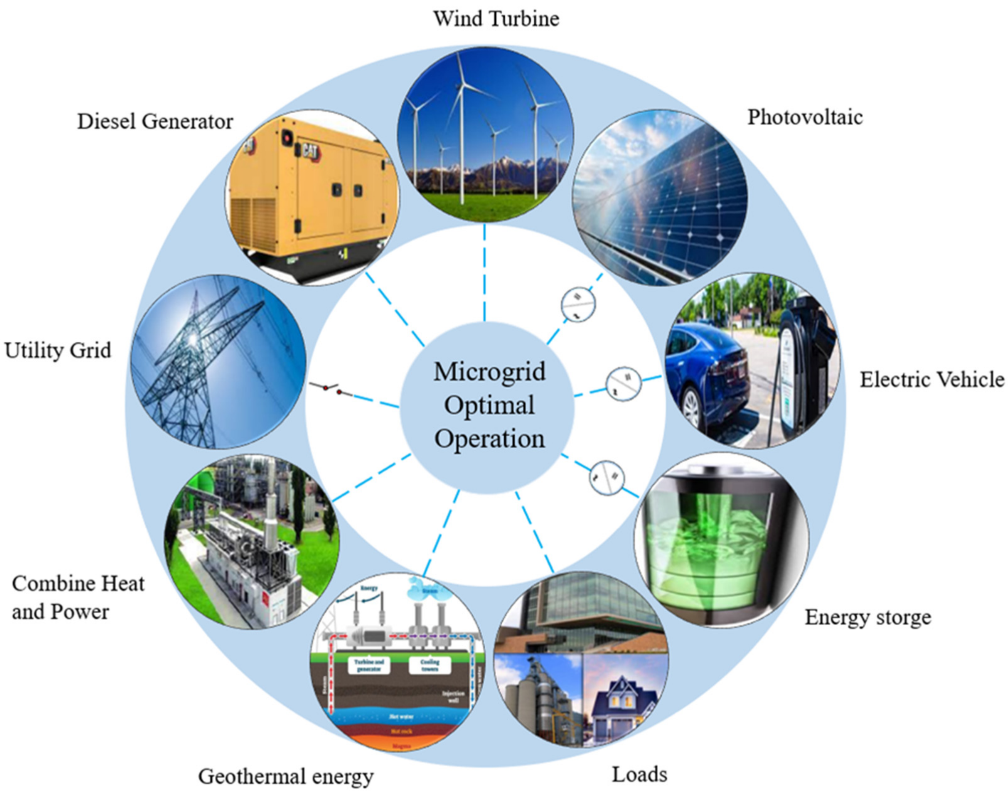

Figure 2. Microgrid architecture.

This paper comprehensively reviews microgrid systems on university campuses, covering principles, types, and geographical locations using algorithms, connections, and applications. It also undertakes a comparative analysis of GE, WT, and PV in terms of installation cost, availability, weather conditions, efficiency, environmental impact, and maintenance. The paper introduces and compares hybrid microgrid system configurations, aiming to identify the optimal configuration for energy production and flexibility.

The rest of the paper is arranged as follows: Section 2 presents microgrid components, including distributed generation, energy storage system, and microgrid loads. Section 3 provides an overview of microgrids at different universities. Section 4 provides proposed optimization techniques. Section 5 presents an overview of campus microgrid architectures, including their configuration. Section 6 provides a brief conclusion.

2. Microgrid Components

The microgrid system has three main components: distributed generation, energy storage system, and loads. Figure 3 illustrates the microgrid components.

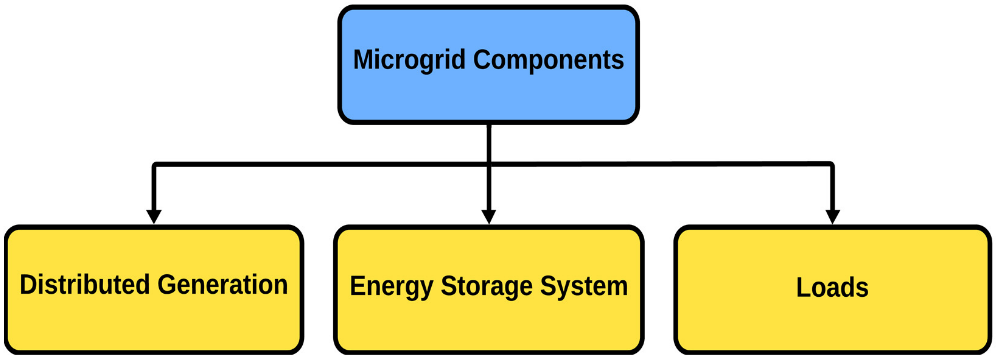

Figure 3. Microgrid components.

2.1. Distributed Generation

Distributed generation (DG) is a method of generating electricity near the building where it is used, rather than sourcing electricity from traditional power plants. DG uses either conventional energy sources, including fuel cells (FCs), diesel, nuclear power, and natural gas, or renewable energy sources, including wind turbines (WT), biogas, geothermal energy (GE), and solar photovoltaic (PV) energy [37]. Some DG types can produce both combined heat and power by recovering some of the waste heat produced by the energy source. In addition, DG can lower energy costs and reduce greenhouse gas emissions. Consequently, this can dramatically enhance the DG unit's efficiency. Some distributed generation systems require a power electronics device (e.g., AC/DC converter) to convert the harvested energy to the utility grid. Distributed generation renewable sources are frequently utilized to generate electricity. The installed capacity of wind energy has increased significantly in the past decade, reaching almost 900 GW at the end of 2022 [38]. Along with solar PV energy, TW energy has become a significant microgrid resource. The world installed capacities for PV, WT, and GE are anticipated to be 2000 gigawatts, 1 terawatt, and 23.4368 gigawatts, respectively, by 2030 [1,39,40]. Furthermore, renewable energy is expected to contribute the most annual additions for the next decade relative to all fossil fuels, according to the International Energy Agency (IEA) [41]. It is crucial to match the system to the user's needs when using renewable energy sources for distributed power generation. The ratio of energy demand coverage and self-consumption rate are two important parameters that should be considered [42,43]. Figure 4 shows the distributed generation system.

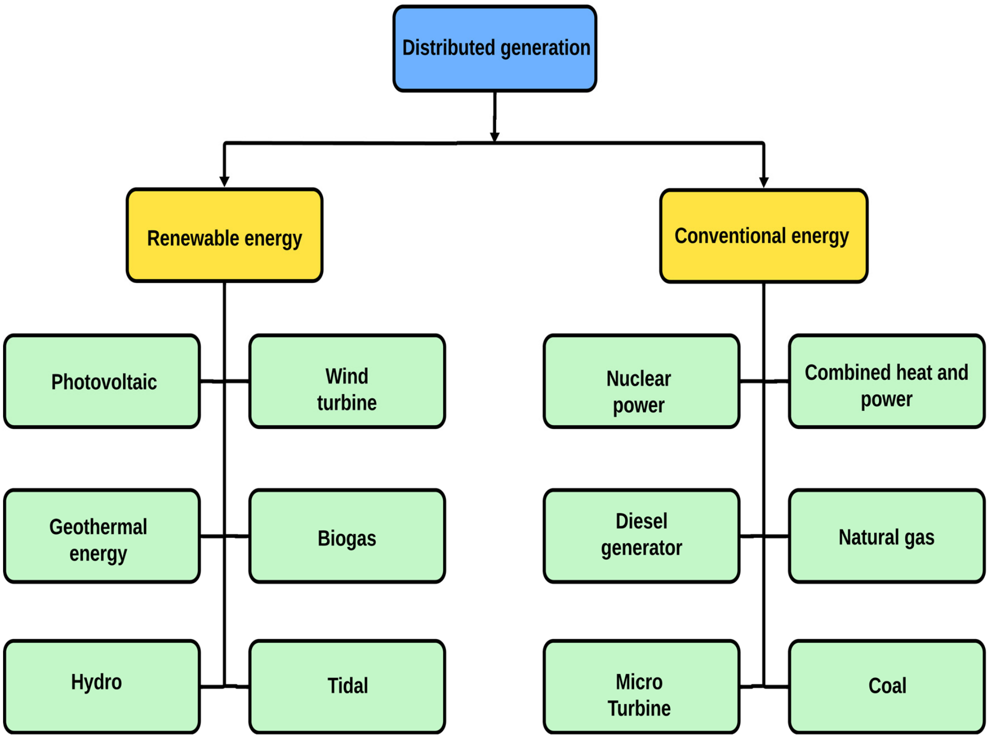

Figure 4. Distributed generation system.

2.2. Energy Storage System

An energy storage system (ESS) is a way of storing power harvested from both renewable and non-renewable sources. This power can then be used for various valuable operations (e.g., homes, air conditioning, electronics, transportation, etc.) [44]. Since energy production does not match consumption due to factors such as energy demands and weather conditions, the ESS is the optimal solution to reduce imbalances between energy production and demands. In addition to reducing electricity costs, an ESS minimizes environmental impact, improves grid reliability, and allows the integration of diverse energy sources [45]. Harvested energy can be stored in various forms, such as electrochemical, thermal, hybrid, chemical, mechanical, and electrical [46]. Figure 5 shows the energy storage system classification. Some requirements of ESS components should be considered during microgrid design, such as balancing energy demand between the load and production. In addition, it is essential to store the highest energy capacity needs during off-peak hours and provide the energy demand when needed. Furthermore, smooth transient conditions from an islanded to a grid-connected microgrid and vice versa [4]. Table 2 illustrates the details of the ESS classification [47].

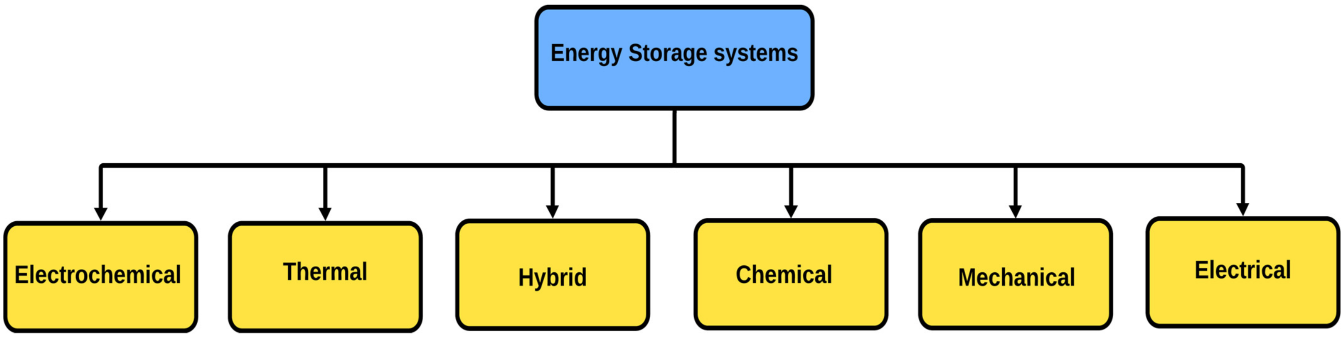

Figure 5. Classification of energy storage systems.

Table 2. Details of ESS classification.

Ref.	Category	Types/Model	Operation	Modes	Advantages	Disadvantages
[48]	Electrochemical	Sodium sulphur, lead acid, nickel-cadium, and lithium-ion	Energy is converted from chemical to electrical energy in active materials	Batteries that are conventionally rechargeable, as well as batteries that are flow rechargeable	Storage devices come in a variety of sizes and require minimal maintenance	Chemical reactions reduce battery life and energy
[49,50]	Thermal	Solid (stone, concrete, metal, and ground), liquid with a solid filler material (molten salt/stone), or liquid (water, molten salt, and thermal oil)	Heat or ice is used to store energy	High-temperature and low-temperature	Technology is an alternative to fossil fuels that can meet the demands of sustainable energy laws. Provides a secure supply of energy, protects the environment, and achieves a high energy density	Low life expectancy
[51–55]	Hybrid	The battery can connect to an SC, an SMES, an FC, an SC, and an RFB.	Multi-ESS integration	Enhances the stability and reliability of the system while decreasing the problems associated with power quality by combining the characteristics of high power and high energy storage systems	Improves system efficiency and extends battery life	High costs
[56,57]	Chemical	Hydrogen, diesel, propane, ethanol, and liquefied petroleum gas	Electricity can be directly generated	Chemical bonds within atoms and molecules are responsible for storing energy	The availability of raw materials significantly reduces the cost per unit because they store significant amounts of energy for long periods	Developing this technology requires a high level of efficiency
[58,59]	Mechanical	Compressed air, flywheel, and pumped hydro storage	Assists mechanical work by delivering the stored power	Kinetic energy potential energy, forced spring, and pressurized gas	Utilizes flexible methods of converting and storing energy	Geologically, it is costly to implement, has a negative environmental impact, and is not economically feasible
[57,60]	Electrical	Super magnetic and supercapacitor	Electrical or magnetic fields can be modified to store energy	Energy is stored in capacitors and superconducting magnets	Conventional capacitors can only store a limited amount of current; they are used as short-term storage devices	Self-discharge rates and costs are high

2.3. Microgrid Loads

Microgrids have several load types vital in their operation, stability, and control. In addition to providing power to several residential, campus, and commercial loads, the microgrid can deliver power to sensitive or critical loads, which demand high reliability. Figure 6 illustrates the load types of microgrids. Several factors should be considered in this scenario, which include prioritizing critical loads, improving the quality and reliability of power for specific loads, and enhancing the reliability of predefined loads. Furthermore, local generation serves as a proactive measure against unforeseen disruptions, supported by swift and precise protection systems [37,61].

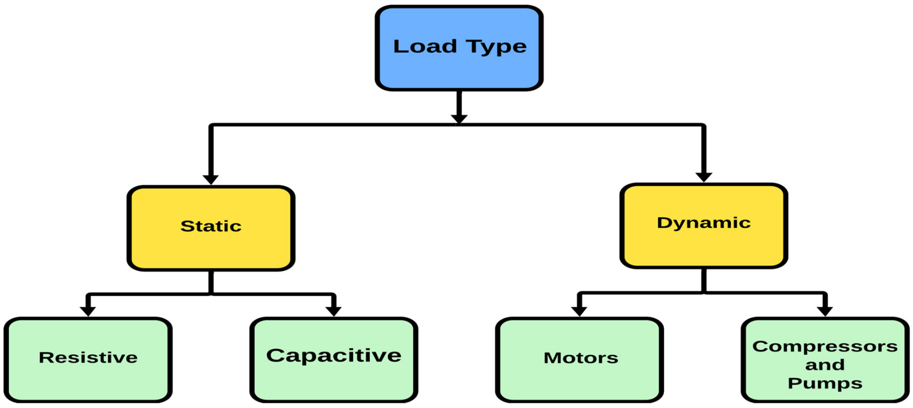

Figure 6. Microgrid load types.

3. Campus Microgrid Overview

The campus consumes considerable electricity, making relying entirely on the utility grid inconvenient. Therefore, hybrid energy sources are an optimal solution to reduce the cost of campus operation. As a result, several universities have installed microgrids, including photovoltaic (PV), wind turbine (WT), geothermal energy (GE), combined heat and power (CHP), and diesel generators (DGs). Installing renewable energy sources depends on factors such as meteorology and campus size. Therefore, the following campuses have installed varying renewable and conventional resources.

Oakland University (USA) installed hybrid geothermal, PV, solar thermal, and CHP energies [62–66]. Researchers in [67] developed an optimal hybrid renewable energy system for microgrid applications, integrating PV, ESS, and WT, and analyzed its performance and efficiency using HOMER software (Version 3.14.5). Figure 7 shows a microgrid at Oakland University. The study uncovered the potential for economical and eco-friendly energy strategies.

Figure 7. Oakland University microgrid [68].

The Illinois Institute of Technology (USA) utilized distributed generation (DG), controllable loads, storage, and switches. In this study, a high-reliability distribution system (HRDS) optimization technique was applied to achieve significant results in terms of operational cost efficiency. The annual operational costs were significantly reduced from USD 140,497 to USD 126,644 per year by 9% [69]. This demonstrates how the energy management system can dramatically reduce operational costs while increasing energy efficiency. Figure 8 shows the Illinois Institute of Technology's microgrid.

Figure 8. Microgrid at the Illinois Institute of Technology [70].

A comprehensive energy infrastructure has been established at Genoa University (Italy), incorporating diverse components such as a PV plant, three solar thermodynamics dishes, three cogenerating micro-turbines, two natural gas boilers, a refrigerating and absorbing plant, and two electrochemical/thermal storages. This intricate system provides a variety of electrical loads, including the integration of charging units for electric vehicles (EVs), seamlessly interfaced with the E-car Operation Center platform, facilitating both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) functionalities. Figure 9 illustrates solar panels and a micro-turbine at the Savona Campus. Furthermore, within the confines of the campus, a district heating system is deployed to fulfill heating demands. This system is augmented by the thermal output of micro-turbines and boilers, all operating under the oversight of an Energy Management System (EMS) developed by the University of Genoa [71].

Figure 9. Solar panels and a micro-turbine at Savona Campus, Genoa University [71].

The University of Coimbra (Portugal) has established a progressive energy system featuring PV plants, lithium-ion batteries, EVs, and advanced controllers. The system's performance and efficiency were analyzed using LabVIEW software. This analysis revealed that the university's energy system significantly lowered energy consumption and successfully met 22.3% of the campus's annual electricity demand. Figure 10 shows the microgrid at the University of Coimbra. Therefore, the system proves its dedication to sustainable energy and its efficiency in fulfilling a significant portion of its energy requirements. The annual energy generation is 115.6 MWh/year, while the specific energy yields 1466 MWh annually. The ratio between the PV system's theoretical and actual energy outputs is 88.2%. The energy sent to the grid is 6.5 MWh, whereas the energy consumed internally is 109 MWh [72].

Figure 10. Microgrid at the University of Coimbra [73].

The University of Connecticut (USA) has developed an advanced microgrid system, incorporating various sustainable energy sources. This system includes PV, WT, fuel cell panels, and hydro-kinetic systems, including an ESS. In addition, the natural gas fuel cell located outside the facility energy center supports the campus's microgrid. The efficiency and viability of these components were analyzed using HOMER software. Figure 11 demonstrates the microgrid at the University of Connecticut. The final configuration of the selected microgrid at the University comprises a significant solar-PV capacity of 203,327 kW, a WT system rated at 225,000 kW, and a robust ESS with a capacity of 730,968 kWh. This setup exemplifies the University of Connecticut's commitment to leveraging diverse and renewable energy sources for sustainable and efficient energy management within its campus infrastructure [74].

Figure 11. Microgrid at the University of Connecticut [75].

The Islamic University of Madinah (KSA) proposed an optimal microgrid system combining solar PV, wind energy, and a hybrid alternative. The system's performance and efficiency were analyzed using HOMER software. The proposed microgrid system aims to integrate renewable energy efficiently within Saudi universities. The PV system could cover 3.03% of the university's annual electricity needs with a payback period of 18.6 years. Although the wind system had a higher capacity factor, it had a more extended payback period due to higher costs and less favorable wind conditions. Figure 12 shows the Islamic University of Madinah's microgrid. The hybrid system provided a balanced solution with a 3.7% renewable fraction and a 20.7-year payback period. Both PV and WT systems significantly reduced CO_2, SO_2, and NOx emissions, aligning with the university's sustainability goals and Saudi Arabia's broader energy strategies [11].

Figure 12. Islamic University of Madinah's microgrid [76].

The University of California, San Diego (UAS) has installed a microgrid system that provides electrical, heating, and cooling services for a 450-hectare campus accommodating a daily population of 45,000. Comprising two 13.5 MW gas turbines, a 3 MW steam turbine, and a 1.2 MW solar-cell array, this system collectively caters to 85% of the campus's electricity demand and 95% coverage for heating and cooling needs. Noteworthy is the environmental efficiency of the turbines, emitting 75% fewer criteria pollutants than a standard gas power plant. The heating, ventilation, and air conditioning (HVAC) system incorporates a 140,674 kW/h thermal energy storage bank with a capacity of 14,385 m^3, complemented by three steam turbine-driven chillers and five electricity-driven chillers. Additionally, California's self-generation sponsored a 2.8 MW molten carbonate fuel cell utilizing waste methane. Figure 13 shows solar panels in the microgrid at the University of California, San Diego. The campus connects to San Diego Gas and Electric (SDG&E) through a single 69 kV substation, employing a straight SCADA system for seamless communication between building systems and energy supply. UCSD is currently integrating an advanced master controller (Paladin) to oversee generation, storage, and loads. Operated with hourly computing for optimal conditions, Paladin can process up to 260,000 data inputs per second. Supporting Paladin is the VPower software, which analyzes market-price signals, weather forecasts, and resource availability. Monitoring is facilitated by approximately 200 power meters on main lines and at building main circuit breakers, tracking usage on a minute-by-minute basis [77].

Figure 13. Solar panels in the microgrid at the University of California, San Diego [77].

Nnamdi Azikiwe University (Nigeria) implemented a hybrid energy system, combining solar PV panels and a DG. Figure 14 illustrates the Nnamdi Azikiwe University microgrid. The system's performance and cost-effectiveness were assessed using HOMER analysis. This evaluation determined that the project's Net Present Value (NPV) was USD 1,738,994, and the Levelized Cost of Energy (LCOE) was calculated to be USD 0.264. This analysis indicates that the university's effort to integrate renewable energy solutions alongside traditional power sources aims for a more sustainable and economically viable energy infrastructure [78].

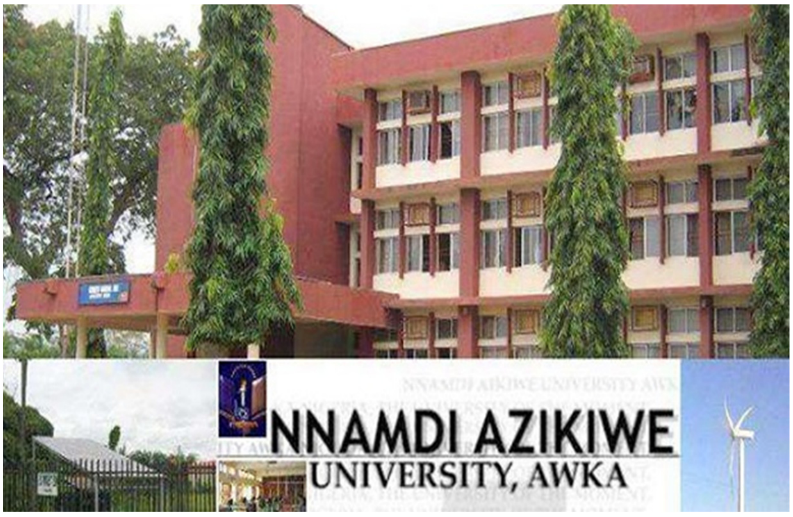

Figure 14. Nnamdi Azikiwe University's microgrid [78].

The primary constituent of the microgrid at Princeton University (USA) installed is a 15 MW gas turbine, which is augmented by 4.5 MW of PV power. During Hurricane Sandy, Princeton's gas-powered CHP facility supplied electricity, heating, and ventilation, ensuring the university's operations continued despite the widespread darkness that engulfed most of the state. The microgrid at Princeton is typically linked to the local grid for operation [79]. Figure 15 illustrates Princeton University's CHP plant microgrid.

Figure 15. Princeton University's CHP plant microgrid [80].

Griffith University's Nathan Campus (Australia) has effectively implemented an advanced energy management system. This system integrates distributed generation (DG) and an ESS with a battery bank, 1164 solar panels, TWs, and full cells (FCs). Figure 16 shows the microgrid at Griffith University's Nathan Campus. An essential feature of this configuration emphasizes effectively controlling and managing a variety of energy sources to accommodate alternating current (AC) and DC loads, including those for EVs. This approach aims at energy management and underscores the university's dedication to sustainable energy practices and its role in pioneering solutions for contemporary energy challenges [81].

Figure 16. Microgrid at Griffith University's Nathan Campus [82].

Nanyang Technological University (Singapore) has implemented a cutting-edge Microgrid Energy Management System (MG-EMS). This system comprises PV panels, FC, and natural gas-operated micro-turbines (MTs), all integrated under the Laboratory of Clean Energy Research (LaCER) [83]. Figure 17 illustrates the microgrid at Nanyang Technological University. This system's focus extends to buildings and transportation within the campus, showcasing NTU's commitment to sustainable energy practices. By incorporating various clean energy sources and advanced management systems, Nanyang Technological University stands at the forefront of energy research and application, particularly in academic institutions.

Figure 17. Microgrid at Nanyang Technological University [84].

Table 3 shows microgrid systems at different universities, including resource, solver, and methodology optimizations.

Table 3. An overview of university campuses' microgrids worldwide.

Ref.	Campus Name	Resources	Solver/Methodology/ Optimization	Load Types	Contribution	Results
[72]	University of Coimbra, Portugal	PV, ESS	Control algorithms, IoT	HVAC loads	Improved building microgrid flexibility	Increased energy efficiency
[85]	National University of Sciences and Technology, Pakistan	PV plant, ESS, EVs, DG	MILP, ant colony optimization, LP	Campus load	Reduction of operational cost, analysis of DGs, and optimally scheduled ESS	ESS minimizes operational costs from USD 798,560 to USD 756.385
[86]	Guangdong University of Technology, China	-	Self-crossover genetic algorithm, DSM optimization model	Controllable and non-controllable loads, micro-market operations	DSM scheme for microgrids with sub-decision makers	Reduction in electricity cost
[87]	Cochin University of Science and Technology, India	PV, WT, biomass, etc.	Static and time domain simulations, eigenvalue analysis	-	Microgrid setup with renewable energy resources. The small signal stability assessed by eigenvalue analysis confirmed the system's stable operation for a load increment of 1.26 p.u in grid mode and 1.25 p.u in off-grid mode without violating system constraints	RESs meet a major part of power demand with minimal loss. Stable operation confirmed for significant load increments in both grid mode and off-grid mode

Table 3. *Cont.*

Ref.	Campus Name	Resources	Solver/Methodology/ Optimization	Load Types	Contribution	Results
[88]	NFC Institute of Engineering and Technology, Pakistan	PV, ESS, and Evs	LP	Campus load	Integration of PV system, ESS, and EV in a university campus, optimal Energy Management System (EMS)	EMS decreases energy consumption cost by nearly 45%, EV as a source reduces energy cost by 45.58%, EV as a load reduces energy cost by 19.33%, continuous power supply impact analyzed
[89]	University in Southern Java Island, Indonesia	PV power generation plant	HOMER Pro software, feasibility analysis	Campus load	Feasibility analysis of solar energy system, techno-economic analysis, potential contributions, and applicability	Simulation studies for identifying cost-effective configurations
[90]	University Campus in Brazil	PV and BESS	Simulated annealing algorithm	Campus load	EMS coordination, optimal operation of battery system, reduction in energy consumption costs	Minimize campus energy consumption and costs
[91]	Clemson University-Main Campus, UAS	PV and BESS	Emulated virtual inertia, coordination controller	Campus load	Design and operation of a microgrid, seamless transition between grid-connected and islanded modes, IEEE Std 1547.4 (Hybrid Microgrid Controller Analysis and Design for a Campus Grid. DOI: 10.1109/ PEDG.2019.8807566) compliance	Emulation of virtual inertia for resiliency
[92]	Faculty of Technical Sciences in Novi Sad, Serbia	PV, WT, EV, BESS, biogas micro-turbine	Microcontroller, interface, consumers	-	Application of distributed energy resources, technical specifications for stable island mode operation, techno-economic and environmental analysis	Proposal for a microgrid, analysis of technical specifications for stable operation, focus on annual energy production and investment costs, and avoided CO_2 emissions
[93]	U.E.T, Taxila, Pakistan	Solar PV panels, diesel Generator, energy storage system (ESS)	MILP, MATLAB simulations	Campus load	Reduction of operational cost, increased self-consumption from green DGs, reduction in grid electricity cost	Proposed EMS model for institutional microgrid, reductions in grid electricity cost

Table 3. *Cont.*

Ref.	Campus Name	Resources	Solver/Methodology/ Optimization	Load Types	Contribution	Results
[67]	Oakland University, USA	Solar PV, ESS, CHP, and WT	HOMER Pro software	Campus load	Optimal planning and design of hybrid renewable energy systems, scalable and flexible MG configurations	Minimization of NPC and LCOE, comprehensive guide for planning and implementing hybrid renewable energy solutions, potential for cost-effective and sustainable energy, addressing unmet load in MG design
[94]	North China Electric Power University, Beijing, China	PV, WT, CHP, ESS, and EVs	MTPSO	Campus load	Optimal scheduling of power sources Consideration of demand response	The model produces favorable outcomes For hybrid energy microgrids. It exhibits superior global search capabilities when compared to PSO. Simulation analysis confirms the model's effectiveness
[95]	University of California, San Diego, USA	PV and full-cell	Economic optimization	Campus load	State-of-the-art microgrid development, 42 MW microgrid, 92% self-generation of annual electricity load	Achieving savings of USD 800,000 per month through microgrid PV panels, improving the existing grid infrastructure, and attaining a high level of self-generation for electricity load
[79]	Princeton University, UAS	Gas turbine (15 MW), solar field (4.5 MW), CHP, ESS	Digital controls	Campus load	Multiple fuel sources, multiple power-generating assets, CHP production, modern digital controls, real-time awareness of fuel and electricity costs	Resilience during Hurricane Sandy, continuity of critical research projects and computing services, lower carbon footprint, higher reliability with behind-the-meter CHP, economic dispatch, underground power distribution, revenue generation through power exports and ancillary services, lessons for successful microgrid operation

Table 3. *Cont.*

Ref.	Campus Name	Resources	Solver/Methodology/ Optimization	Load Types	Contribution	Results
[77]	University of California, San Diego, USA	Two 13.5 MW gas turbines, 3 MW steam turbine, 1.2 MW solar-cell array, 2.8 MW molten carbonate FC, 140,674 kW/h thermal energy storage bank, Paladin master controller, VPower software	Environmental efficiency, Paladin integration, VPower analysis, thermal energy storage, SCADA system	Campus load	85% of electricity, 95% of heating and cooling needs, 75% fewer criteria pollutants, 30% federal investment tax credit	Improved environmental efficiency, significant coverage of campus energy demands, financial incentives for sustainability
[96]	University of Genoa, Italy		Model Productive Control (MPC)	Campus load	Increased overall energy efficiency, lower primary energy consumption, environmental and economic sustainability	Reducing emissions, primary energy use, and costs
[97]	Chiang Mai Rajabhat University, Thailand	PV, DG, and biomass gasifier	-	Smart community	Hybrid PV-DC microgrid system design and evaluation, application of DC loads	An enhanced and practical hybrid PV-DC microgrid system was developed, comprising components such as a PV-AC microgrid, diesel generator, biomass gasifier, and connection to the local grid
[98]	Hangzhou Dianzi University, China	PV, DG, fuel cells, and BESS unit	-	Campus load	The primary power source consists of PV panels supported by a small diesel generator and fuel cells. These are integrated with a capacitor bank and storage battery unit	The world's first microgrid to achieve a 50% PV penetration rate utilized 728 solar panels covering 946 m^2. It established a stable microgrid system despite the high penetration of intermittent power sources

Table 3. *Cont.*

Ref.	Campus Name	Resources	Solver/Methodology/ Optimization	Load Types	Contribution	Results
[99]	Technical University of Denmark	PV, WT, and vanadium-based battery system	Experimental tests for static and dynamic stability analysis	Laboratory scale load	The implementation and testing of various control strategies for the combined system followed the development of appropriate models for the SYSLAB microgrid	Test findings encompassed static and dynamic stability, the impact of disturbances on power system equipment and network, parameters for dynamic modeling of DER components, and the creation of appropriate models for the SYSLAB microgrid
[100]	Nigerian University	PV panels, inverter, grid system, DG set	HOMER Pro software	University community load	A microgrid system was designed and sized to tackle power challenges within the Nigerian national grid	PV panels have the potential to generate 88.0% of the campus's annual energy, leading to an 88.0% reduction in the university community's electricity bill and CO_2 emissions

4. The Proposed Optimization Techniques

Numerous different optimization techniques have been proposed to analyze the campus microgrid performance systems. Among these techniques, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Tuna Swarm Optimization (TSO), Cuckoo Search (CS), Grey Wolf Optimizer (GWO), and Gradient-based Grey Wolf Optimizer (GGWO), the Hybrid Optimization of Multiple Electric Renewables (HOMER), Firefly Algorithm (FA), LabVIEW Simulation Model (LSM), Mixed Integer Linear Programming (MILP) [101], nonlinear programming [90], High-Reliability Distribution System (HRDS), YALMIP toolbox of MATLAB, Mixed Integer Conic Programming (MICP), and Quantum Teaching Learning-Based Optimization (QTLBO), NSGA-II, and EDNSGA-II [102–107]. Sardou et al. [108] proposed a robust algorithm that integrates the PSO algorithm with the primal–dual interior point (PDIP) method for the efficient management of microgrid energy. Jaramillo et al. [109] developed the MILP algorithm to optimize microgrid operation. Guo et al. [110] designed an economically optimal energy management model that combines the dynamic programming technique with the grid input and output strategy for grid-connected PV systems. Optimizing the size of the components for an islanded hybrid PV/WT system with an integrated energy management system was carried out by Rullo, P. et al. [111]. The optimization approach was based on an economic model predictive control (EMPC) model. Furthermore, Indragandhi, V. et al. [112] proposed a Multi-Objective Particle Swarm Optimization (MOPSO) algorithm to investigate AC/DC microgrid power management. Mellouk et al. [113] developed the Parallel Genetic-Particle Swarm Optimization Algorithm (PGPSO) to address the challenges of solving energy management optimization problems and determining the appropriate size of renewable energy components. Li et al. [106]

introduced a novel approach that combines incremental conductance (INC) and Improved Tuna Swarm Optimization Hybrid INC (ITSO-INC) to accurately track the maximum power point. Moreover, Rajagopalan et al. [107] enhanced the Oppositional Gradient-based Grey Wolf Optimizer (OGGWO) algorithm to clarify the microgrids' optimal operation.

Authors in [114] proposed a novel optimization technique for grid-connected solar PV to minimize the total life cycle cost and energy purchased from the utility grid while maximizing reliability, considering the instability of solar energy. The mixed integer linear programming study focuses on the loss of power supply probability (LPSP) to measure microgrid system reliability.

However, the mathematical models include the Genetic Algorithm (GA), Genetic Programming (GP), Differential Evolution (DE), Artificial Bee Colony (ABC), Simulated Annealing (SA), and Particle Swarm Optimization (PSO) [115,116]. Some optimization techniques perform better in terms of effectiveness and accuracy. For instance, Güven, A. F. et al. [117] compared GA, PSO, FA, HOMER, and a novel Firefly and PSO algorithm (HFAPSO) hybrid to ensure the hybrid microgrid's optimal sizing. The results revealed that the HFAPSO was the most effective algorithm compared to the techniques mentioned. Hertzog, P. E et al. [118] concluded that the LabVIEW simulation model (LSM) was more confident than HOMER. Furthermore, Li et al. [106] proved that the ITSO-INC algorithm outperformed both the CS and TSO algorithms in high accuracy, fast response to dynamic changes, rapid convergence, and the lack of steady-state oscillation. Rajagopalan et al. [93] found that the OGGWO algorithm surpassed the PSO, CS, GWO, GGWO, NSGA-II, and EDNSGA-II to reduce costs and mitigate pollution.

5. An Overview of Campus Microgrid Architectures

Microgrid hybrid systems typically consist of four components: photovoltaics (PVs), energy storage systems (ESSs), wind turbines (WTs), and combined heat and power (CHP). The configuration of the microgrid system depends upon considering factors such as campus size, climatic conditions, and geographical location. These factors have a substantial impact on the overall performance of the system. The microgrid components are organized into various configurations, which are categorized as follows:

5.1. Configuration A: (Hybrid PV-Grid-Connected)

This configuration consists of a utility grid, PV panel, converter, inverter, and energy storage, as shown in Figure 18. PV panels are regarded as the primary renewable energy source that harnesses sun irradiation to generate power. Subsequently, the harvested power obtained from PV panels in direct current (DC) requires an inverter to convert it into alternating current (AC) for compatibility with power-consumption devices. Diesel generators (DGs) are used during power outages to provide electricity to individual buildings on campus.

The advantages of a hybrid PV-grid connection are that it is simple, free to operate, and sometimes does not require energy storage, such as when solar power generates less electricity than the campus demands. However, on the other hand, PV panels are influenced by weather conditions, which could limit their ability to generate power. Moreover, the hybrid PV-grid-connected system is commonly installed in residential and commercial buildings due to its simplicity. For instance, many university campuses worldwide have installed hybrid PV-grid-connected systems, such as the University of Energy and Natural Resources [119], GITAM Deemed To be University in Andhra Pradesh [120], University Malaysia Pahang [121], Effat University [122], Heriot-Watt University [123], Chiba University of Commerce [124], The Hashemite University [125], University at Albany [126], Aga Khan University [127], Colorado State University [128], University of Northern Colorado [129], University of Wisconsin [130], Iowa State University [131], University of Nottingham, Bath University, Exeter University and University of the West of England [132], and Washington and Lee University [133].

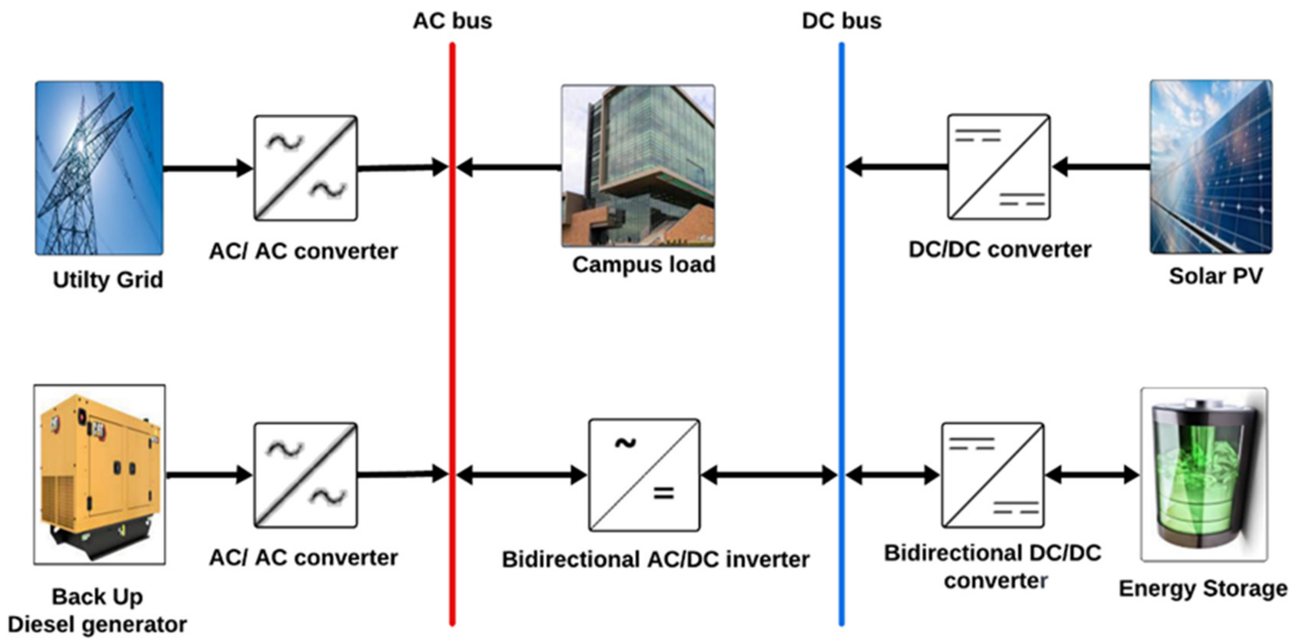

Figure 18. Grid connected with solar PV and energy storage.

It is important to note that the required energy storage system (ESS) depends on the amount of solar capacity installed on the campus. When the power produced by the PV panels exceeds the consumption demand, an energy storage system is required. For example, the University of Texas [134], British Malaysian Institute [135], Mulhouse campus [136], North Central College [137], Gavilan College [138], Sanford Burnham Prebys Campus [139], New Mexico State University [140], and California State University [141]. Other university campuses such as Beloit College, Fairleigh Dickenson University, Georgia Tech, Lake Superior College, Lane Community College, Luther College, Northern Arizona University, Milwaukee Area Technical College, South Central College, Thomas College, Tuskegee University, University of California Riverside, University of Colorado–Colorado Springs, University of Minnesota Duluth, and Washington and Lee University are suitable for installing solar power and energy storage systems owing to their weather conditions and geographical locations according to the National Renewable Energy Laboratory [142].

5.2. Configuration B (Hybrid PV-WT-Grid-Connected)

This hybrid configuration uses photovoltaic panels, wind turbines, a utility grid, converters, and inverters, among other essential components. Figure 19 illustrates the components of this configuration; WT and PV panels are considered the main sources of renewable energy. The National Renewable Energy Laboratory (NREL) states that wind turbines can be installed in distributed wind (that is, small turbines on site), land-based wind (i.e., farms and forests), and offshore wind (i.e., ocean) [143]. Since wind generators work best in an isolated environment, few universities have installed wind turbines, such as Quinnipiac University [144], University of Delaware [145], Carleton College, University of Minnesota [146], St. Olaf College [147], and Macalester College, St. Paul [148].

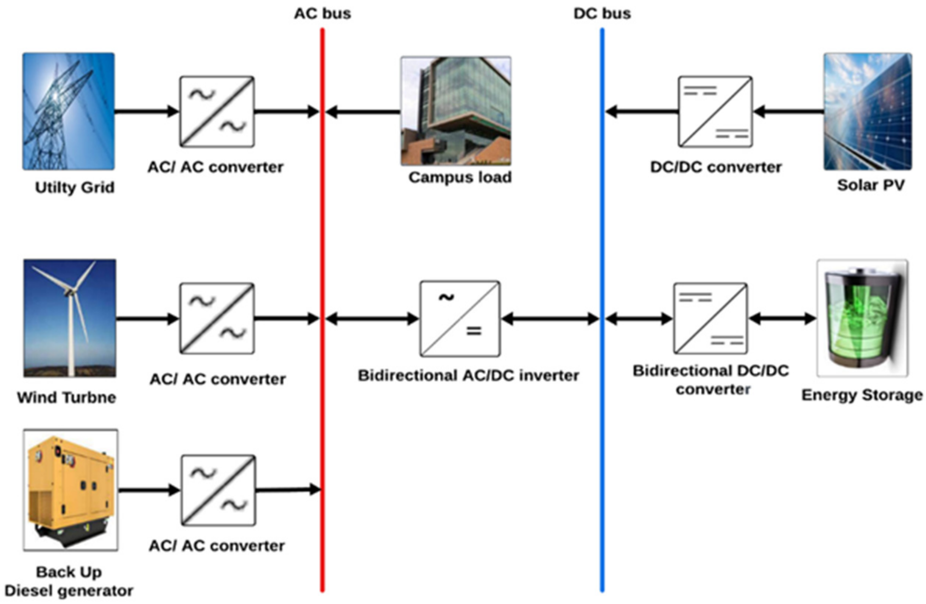

Figure 19. Microgrid connected with solar PV, WT, and ESS.

5.3. Configuration C (Hybrid PV-Diesel Generator-Grid Connected)

Like the one shown in Figure 20, a hybrid system consists of PV, DG, and grid connection. This configuration has been installed at the following universities: Florida International University [149], University of the Free State [150], University of KwaZulu Natal [2], and Jomo Kenyatta University of Agriculture and Technology [151].

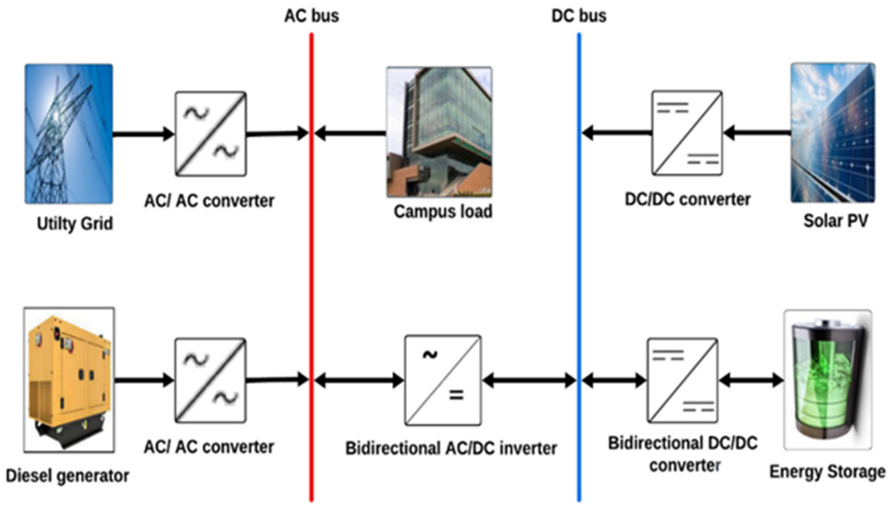

Figure 20. Grid connected with PV, diesel generator, and energy storage.

5.4. Configuration D (Hybrid PV-CHP-Grid Connected)

This configuration illustrates the usage of a hybrid system composed of PV, CHP, utility grid, converter, and an inverter. The CHP allows electricity and heat to be produced simultaneously, compared with generating them separately [152]. Microgrid generation and consumption are characterized by distinctive properties, which increase their flexibility when utilizing renewable energy and CHP [153]. Thus, centralized grids are more adaptable. Figure 21 illustrates the components of this configuration.

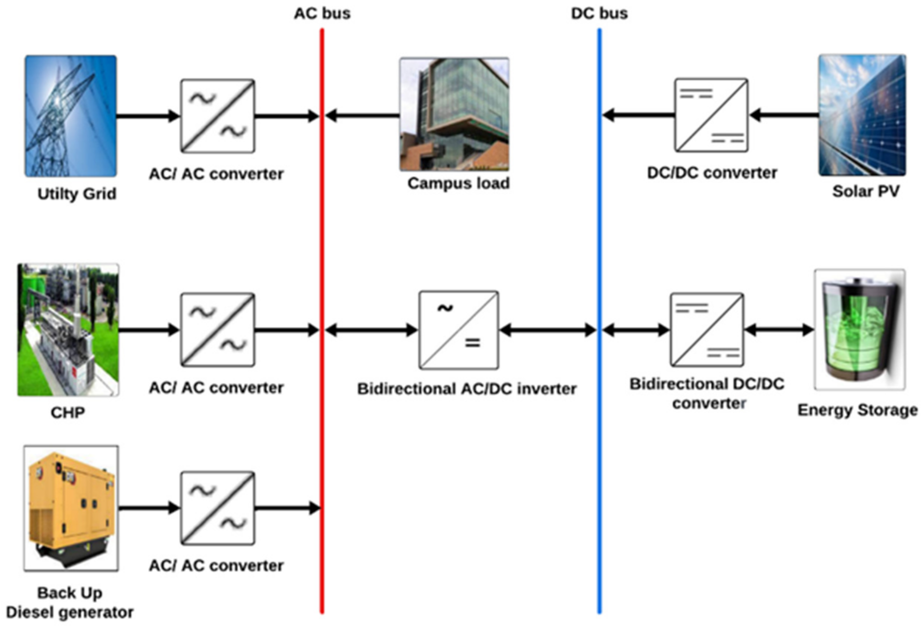

Figure 21. Microgrid connected with PV, CHP, and ESS.

Other universities have installed this configuration, such as Oakland University [54], University of the West of England [140], Kent State University [141], Chalmers University of Technology [142], Stanford University [143], Clemson University [144], IST—Alameda Campus [145], Rowan University [146], the University Campus of UNICAMP [147], and the University of Genoa [154].

Numerous universities worldwide have installed microgrids on their campuses, as shown in Figure 22. The installations of configuration A, configuration B, configuration C, and configuration D are %0.54, %0.08, %0.07, and %0.14, respectively. The most common configuration used is configuration A due to its simplicity and free-charge operation, which does not require energy storage and is cheaper than other configurations. However, configuration C is less common due to the high cost of fossil fuels and the caused air pollution.

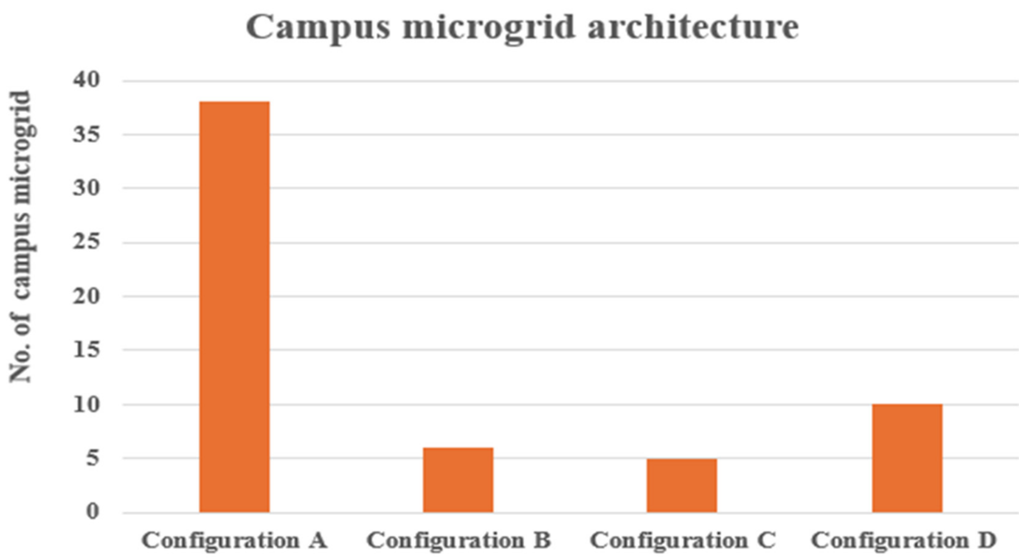

Figure 22. Comparison of the configurations, where configuration A is (Hybrid PV-grid-connected), configuration B is (Hybrid PV-WT-grid-connected), configuration C is (Hybrid PV–diesel generator-grid-connected), and configuration D is (Hybrid PV-CHP-grid-connected).

As a result, this study comprehensively reviews microgrid systems on university campuses, covering principles, types, graphical locations, used algorithms, connections, and applications. It also undertakes a comparative analysis of geothermal (GE), wind turbines (WTs), and photovoltaics (PVs) in terms of installation cost, availability, weather conditions, efficiency, environmental impact, and maintenance. Furthermore, the paper introduces and compares hybrid microgrid system configurations, aiming to identify the optimal configuration for energy production and flexibility.

6. Conclusions

This paper comprehensively reviewed the pending university campus microgrids regarding principles, types, geographical locations, algorithms, connections, and applications. Some renewable energy sources, such as geothermal (GE), wind turbine (WT), and photovoltaic (PV), were compared in terms of installation costs, availability, weather conditions, efficiency, environmental impact, and maintenance (see Table 1). Furthermore, a description of microgrid systems and their components, including distributed generation (DG), energy storage system (ESS), and microgrid load was presented. The most common optimization models for analyzing the performance of campus microgrids were discussed. Some optimization techniques perform better in terms of effectiveness and accuracy. For instance, novel Hybrid Firefly Algorithms and Particle Swarm Optimization (HFAPSO), Improved Tuna Swarm Optimization and Incremental Conductance (ITSO-INC) algorithm, and Oppositional Gradient-based Grey Wolf Optimizer (OGGWO) algorithm. Also, the LabVIEW Simulation Model (LSM) was more confident than HOMER. Hybrid microgrid system configurations were introduced and compared to find the optimal configuration in terms of energy production and flexibility. Hence, configuration A (Hybrid PV-grid-connected) was the most common configuration used compared to the others (see Figure 22) owing to its simplicity and free-charge operation, which does not require energy storage and is cheaper than other configurations. However, configuration C is less common due to the high cost of fossil fuels and the causes of air pollution.

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Abbreviations

ABC	Artificial bee colony
AC	Alternating current
BESS	Battery energy storage system
CHP	Combined heat and power
CO_2	Carbon dioxide
CS	Cuckoo search
DC	Direct current
DE	Differential evolution
DG	Diesel generator
DG	Distributed generation
DSM	Demand side management
EDNSGA-II	Economic dispatch-based non-dominated sorting genetic algorithm II
EMPC	Economic model predictive control
EMS	Energy management system
ESS	Energy storage system
EVs	Electric vehicles
FA	Firefly algorithm

FC	Full cell
GA	Genetic algorithm
GA	Genetic programming
GE	Geothermal energy
GGWO	Gradient-based grey wolf optimizer
GW	Gigawatts
GWh	Gigawatt-hour
GWO	Grey wolf optimizer
HFAPSO	Hybrid of FA and PSO algorithms
HOMER	Hybrid optimization of multiple energy resources
HPS	Hybrid power systems
HRDS	High-reliability distribution system
IEA	International energy agency
INC	Incremental conductance
IoT	Internet of things
KW	Kilowatts
LCOE	Levelized cost of energy
LP	Linear programming
LSM	LabVIEW simulation model
MICP	Mixed-integer conic programming
MILP	Mix integer linear programming
MOPSO	Multi-objective particle swarm optimization
MTPSO	Multi-team particle swarm optimization
MW	Megawatts
NPC	Net present cost
NSGA-II	Non-dominated sorting genetic algorithm II
PDIP	Primal–dual interior point
PGPSO	Parallel genetic-particle swarm optimization algorithm
PSO	Particle swarm optimization
PV	Photovoltaic
QTLBO	Quantum teaching learning-based optimization
RES	Renewable energy sources
SCADA	Supervisory control and data acquisition
TSO	Tuna swarm optimization
TW	Terawatts
WT	Wind turbine

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