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Internet of Things-Based Robust Green Smart Grid

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Abstract: Renewable energy sources play a critical role in all governments' and organizations' energy management and sustainability plans. The solar cell represents one such renewable energy resource, generating power in a population-free circumference. Integrating these renewable sources with the smart grids leads to the generation of green smart grids. Smart grids are critical for modernizing electricity distribution by using new communication technologies that improve power system efficiency, reliability, and sustainability. Smart grids assist in balancing supply and demand by allowing for real-time monitoring and administration, as well as accommodating renewable energy sources and reducing outages. However, their execution presents considerable problems. High upfront expenditures and the need for substantial and reliable infrastructure changes present challenges. Despite these challenges, shifting to green smart grids is critical for a resilient and adaptable energy future that can fulfill changing consumer demands and environmental aims. To this end, this work considers developing a reliable Internet of Things (IoT)-based green smart grid. The proposed green grid integrates traditional grids with solar energy and provides a control unit between the generation and consumption parts of the grid. The work deploys intelligent IoT units to control energy demands and manage energy consumption effectively. The proposed framework deploys the paradigm of distributed edge computing in four levels to provide efficient data offloading and power management. The developed green grid outperformed traditional grids in terms of its reliability and energy efficiency. The proposed green grid reduces energy consumption over the distribution area by an average of 24.3% compared to traditional grids.

Keywords: smart grids; IoT; green smart grids; energy consumption; reliability; distributed computing

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1. Introduction

Traditionally, the conventional power grid's primary function is to provide power from the main bulky generators used by fossil fuels to the different end users. The power grid gradually became smarter at the beginning of the 20th century. By integrating multiple sensors and controllers over the whole grid, the smart grid (SG) expression appears. The integration between modern information and communication technologies (ICTs) and the conventional power grid contributed to the spreading of this term [1]. The definition of SG is different from one organization to another; however, the simple definition of the SG expression is transferring power and information in a two-way system [2].

The main function of the SG is collecting data from transmission lines, distribution substations, and customers and for analysis in a data communications network linked with the power grid. Based on this data, SG can forecast its suppliers' and customers' needs for power management [3]. Traditional power grid sources are mainly dependent on fossil fuels. An increase in the prices of conventional fossil fuels as well as their finite nature means that the need to discover other efficient and low-cost power sources is not optional.

The race to discover the cheapest power sources is not the main problem; the sustain capability of these sources is the main issue. Renewable energy sources (RESs), also referred to as green power sources, are the only sources that meet these demands [4]. Global warming is one of the main reasons that electricity suppliers depend on and encourage clean and safe renewable power resource usage for maintaining and achieving the required end-user power demands with low carbon dioxide emissions. RESs, e.g., sun, wind, water, biomass, geothermal, and tidal sources, are promising, safe, clean power sources not only for their sustainability but also due to their usage reducing the greenhouse emissions that harm the environment [5]. Integrating these types of sources within the modern SG results in what is called the green smart grid (GSG). The GSG is a smart power grid that uses only renewable energy sources. One of the prominent RESs is the sun, which has massive energy, enough to meet the power demand of the entire planet in one day [6].

Researchers focus on obtaining the maximum power output from this tremendous power source. This is done by collecting the incoming radiation either on the surface of solar panels to generate electricity directly or by using it as thermal energy and then converting it into electrical energy using thermoelectrical generators (TEGs) [7]. The SG combines renewable energy sources with old conventional sources in the real power world to avoid the continuous disruption of distributed energy resources (DERs) due to climate change. For financial and technological reasons, combining multiple generator modules makes it more difficult to control the power system to run at constant output. Without the assistance of a smarter grid, it is difficult to supervise and monitor the cost-effective and coordinated operation of such a power system. As a result, SG is critical for a robust future power grid [8].

The expanding population and the need for sustainable energy have boosted global demand for electricity. However, increased demand has resulted in challenges such as power outages, voltage fluctuations, and transmission network congestion. To address these issues, the concept of an SG has evolved. SG solutions use self-healing properties and real-time data processing to reduce outages, losses, and voltage fluctuations. Integrating renewable energy sources into the primary power-producing system is also important [9]. This integration entails increasing the use of energy storage devices and stabilizing system voltage. The SG relies on reliable and fast data transmission, which is made possible by communication infrastructure. The SG delivers effective power transmission and efficient resource utilization by collecting and analyzing data linked to power generation and consumption [10]. However, traditional grids face many limitations and challenges, including the following [11,12]:

- Infrastructure: Many grids were built decades ago and are now nearing the end of their useful lives. This aging infrastructure frequently degrades over time, demanding regular maintenance and growing more prone to collapse. As a result, operational expenses rise, and the danger of outages increases, emphasizing the critical need for modernization and replacement of obsolete components.
- Reliability and resilience: Ensuring the reliability of the SG is a critical challenge for current power infrastructures. Power outages can arise from equipment failure, natural disasters, or cyber-attacks, affecting power delivery to customers and businesses. Severe weather phenomena, such as hurricanes, wildfires, and snowstorms, have the potential to cause significant harm to grid infrastructure, resulting in long-lasting power outages. This emphasizes the importance of implementing stronger resilience measures.
- Integration of renewable sources: The increasing integration of renewable energy sources, such as solar and wind power, poses considerable hurdles due to their intermittent nature. Unlike traditional power sources, renewables create electricity in response to weather conditions. This intermittency complicates maintaining a contin-

uous power supply, necessitating modern grid management and storage systems to ensure stability and reliability.
- Demand growth and load management: Regulating peak demand becomes more complex as electricity demand rises. Additional capacity is necessary during peak times, typically resulting in higher operational expenses, because this capacity is underutilized during off-peak hours. Effective load balancing across regions and times is extremely difficult, demanding advanced forecasting techniques and real-time management to ensure grid stability and efficiency.
- Technological integration: The adoption of smart grid technologies offers various advantages, including increased efficiency and dependability. However, integrating these advanced systems into existing infrastructure is difficult and expensive. Ensuring interoperability between new technologies and existing grid components is a huge undertaking that necessitates careful planning and commitment.

Next-generation SGs are expected to be more renewable, robust, efficient, distributed, reconfigurable, and interactive, with faster response to face any crises with higher power quality, as global resources become scarcer and power users demand higher quality and reliability [13]. We consider developing novel SG based on the Internet of Things and distributed edge computing technologies to overcome such challenges. Deploying such novel technologies for smart grids provides a reliable infrastructure for the grid and better management and control. This increases the grid's overall performance and provides the next generation of SGs. The main contributions of this work are summarized as follows.

- Developing a main IoT-based control unit between the generation and distribution parts of the SGs. This control unit deploys distributed computing technology to assist IoT nodes. The unit is responsible for monitoring and controlling power generation and consumption.
- Developing an IoT unit to improve the performance of power generation plants, including solar arrays used for power generation. The unit has a direct interface to the main IoT control unit.
- Developing a data monitoring network to monitor power generation and usage and assist grid decision making.
- Developing a distributed computing edge model to assist data handling over the network. The model deploys a hierarchical structure of heterogeneous edge servers, including multiple access edge (MEC) and fog servers.
- Performance assessment of the developed systems.

2. Related Works

Integrating IoT technology into smart grids has attracted considerable attention from academia and industry, owing to its ability to improve energy systems' effectiveness, reliability, and sustainability. IoT-enabled smart grids utilize interconnected devices, real-time data analytics, and modern communication networks to optimize power generation, distribution, and consumption [14,15]. Many existing works have considered developing IoT-based frameworks for smart and green smart grids. Each framework mainly focuses on one or more aspects of smart grids, including energy efficiency, reliability, availability, and security. This section presents the parts of these frameworks that are most related to our proposed work.

The latest developments in smart grids went beyond deploying IoT to improving the deployment and performance of IoT networks. Recent technologies have been introduced with IoT to provide efficient smart grids. M. Jamshidi et al. [16] developed a connectivity-based platform for edge computing-powered smart grids. The authors also considered proposing platforms for integrating the metaverse into the proposed smart grid. The work provided a highly efficient GSM triplexer specifically engineered for 5G-enabled IoT applications within sustainable smart grid edge computing environments and the metaverse. This triplexer was designed to operate at 0.815, 1.58, and 2.65 GHz, targeting the specific frequency bands essential for 5G applications. The triplexer features a pioneering physical design, including an incredibly small size, making it the smallest triplexer ever created in comparison to earlier designs. The triplexer indicated the lowest levels of insertion losses achieved so far, surpassing the performance of current triplexers by a wide margin. This work focused mainly on the physical layer design for IoT-based smart grids; however, our developed work considers an end-to-end framework covering all communication layers and subsystems.

The IoT-enabled smart grid provides two-way communication among connected devices and technologies, enabling the system to recognize and respond to human needs. The authors of [17] developed and implemented an IoT-based power monitoring system designed to measure and analyze critical electrical parameters, including the voltage, current, active power, and energy consumption of various loads. Using modern IoT technologies, the system provided a solution for real-time monitoring and administration of electrical data, considerably improving the capacities of both customers and electric power corporations within the smart grid. The core component of the system was the IoT-based software program 'ThingSpeak', which acts as a platform for collecting real-time electrical data from customers. ThingSpeak offers continuous collecting, visualization, and analysis of electrical characteristics, providing real-time insights into energy use patterns. This work mainly considered the application layer of the smart grid; however, our proposed framework investigated all communication layers.

S. Poorna et al. [18] investigated the implementation of IoT-based smart sensor technology to enhance smart grid systems' reliability and power efficiency. The authors introduced a framework that integrated key monitoring, communication, and analysis elements. The monitoring component includes current and voltage sensors directly connected to consumer loads, providing real-time data on electrical parameters. The communication component comprises an Arduino sensor and a WiFi module, facilitating seamless wireless communication between the sensors and the central monitoring system. The analysis component is a remote service that processes data to create voltage profiles, energy reports, and detailed voltage and current readings. This program allows extensive monitoring and assessment of the smart grid's performance. The suggested framework's performance was evaluated using a variety of characteristics, including voltage, current, power, perceived power, and energy. These factors were measured and analyzed during testing to guarantee the system's reliability and efficiency. Integrating IoT-based smart sensors into the smart grid enhanced power efficiency and reliability and enabled proactive energy consumption and distribution control.

As IoT-based smart grids become increasingly important for regulating fluctuating electricity demand, the wide range of equipment necessary to realize these cyber-physical systems (CPSs) poses substantial security issues. The authors of [19] tackled these concerns by presenting a mutual authentication and key agreement approach for smart grid applications that secures communications while also protecting user privacy. The suggested approach uses both elliptic curve encryption (ECC) and physical unclonable function (PUF) modules. This dual technique ensures the secrecy and integrity of the data sent inside the smart grid network. The security analysis of the proposed approach demonstrated its robust defense capabilities against various threats, including those aimed at message integrity and secrecy on the communication channel and physical attacks on the hardware. This robustness is crucial for ensuring the integrity and security of smart grid activities. The proposed security model was tested for practicality on an Arduino UNO microcontroller. A full comparative performance evaluation was carried out, demonstrating that the proposed model is secure and resource-efficient.

Despite the potential of IoT-based smart grids, the communication network's intrinsic openness and the devices' resource restrictions present serious security and privacy challenges. A. Zahoor et al. [20] addressed these issues by developing a private blockchain-based access control protocol for IoT-based smart grids utilizing PUF technology. The protocol allows secure and efficient data flow between service providers and smart meters. In this approach, the participating service providers form a peer-to-peer (P2P) network, with each peer node responsible for securely generating blocks from acquired data. The newly formed block is then verified and added to the blockchain network by all peer nodes using a voting-based consensus method. The protocol takes advantage of PUF's unique capabilities to improve security by establishing a hardware-based root of trust, ensuring that only legitimate devices can access the network. Blockchain technology secures data transfer by generating an immutable ledger of all transactions, preventing manipulation and ensuring data integrity. The authors evaluated the protocol's security using the random or real (RoR) model, which simulates probable attack scenarios and tests the durability of our security mechanisms. The findings of the security analysis showed that the protocol is more efficient than existing alternatives and has better security qualities, such as resistance to spoofing, man-in-the-middle attacks, and unauthorized access.

Integrating renewable energy resources into the smart grid provides considerable financial and environmental benefits. However, the absence of real-time monitoring for these renewable energy-based microgrids and substations creates issues such as inefficient resource allocation, poor load management, grid instability, and insufficient real-time decision-making. Z. Ullah et al. [21] proposed an IoT-based monitoring and control system for power substations and distributed renewable-energy-based smart grids. They aimed to improve visibility and decision-making capabilities for integrating and segregating these grids within the power distribution networks. The work used IoT technology to effectively manage load distribution, addressing industrial, domestic, commercial, and electric vehicle demands to prevent power fluctuations and contingencies. The authors used HOMER Grid® software to analyze annual power production and consumption patterns, allowing for more proactive energy management decisions. The suggested IoT-based solution enabled real-time monitoring of power characteristics, resulting in improved load control and smart grid integration, lowering energy costs and carbon emissions. The model was validated using a prototype that shows real-time monitoring and control. This allows power distribution companies to manage loads more efficiently during peak demand or crises. This strategy improved grid stability and energy efficiency, demonstrating the value of IoT technology in furthering smart grid integration and optimizing load control inside power distribution networks.

Smart grids use bidirectional communication technologies, in which smart meters connect with multiple organizations and collect data from the electrical grid. This interaction gives specialized features to various energy market participants. M. Orlando et al. [22] proposed a distributed metering infrastructure that offers bidirectional communication, self-configuration, and auto-update capabilities. The proposed solution features three-phase smart meters designed according to fundamental IoT principles. The introduced smart meters can run multiple algorithms for smart grid management either onboard or distributed across the network. The system's auto-update feature allows for the seamless addition, updating, or removal of these algorithms in real time. The authors evaluated the work using the Opal-RT tool, demonstrating that the proposed infrastructure performs efficiently, with Internet data transmission latency remaining within acceptable limits. This confirms that the developed architecture is suitable for real-time grid operations and can support the deployment of innovative services without compromising performance.

In [23], the authors investigated the deployment and performance evaluation of IoT-based smart energy management systems (SEMSs) across various settings, including industrial, commercial, building, and warehouse environments. The SEMS is designed to optimize energy usage and enhance efficiency in these diverse applications, providing a comprehensive solution for energy management. The SEMS shows flexibility and adaptability by being utilized in many environments, including industrial facilities, commercial buildings, residential complexes, and warehouses, each with distinct energy consumption patterns and needs. The SEMS provides instantaneous monitoring and regulation of energy usage using IoT technologies. Sensors and IoT devices gather data on different energy characteristics, which are subsequently analyzed to enhance energy utilization. The SEMS was evaluated for its effectiveness in conserving energy within air-conditioning systems as a specific test case. This evaluation highlights the system's ability to target significant energy-consuming components and implement strategies for energy reduction. The SEMS achieved substantial energy conservation, with savings ranging from 5% to 53% across different settings. This wide range of savings proves the system's effectiveness in adapting to various energy management needs and optimizing consumption accordingly. The system utilizes real-time data to make informed decisions about energy usage. This data-driven approach ensures that energy management strategies are based on current consumption patterns, leading to more effective conservation measures. The research demonstrated the practical application and benefits of the SEMS through detailed case studies. These case studies provide concrete examples of how the system is implemented and the tangible results it achieves in different environments.

To demonstrate the proposed framework's novelty compared with the existing methods, we introduce Table 1. This table summarizes the main features of the previously mentioned studies and approaches, including key technologies, performance metrics, and evaluation approaches.

Table 1. Main features of existing approaches compared with the proposed framework.

Ref.	Renewable Energy Sources	Key Technologies					Evaluation	Performance Metrics
		IoT	Fog	MEC	Blockchain	AI/ML		
[16]	x	√	x	√	x	x	Simulation-based	• Frequency response • Compact size of triplexer • Insertion losses
[17]	x	√	x	x	x	x	Experiment-based	• Energy consumption • Load management
[18]	x	√	x	x	x	x	Simulation-based	• Reliability • Energy consumption
[19]	x	√	x	x	x	x	Experiment-based	• Threat detection • Resistance to attacks
[20]	x	√	x	x	√	x	Simulation-based	• Resistance to attacks
[21]	√	√	x	x	x	x	Simulation-based	• Energy cost • Load management
[22]	x	√	x	x	x	x	Simulation-based	• Latency
[23]	x	√	x	x	x	x	Experimental-based	-
Proposed	√	√	√	√	x	x	Simulation-based	• Energy efficiency • Reliability • Availability

3. Proposed Smart Grid System

The proposed model can control and manage power generation and the usage of this power in a specified area. To meet the loads of a specified area, the proposed system calculates and monitors the loads of the end nodes, including homes, factories, and buildings. The proposed model looks deeper inside these nodes, dividing the loads into critical and non-critical loads to balance the grid loads and achieve customer satisfaction. Additionally, it aligns the grid's power generation capacity with clean, affordable power, and only a sophisticated control and management system can make this happen.

The proposed system consists of three different layers. The first layer is the input power source; in our case, solar power is the main source. The second layer is the brain and the connection between the power generation and end consumer layers, which controls and manages a specific area's grid generation and loads. The third layer is the consumer or the load side, which includes the power consumption devices located at different places, including homes, offices, and factories. Figure 1 presents the structure of the proposed system. In the following, we introduce the three layers deeply by mentioning the main functions of each layer and how it works.

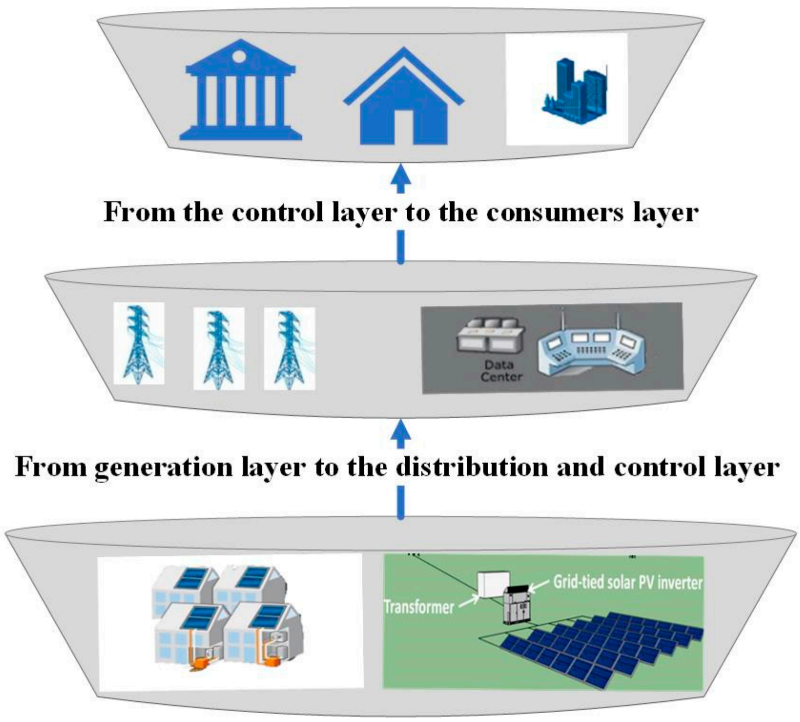

Figure 1. Structure of the proposed system.

A. The first layer (power generation layer)

Two power sources are considered for the proposed system, which may be working together or working independently according to the needs of the end devices, i.e., devices at the third layer. The main source is the solar power plant, which consists of solar panel arrays, power banks (batteries), controllers, and inverters. This source represents the grid's main and bulky input power, which provides power for all grid branches. The second power source is a small distributed photovoltaic (PV) system with solar panels on the building's roofs or windows.

The power extracted from these PV systems is directed through the controller and inverter to convert it into alternating current (AC) power. At the end of this layer, the AC power passes through the IoT-based management and metering layer, i.e., the second layer, for calculating and monitoring the produced and consumed power.

B. The second layer (IoT control and management layer)

The second layer is the IoT-based control and management layer, which is considered the proposed model's organizer. It calculates and provides the proper needs for each side, either by collecting, monitoring, and controlling the power grid usage details such as the congestion, peaks, and outage times of the grid behavior or by informing the end consumers about their consumption rate and how to reduce it by controlling their end devices. To provide these capabilities for a smart power grid, IoT devices, IoT gateways, and edge computing servers are utilized. The main parts of this layer are introduced as follows.

- IoT devices: IoT technology is used in the proposed system to improve the performance of power generation, distribution, and consumption rate. IoT devices are used to monitor the output of the solar panels and the end devices' consumption rate, and other IoT devices are deployed to monitor and control the whole grid traffic load and capacity. Also, some of these devices are used to control the PV arrays to enhance their efficiency by tracking the sun, cleaning its surface, or controlling the loads on the end device side. These IoT nodes are integrated using inter-integrated circuit (I2C) connections for wired interfaces and are assumed to support both dedicated short- and long-range communication interfaces, including Wi-Fi, Zigbee, and LoRaWAN. All these devices deal with a huge amount of data, either by sending or receiving data [24]. The IoT gateway is the perfect solution for controlling, analyzing, and securing this valuable amount of data with different devices and communication protocols.

- IoT gateways: An IoT gateway is the optimum solution for handling the data for smart and fast power grid response in different scenarios. This comes from the multiple IoT devices mentioned in the previous section in a way that ensures the right action in a short time. It collects, analyzes, and manages data from different sensors. Also, it secures the collected data from intrusions or hacking while sending them via the Internet to cloud servers or edge computing servers [25].
- Edge computing servers: Edge computing servers at the edge of the end consumer nodes are used for collecting and processing the data before sending it to the main monitoring and controlling station. They are also used for storing these valuable data in the case of communication drop between them or for reducing the data traffic according to their programmed functions. This makes communication and monitoring of the power grid behavior known and ready for any unusual intrusions or drops. The edge computing servers offer more accurate and faster responses for decision making in different scenarios [26].

C. The third layer (consumption layer)

The third layer is the end user or consumer side, which is the main layer of the proposed model. This layer can consume power according to the controlled loads. The loads are controlled to achieve an efficient consumption rate. This happens by calculating the power consumption for each device and sending these measurements to the end user and the grid operators by using embedded IoT sensors that measure and monitor the power for both. Consumer satisfaction is one of the main purposes of this model, and it includes the following [27,28]:

- Offering real-time monitoring and controlling their premises and their consumption rate.
- Making a profit by selling their extra energy to the grid.
- Reducing their consumption rate during grid congestion or peak hours.
- Scheduling and controlling their devices' operation times according to their needs by dividing them into two sections; critical and non-critical loads. The critical loads cannot be lowered under any circumstances, and they differ according to the end user's willingness. The critical load for a building full of offices differs from that of homes or factories; each has a different definition of the critical load. While non-critical loads can be de-energized or lowered according to the power grid peak hours or congestion times.

4. Performance Enhancement of the Generation Subsystem

This section investigates the structure of both power generation sources, describes each source's main components, and suggests ways to improve their performance.

4.1. Distributed PV Subsystems

The distributed PV system is a kind of grid-tied connected PV system that is less expensive and easier to install than stand-alone PV systems. Figure 2 presents the main components of the PV system. It consists of several PV panels connected in series on the buildings' roofs. The output goes to the DC/AC inverter to convert it and make it suitable for consumer use or the grid if their loads are low [29].

The solar tracking system is exploited to increase the efficiency of the proposed PV system. This is done by inserting multiple sensors into the PV panels or arrays to track the sun. There are two types of sun tracking: single- or dual-axis tracking. Single-axis tracking, or one-dimensional tracking, is more effective than fixed PV systems and also presents lower cost than a dual-axis sun tracking, or two-dimensional tracking, PV system [30].

The proposed work uses the single axis sun tracking PV system by using light detection sensors (LDRs) to detect the light intensity and send it to the microcontroller, which compares the output of the top to that of the bottom sensors mounted on the PV array, calculates the proper angle, and sends it to the servo motor to move the PV array at the right angle to collect the maximum output radiation from the sun. The system deploys current and voltage sensors to measure the output power from the PV array. Figure 3 displays the flowchart of the proposed efficient tracking system.

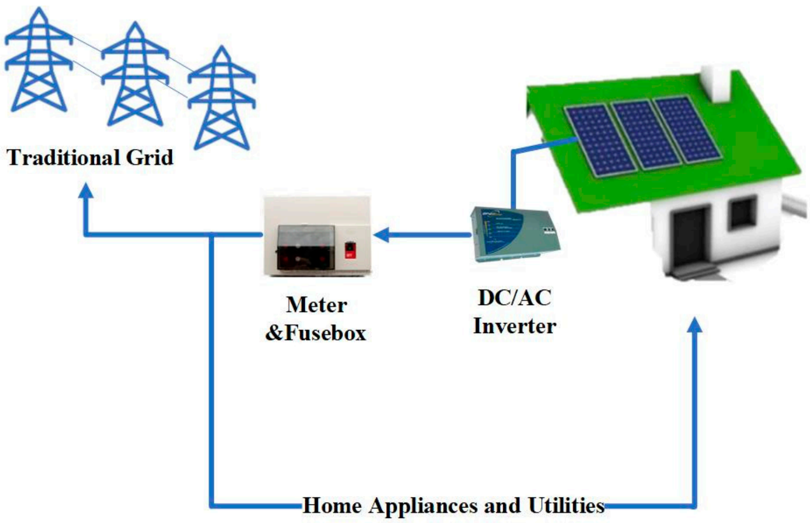

Figure 2. Grid-tied connected PV system.

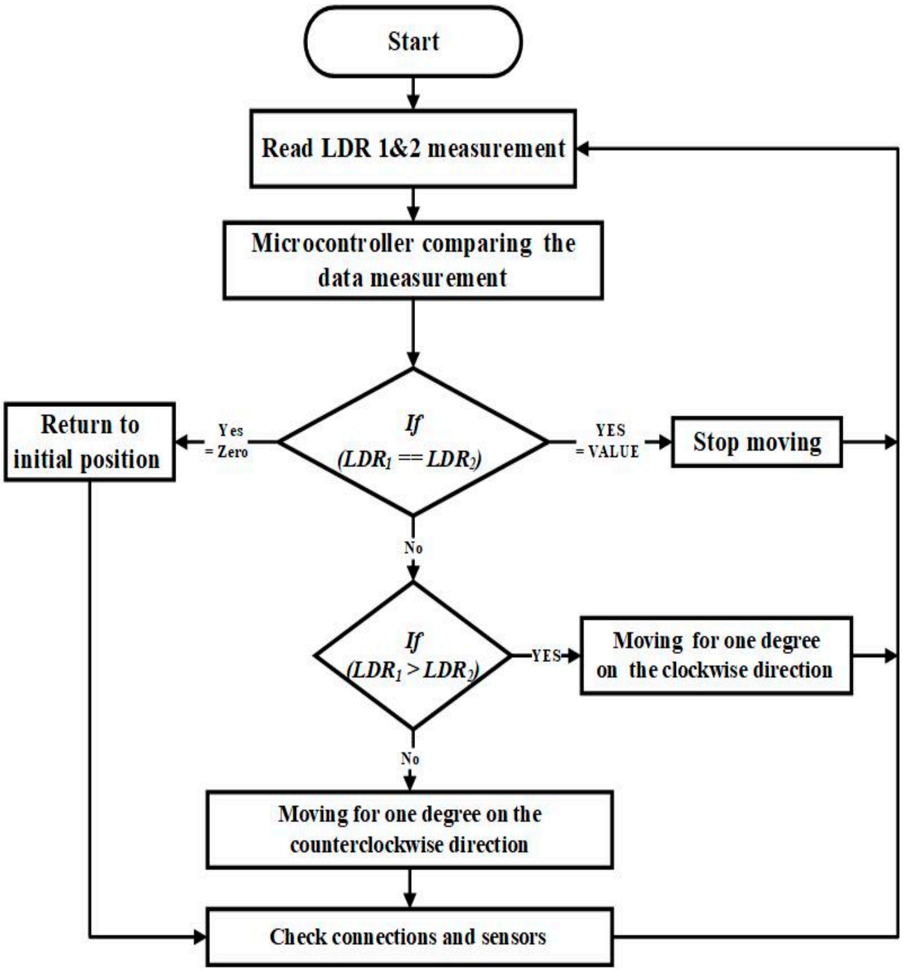

Figure 3. Flowchart of the PV array sun tracking system.

The automatic sun tracking technique compares the LDR values and executes an action by moving the PV array according to the comparison results. The PV system's output is connected to the grid through the smart metering device, which calculates the power consumption of end users, either from the PV system or the grid. Also, the smart meter calculates the benefit difference for the customer if the output of the PV system is larger than the loads or for the grid utility operator if the output is insufficient for the loads.

4.2. Grid Main Power Source (PV Power Plants)

PV power plants are usually planted in rural areas where the land cost is low and the land available is extensive; thus, they are built outside of large cities. In the proposed model, a PV power plant is used as the main source of electricity for the grid to reduce greenhouse the gas emissions and power costs that come from traditional diesel engine generators, which depend only on fossil fuel. The cost of traditional power plant generation is growing higher due to the increasing price of fossil fuels [31]. Figure 4 presents the proposed PV power plant, which consists of a large number of PV strings made from a huge number of PV panels connected to each other in series to make the PV array; the strings are connected to the inverters through the string box and then through the grid.

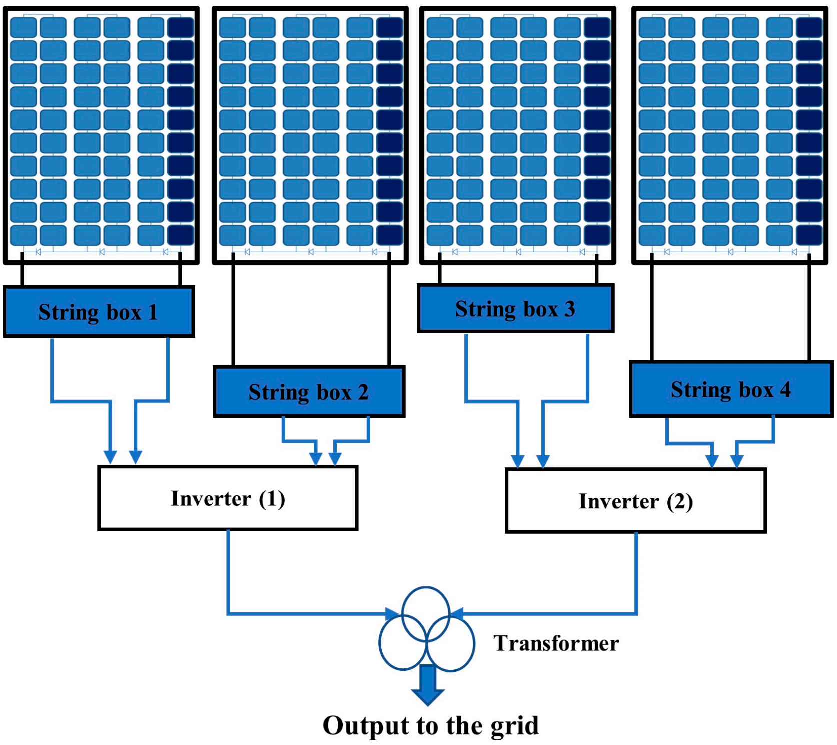

Figure 4. Proposed PV power plant.

The installation cost of the PV power plant is considered a problem, especially if we add the cost of the power used to move the arrays to track the sun. The sun tracking power increases according to the wind speed and direction. To avoid this cost in PV plants in the proposed model, good-quality dust, humidity, and wind speed sensors are installed on PV arrays. The reason for using these types of sensors is that the PV plants are installed in rural areas. There is a high probability of dust and sand accumulating, which is carried by the wind, in addition to the humidity in these areas, which is the reason for the formation of a layer of mud on the surface of the panels. Dust and humidity are the reasons behind the reduction of the output power of the PV panel and, consequently, the output power of the PV plant [32]. As a monitoring node, the proposed model adds dust, humidity, and wind speed sensors on multiple power plant sections. According to the power plant area, every node on the PV plant is connected to another node or directly to the gateway via a wired or wireless connection.

Also, it adds current and voltage sensors for each array to help monitor the PV plant's power, which is discussed later in the monitoring subsystem section.

5. Monitoring Subsystems

The proposed system uses IoT networks, and IoT nodes are distributed on the whole grid to achieve effective real-time monitoring through the proposed power grid model. IoT networks are used to achieve real-time monitoring of two different categories: grid power monitoring and data monitoring between the grid operator and the end user.

5.1. Power Monitoring System

The function of the power monitoring network is to monitor the current and voltage of each node in the system. The nodes are distributed throughout the system from the generation layer, passed by the grid power transmission lines, and end on the customer side. Current and voltage sensors are installed on the generation nodes to measure the PV arrays and the inverter output and transmission lines to detect any changes in the power transmission values through the grid due to any intrusions or power drops and also measuring the output of the distributed generations (DGs) on the end user layer. In the following, we introduce the monitoring subsystems at different parts of the network.

A. Distributed PV monitoring subsystem

The monitoring nodes in the DG layer are used to constantly measure the output of the PV arrays and the inverter of the DG. Each node consists of PV panels, i.e., PV arrays; and current and voltage sensors, i.e., I&V sensors, inserted on the PV array output and on the inverter output for each DG node [33]. The taken measurements are amplified and converted into a digital form to be processed. The data go to the microcontroller for processing and handling before being sent to the higher level of the communication network. Figure 5 shows the main structure of the DG node. By collecting this huge amount of data from the system, any drops or attenuations can be easily monitored.

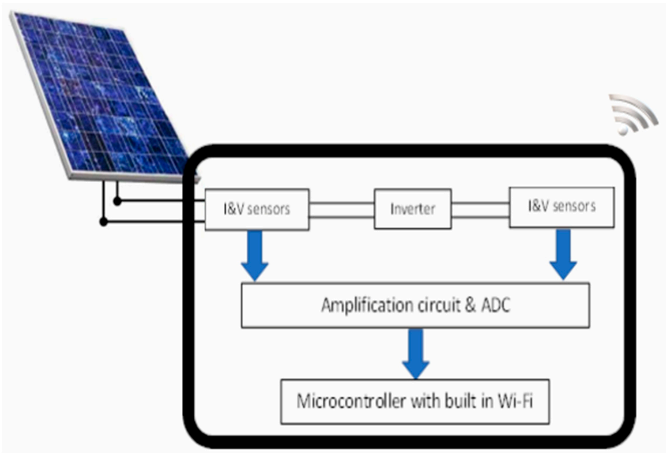

Figure 5. DG monitoring node.

B. PV power plant monitoring subsystem

The PV power plant monitoring nodes are distributed through the generation plants. The monitoring nodes are distributed to cover the whole generation section by dividing the generation plant area into sections or strings. Monitoring the I&V behavior for the strings and DC inverters can be achieved by inserting the I&V sensors on the output of each string and the inverters. The collected data from the I&V sensors are regulated and converted into a digital form. The microcontroller processes these types of data before sending the data on to the next communication level. Figure 6 shows the main components of the PV power plant monitoring subsystem.

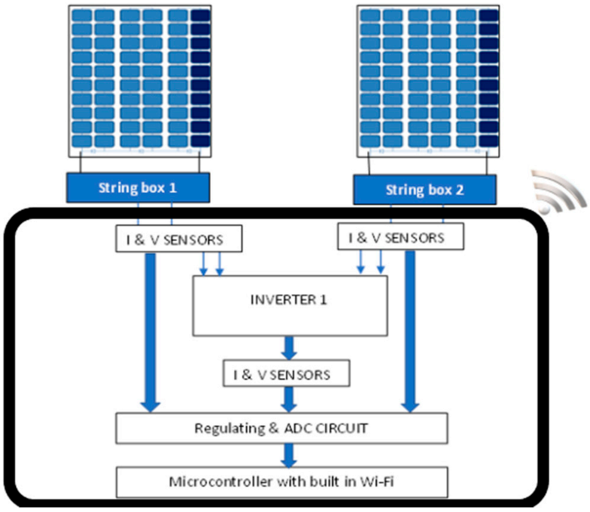

Figure 6. PV power plant monitoring subsystem.

C. Transmission line monitoring subsystem

The distributed monitoring nodes on the transmission lines consist of I&V sensors, a conditioning circuit containing regulating and analog-to-digital conversion (ADC) circuits, and a microcontroller with a built-in wireless transmission module, e.g., Wi-Fi. All these components are combined and installed on transmission line towers for real-time power monitoring through the whole grid. The collected data are processed and sent through the communication network. The monitoring node's purpose is to continuously monitor the power lines by checking for the presence of power and measuring it through the grid transmission lines. Collecting this information from the distributed nodes can detect any drop, intrusion, or harmful attenuation through the power grid. Figure 7 shows the main components of the transmission line monitoring subsystem.

Figure 7. Transmission line monitoring subsystem.

5.2. Data Monitoring Network

The amount of data measured by IoT sensors is huge and vital, so there is a need to handle and protect this data. Securing and protecting these data occurs on the grid utility operator side according to the proposed algorithm previously introduced in Section 3. This process starts from the sensor itself, according to its resources, and ends with the grid operator's core network servers. The sensors' collected data are transferred through the network using the transmission line monitoring nodes as a bridge in case of low coverage or drops. The monitoring network nodes are used for achieving grid reliability and real-time monitoring of the whole grid. Figure 8 presents the data monitoring nodes and data flow through the whole grid monitoring network.

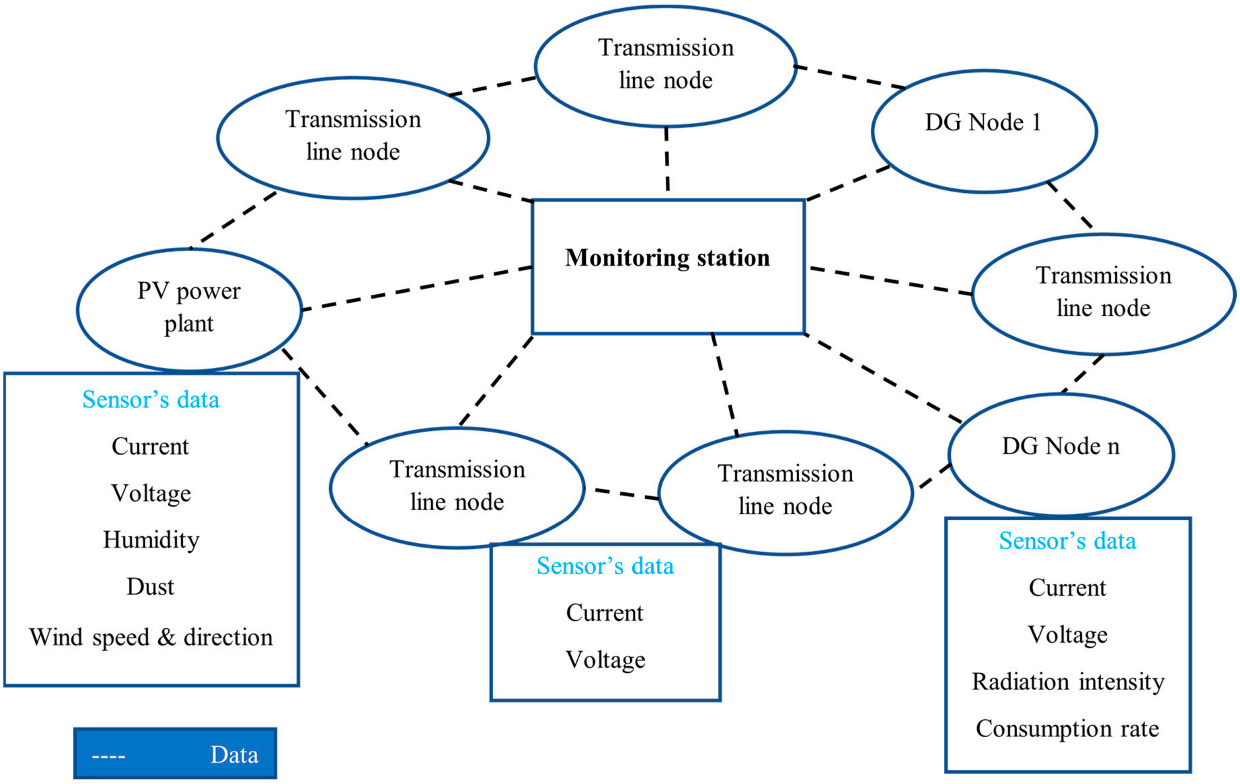

Figure 8. Data monitoring nodes and data flow through the power grid.

6. Edge Computing Model

The huge amount of data explained in the monitoring network subsection clarifies the importance of these types of data. Transferring these amounts of data between the multiple monitoring nodes on the whole grid ending with the monitoring station should be defined and explained. Due to the large capacity of the transferred data between nodes, the latency and the energy consumption are the main factors of the communication network. This section will explain the multiple levels of communication and the responsibility for each level from the communication energy and latency-aware point of view. These two communication factors are important, especially in our proposed power grid model, which is concerned with achieving real-time monitoring of the grid with a minimum amount of energy.

The proposed SG deploys a hierarchal structure of distributed edge computing units. The considered SG deploys two heterogeneous edge servers: MEC and fog. The proposed hierarchal edge computing scheme consists of four main levels deployed at different locations of the SG. Figure 9 presents the main levels of the proposed edge computing model for the developed SG. The first level represents the main edge cloud deployed at the main IoT control and monitoring level. This level represents the interface between remote servers and the SG. The second level is the MEC servers distributed over each main distribution area. The distribution area is divided into main areas, referred to as urban regions, served by MEC servers with powerful resources. This level has direct high-speed fiber connections to the main MEC. Also, these servers have direct connections with IoT gateways. The third edge computing level is the MEC servers deployed to serve different regions inside each urban area. Each urban area is divided into smaller distribution areas, referred to as districts. Each district is served by a MEC server with lower resources than urban MEC servers. Table 2 provides variants of possible computing devices that can be deployed in the proposed grid. The table provides the main category of each device, the specifications of the devices, and the main applications of the device. Also, the manufacturer and a link to each device's specifications are introduced in the table.

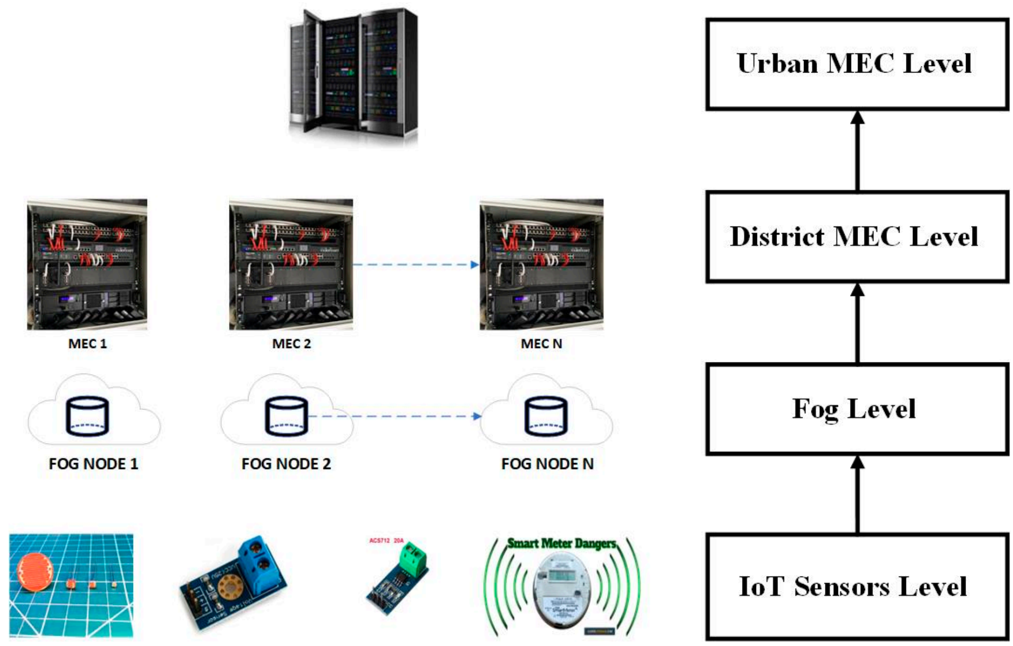

Figure 9. Main offloading levels of the considered offloading model.

We consider our previously developed offloading scheme developed in [34] to enable efficient data transfer between multiple communication levels. Computing tasks are handled on IoT devices if there are sufficient resources or offloaded to higher-level edge servers. Fog nodes handle tasks received from IoT nodes or move them to district MEC servers based on the available resources. Tasks that cannot be handled by district MECs are offloaded to urban MECs to be handled or terminated based on the available resources.

Table 2. Variants of possible endpoint computing devices.

Category	Ref.	Device Model	Manufacturers	Main Features	Applications
Smart meters	[35]	OpenWay Riva CENTRO	Itron	• Hybrid meter • Robust functionality • High-performance communications capabilities • Supports both RF mesh and PLC communications • Distributed intelligence platform	• Meter-to-grid applications
	[36]	E450 m	Landis+Gyr	• Residential meters • Multi-energy data collector • Remote two-way communication node • Supports multiple communication technologies • Integrates with various utility management systems • Programmable demand-response functions	• Meter-to-grid applications
Smart sensors	[37]	Gridsense Line IQ	Franklin Electric	• Fault and load monitor device • Has a wireless interface to the controller • Hot stick installation • Has multiple communication interfaces	• Provides real-time monitoring of line current and voltage
	[38]	EPM 7100	GE Grid Solutions	• Supports hybrid wired and wireless connections, including RJ45 Ethernet or IEEE 802.11 WiFi connection • Enables advanced analysis and predictive maintenance • Supports RS485 output speaking Modbus protocol	• A multifunction power quality meter that provides data on a wide range of electrical parameters • Detects power problems at early stages
Edge IoT gateways	[39]	Cisco IR829	Cisco	• Industrial integrated services routers • Provides integrated storage and computing capability for edge applications • Supports multiple communication interfaces, including cellular and low-power wide-area network (LPWAN) interfaces	• IoT gateway that provides an interface to the Internet
	[40]	UTX-3117	Advantech	• Has a high-performance, low-power Intel processor (Intel Apollo Lake E3900 series and N series Processor) • Has the ability to be integrated with multiple IoT platforms • Supports different types of operating systems, including Linux and Windows	• IoT gateway that provides an interface to the Internet
Embedded devices	[41]	FETMX8MM-C	Forlinx Embedded Technology	• System on module (SoM) based on NXP's i.MX8M Mini processor • Has embedded memory • Has high-performance computing • Has multiple communication interfaces, including cellular and IoT dedicated interfaces	• Specialized computing device integrated into a larger system to perform dedicated functions • IoT and industrial applications
Programmable logic controllers (PLCs)	[42]	SIMATIC S7-1200	Siemens	• Modular PLC system	• Automation and control tasks
MEC	[43]	Jetson Xavier NX	NVIDIA	• High-performance MEC • Edge intelligence server	• Edge computing applications
	[44]	Intel Movidius Myriad X	Intel	• A vision processing unit designed for AI and computer vision tasks at the edge	• Edge computing applications
Switch	[45]	Cisco Catalyst IE3400	Cisco	• Software-based segmentation and flow visibility for security-threat detection and isolation	• Industrial Ethernet switching applications • Platform for extending IoT connectivity

7. Simulation and Results

In this section, we evaluate the performance of the proposed system and subsystems. We simulated the developed framework, including subsystems and algorithms, and carried out experiments to assess the performance of the subsystems.

7.1. Simulation Setup

We simulated a system in which the main power generation source is a solar panel PV system with the data introduced in the dataset available in [46]. We considered the Java-based event-driven-based simulator introduced in [47,48] for this evaluation. The simulator was built on the CloudSim platform. The National Renewable Energy Laboratory collected the data, which consists of one million solar cell systems. The output data from the generation planet, i.e., the solar panel PV system, were fed to the distribution area through the IoT control and monitoring unit. We considered a distribution area, i.e., a consumption area, of a square shape of 10 km per side, near the area of Cairo city, the capital of Egypt. This area was divided into four main square areas of 5 Km per side, representing the city's four main urban areas. Each urban area was divided into districts of one Km square area. Figure 10 presents the topology of the simulated consumption area.

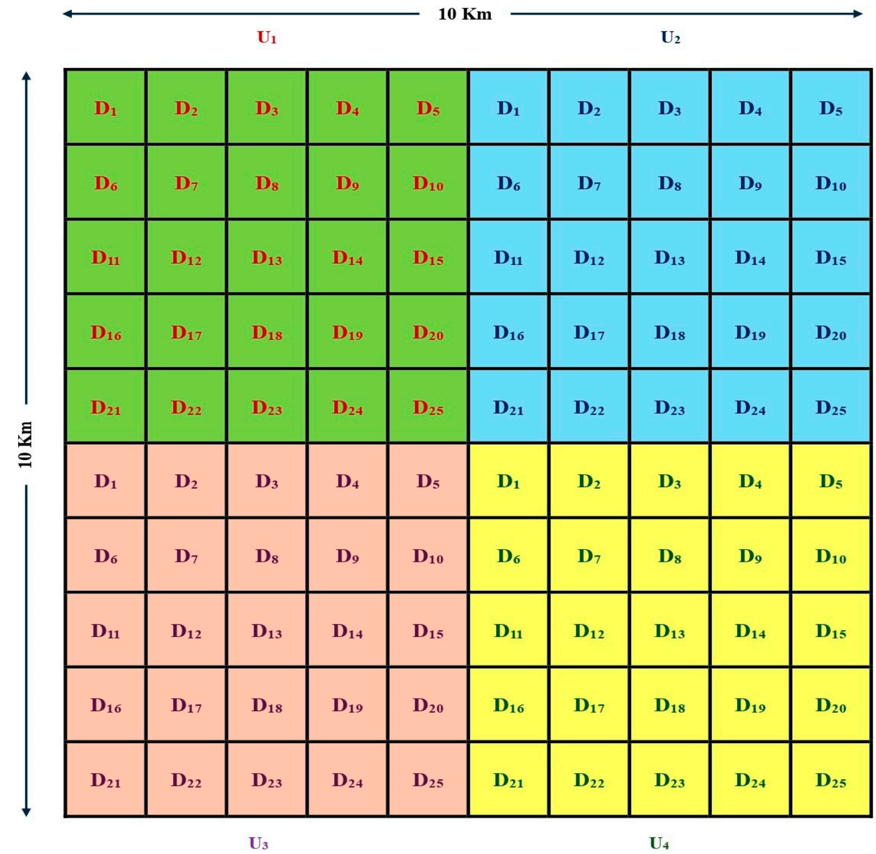

Figure 10. Topology of the considered consumption area.

The main IoT control and monitoring system was connected to the main cloud server, referred to as the main MEC, to handle and store the system data. A MEC server was located at the center of each main urban area and is referred to as the urban MEC. Each district was served by a MEC server, referred to as the district MEC. The urban MEC is a powerful server with a higher computing capacity than the district MEC. The district MECs in the same urban area are connected to the urban MEC. For each district region, twenty fog nodes are normally distributed to serve houses in the district area. All end devices share their computing tasks with nearby fog nodes. Figure 11 presents the topology of the distributed edge computing devices over the system. Table 3 presents the considered parameters during the simulation.

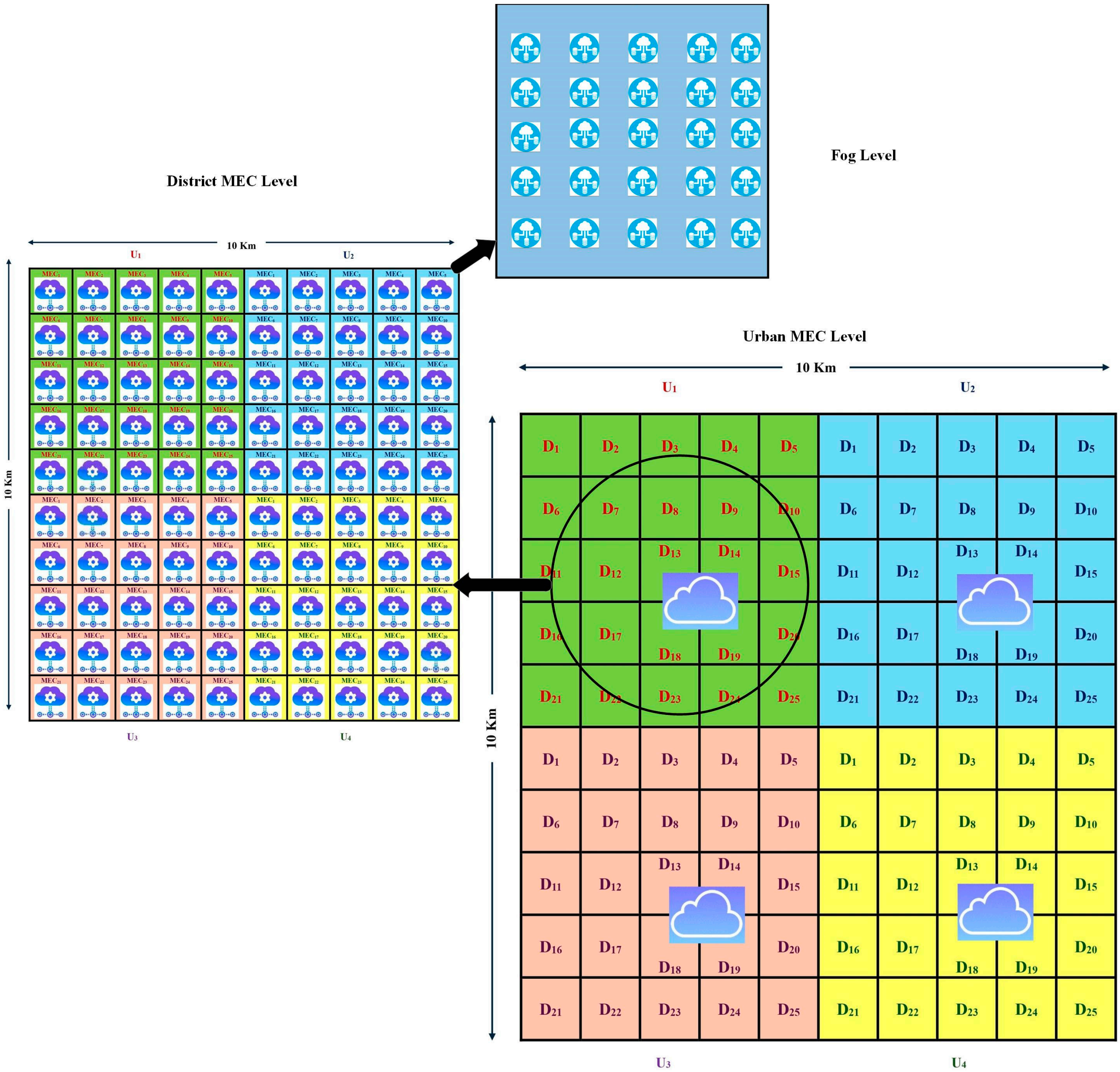

Figure 11. Topology of the deployed edge computing approach.

We considered measuring the energy efficiency before and after deploying the proposed framework for performance evaluation. This evaluation is from the energy point of view for the overall proposed system. However, we also considered evaluating the proposed grid's communication network, including the communicated data's reliability and system availability. In this part of the evaluation, we mainly consider the IoT edge computing system. For this evaluation, we simulated the system for different categories of end-device loads. This is to ensure the performance of the network under different real conditions. Ten load categories were considered for the system evaluation. The first load category maps to a low grid loading, while the tenth load category maps to a high grid loading.

Table 3. Simulation parameters.

Parameter	Value
Consumption area	10 km × 10 km
Area of urban region	5 km × 5 km
Number of urban regions	4
Area of district region	1 km × 1 km
Number of district regions per urban area	25
Number of district MECs	4 × 25
Number of urban MECs	4
Number of fog nodes	4 × 25 × 20
MEC placement	equidistant
Bandwidth of IoT gateway	868 MHz
Packet size	32 Byte
District MEC—Storage	16 Gb
Urban MEC—Storage	32 Gb
Fog node—Storage	2048 Mb
District MEC—Processing	ϵ[2.4,3.2] GHz
Urban MEC—Processing	ϵ[3.2,4.7] GHz
Fog node—Processing	ϵ[0.7,2.4] GHz
Max. server load (fog)	20 events/s
Max. server load (MEC)	50 events/s
Data traffic	3 packets

7.2. Results and Discussion

Figures 12–15 present the average energy efficiency for the four considered urban areas. We compared the energy efficiency of the proposed system with IoT nodes and edge computing servers with the traditional grid. Each figure of the four figures presents the average energy efficiency of each district in a zone. i.e., urban area, of the four zones for the two compared grids. We calculated the average energy efficiency for each district among all deployed end devices. The proposed IoT-based grid achieved higher energy efficiency than the traditional grid for all districts in the four zones. The proposed system outperformed the traditional grid in terms of energy efficiency by an average of 24.3%. This is due to the efficient management of the IoT nodes deployed at the different levels of the grid. Controlling the energy at different levels through IoT nodes reduces energy consumption and waste.

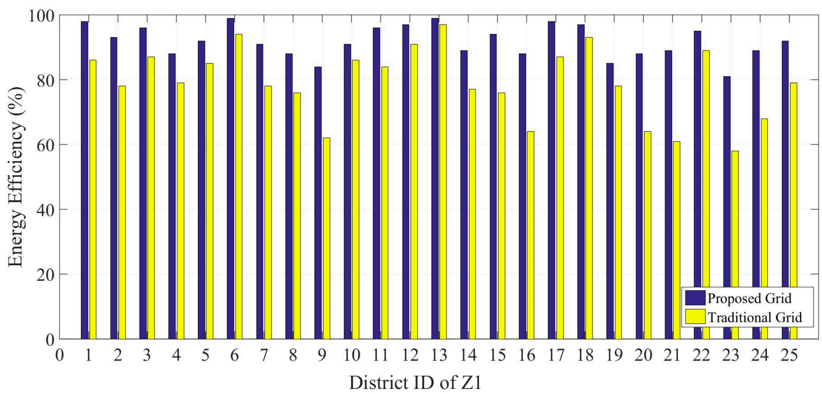

Figure 12. The energy efficiency of each district in the first zone.

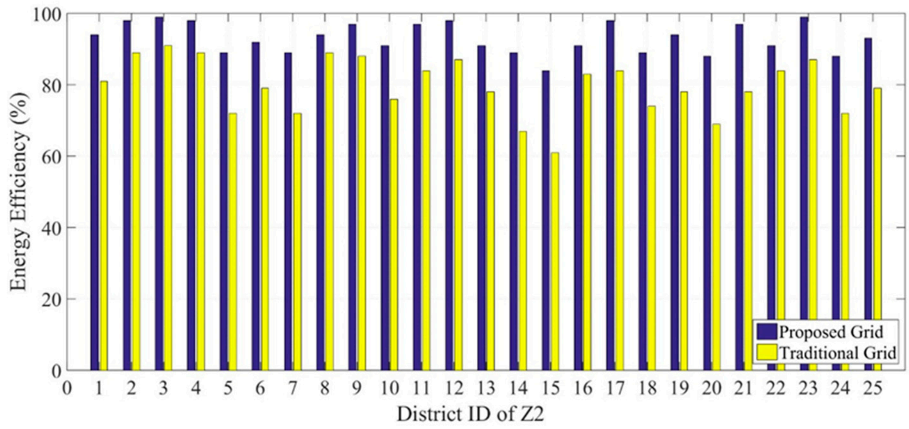

Figure 13. The energy efficiency of each district in the second zone.

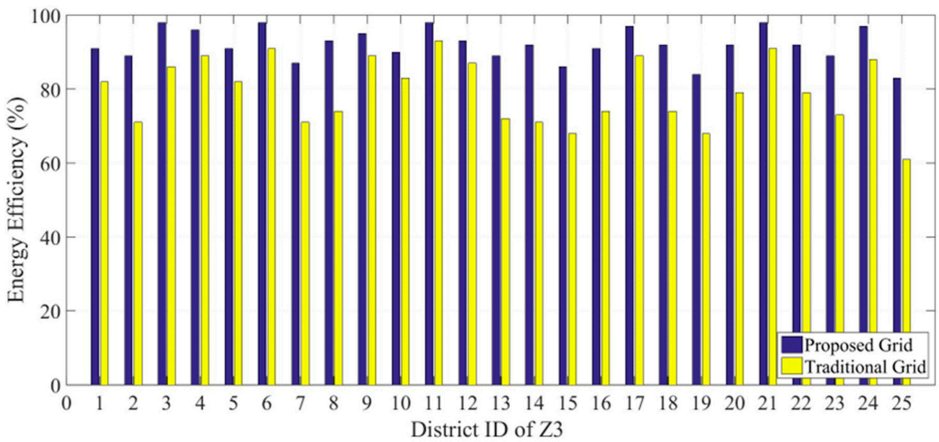

Figure 14. The energy efficiency of each district in the third zone.

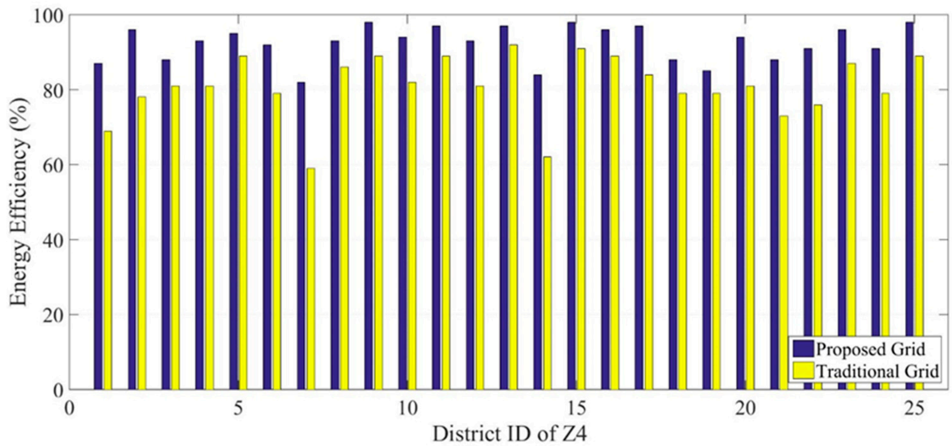

Figure 15. The energy efficiency of each district in the fourth zone.

Moving to the proposed communication network with the introduced edge computing model and the deployed offloading scheme, the systems achieved improved performance in terms of availability and reliability and outperformed the existing traditional networks. Figures 16–19 present the average packet delivery ratio (PDR), as a percentage, for different zones in the system. Figure 16 presents the average PDR for all communicated packets of the first zone. The system was simulated for ten different load categories, and the PDR was measured for each. As the load increases, the communication overhead increases due to the massive exchange of control messages. The proposed grid achieved a higher packet delivery ratio in all communication networks covering the four zones by an average of 28%. This metric mainly maps to the network reliability, and thus, the proposed grid outperforms traditional grids in terms of network reliability, as indicated in the results presented in Figures 16–19. The main reason behind this performance improvement is the deployment of distributed edge computing, fog, and MEC.

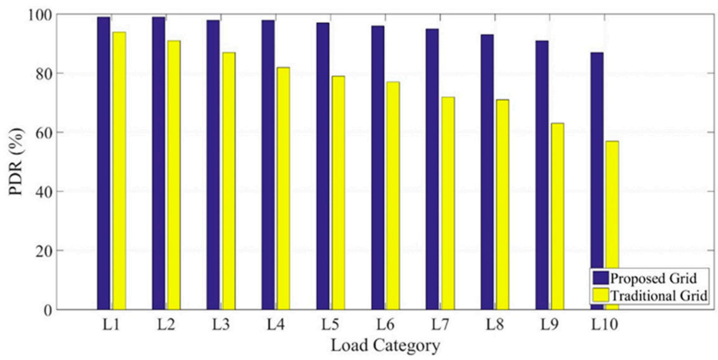

Figure 16. Average PDR at different load levels for the districts of the first zone.

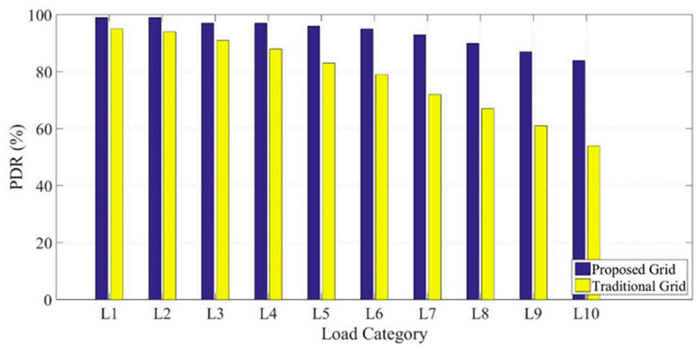

Figure 17. Average PDR at different load levels for the districts of the second zone.

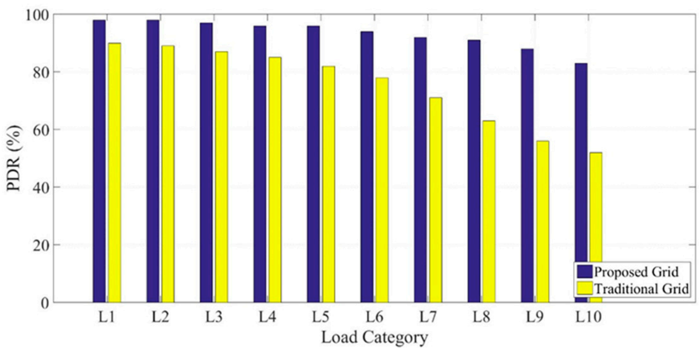

Figure 18. Average PDR at different load levels for the districts of the third zone.

We considered another metric for evaluating the IoT-based edge computing network: the efficiency of utilizing network resources. We mainly considered evaluating the efficiency of utilizing resources of edge servers since we deployed four hierarchical levels of these servers. This deployment increases the overall cost, which makes it necessary to ensure that the proposed grid needs such deployment and that this cost is paid for higher efficiency. Figures 20–23 present the average efficiency of utilizing resources for the fog nodes deployed in each district. Three measures were calculated for each district; each of these was calculated as a load category. Three load categories were considered: low, medium, and high load. The value calculated for each district represents the average resource utilization value of all fog nodes deployed in this district. The figures indicate that the proposed grid utilizes fog computing resources efficiently, even at high load values. The proposed model utilizes an average of 90.5% of fog computing resources, outperforming existing edge computing models [34].

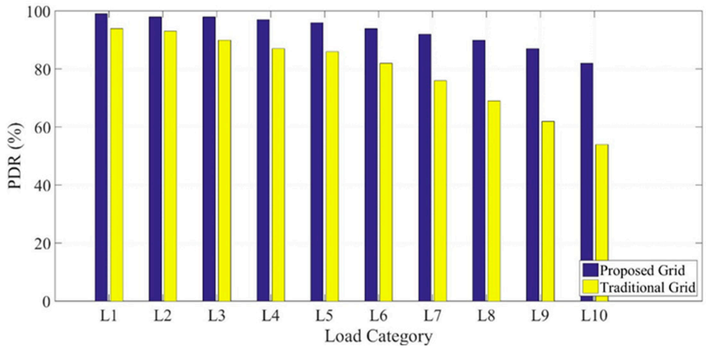

Figure 19. Average PDR at different load levels for the districts of the fourth zone.

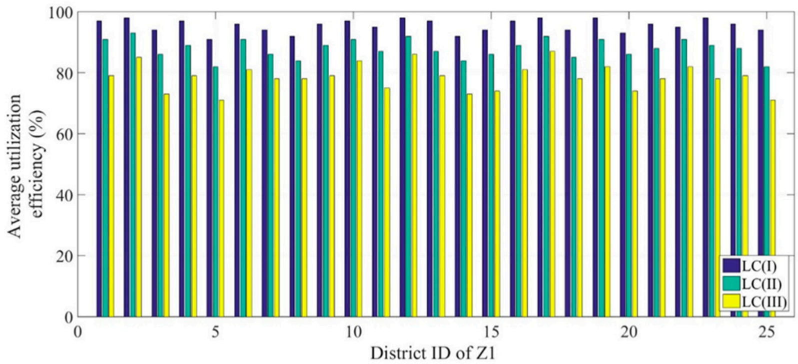

Figure 20. Average utilization efficiency of fog nodes, at different load levels, in each district in the first zone.

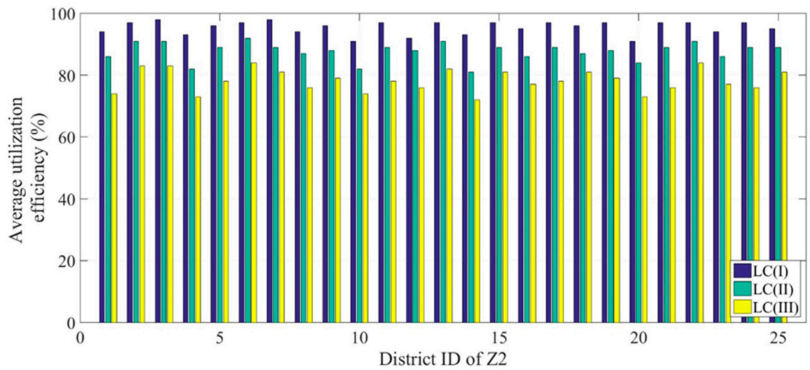

Figure 21. Average utilization efficiency of fog nodes, at different load levels, in each district in the second zone.

Figures 24–27 present the utilization efficiency of all district MEC servers deployed in all system zones. The efficiency of utilizing district MEC resources was measured at three different load categories. This is to test the system for all possible real situations. The proposed model utilizes the district MEC with an average of 92.9%. Also, Figure 28 presents the efficiency of utilizing urban MEC computing resources under the different load categories. The system uses the urban MEC resources with an average of 93.8%.

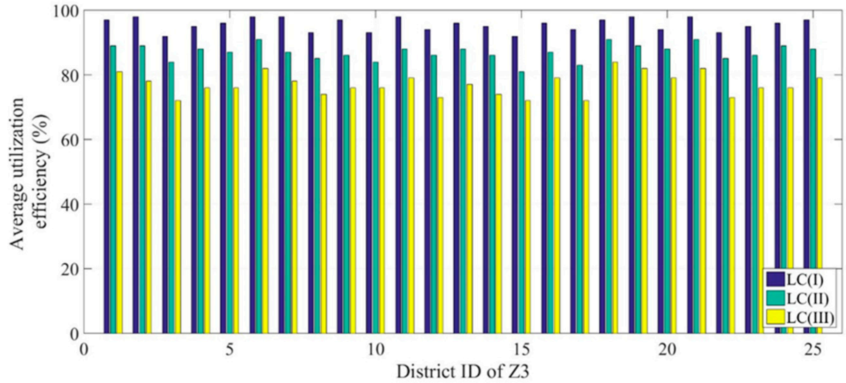

Figure 22. Average utilization efficiency of fog nodes, at different load levels, in each district in the third zone.

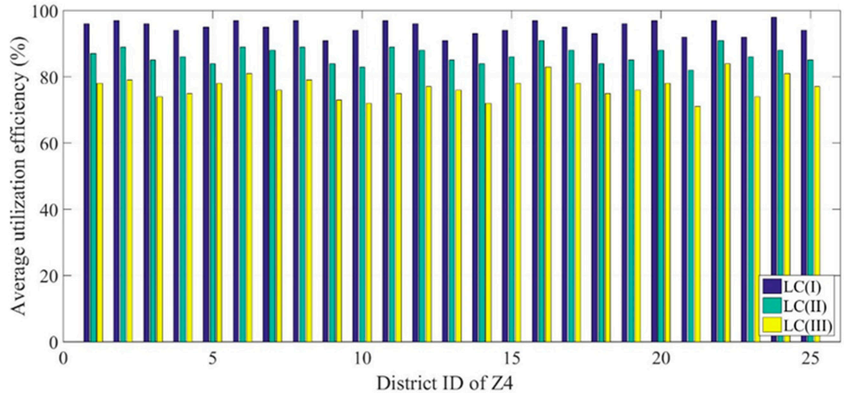

Figure 23. Average utilization efficiency of fog nodes, at different load levels, in each district in the fourth zone.

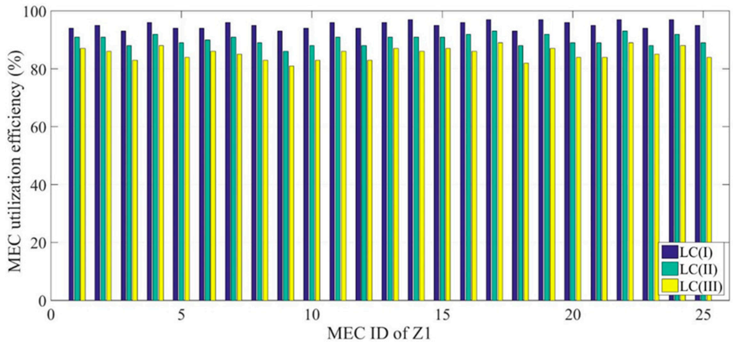

Figure 24. Utilization efficiency of district MECs in the first zone at different load levels.

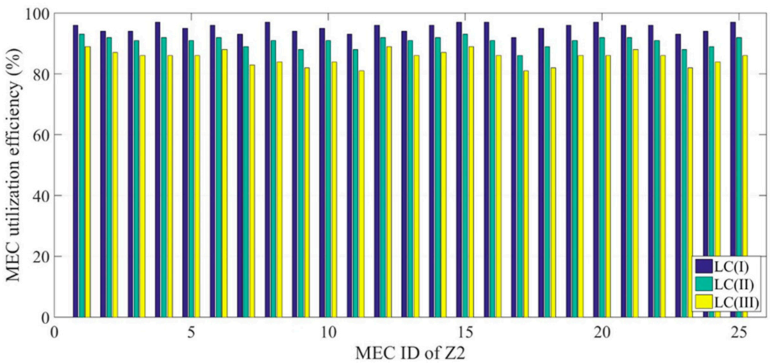

Figure 25. Utilization efficiency of district MECs in the second zone at different load levels.

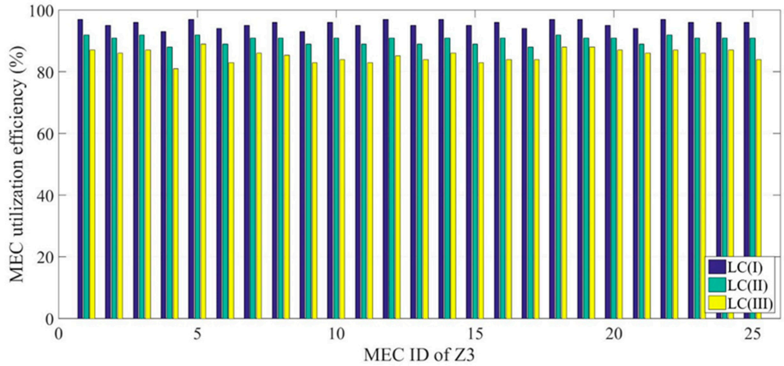

Figure 26. Utilization efficiency of district MECs in the third zone at different load levels.

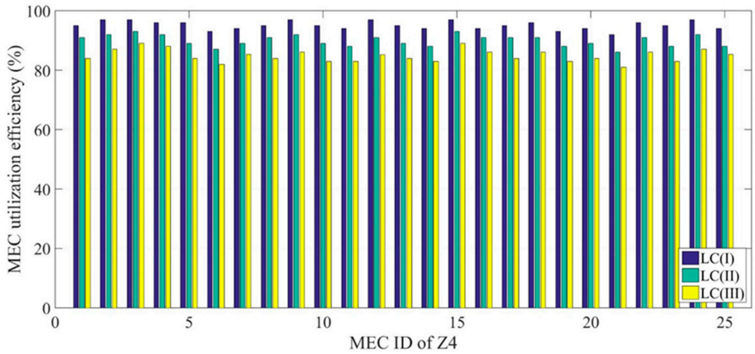

Figure 27. Utilization efficiency of district MECs in the fourth zone at different load levels.

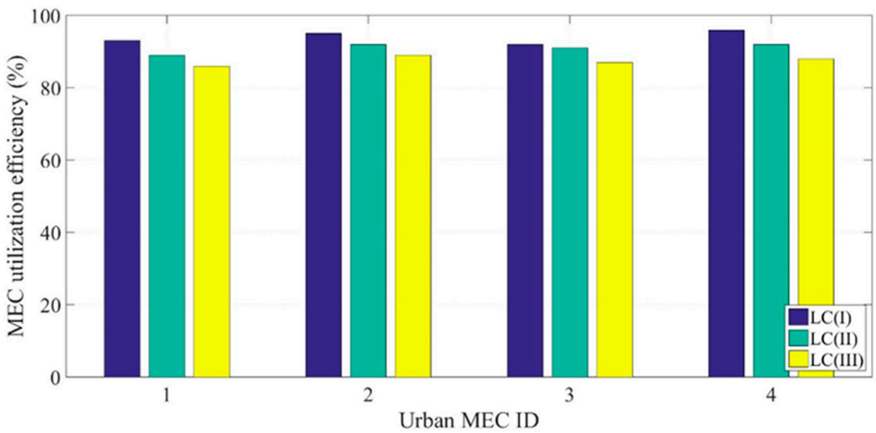

Figure 28. Utilization efficiency of urban MECs at different load levels.

Summing up, the proposed edge-computing-based green grid reduces energy overconsumption and achieves higher energy management efficiency. Also, the proposed grid is highly reliable and available. The proposed model also facilitates the integration and management of renewable energy sources. The proposed grid is mainly limited to the capabilities of the edge-computing nodes. While the proposed grid was approved to achieve different benefits that match the demands of the upcoming generations of smart grids, this all comes at the overall cost of the grid.

8. Conclusions

As sustainability becomes a top priority for governments and companies, the adoption of green smart grids is essential for creating a strong and adaptable energy future that meets evolving consumer demands and environmental goals. This study provides a promising solution for future energy systems, highlighting the significance of innovative technology in building a sustainable energy environment. This work provides an end-to-end IoT-based green smart grid that meets the demands of next-generation grids. The work introduced solar energy as a renewable energy and integrated it with the traditional grids through an IoT control scheme. This integration of solar cells with smart grids represents a significant shift toward sustainable and efficient energy management. The proposed IoT-based green smart grid framework deploys distributed edge computing at different levels to improve energy management and minimize consumption. Two main edge computing units were deployed to support data gathering and decision making over the proposed green grid: fog and MEC units. A method of integrating such edge units into the grid was introduced, and the required approaches to facilitate the work of these nodes were developed. The proposed framework was tested considering energy efficiency, data reliability, and resource efficiency. The results indicated a reduction in energy use of 24.3%, highlighting the potential for such systems to greatly outperform existing grids. Moreover, the proposed edge-computing-based grid outperformed traditional models in the latency and reliability of communicated data.

Author Contributions: Conceptualization, R.A.A., M.A., S.A.E., M.E., A.A.A.E.-L., A.A.S. and A.A.A.; methodology, M.A., S.A.E. and A.A.A.; formal analysis, M.A., R.A.A., M.E., S.A.E. and A.A.A.; investigation, M.E., A.A.A.E.-L., A.A.S. and A.A.A.; resources, R.A.A., S.A.E., M.E., A.A.A.E.-L., A.A.S. and A.A.A.; data curation, R.A.A., M.A. and S.A.E.; writing—original draft preparation, R.A.A., M.A., S.A.E., M.E. and A.A.A.; writing—review and editing, M.E., A.A.A.E.-L., A.A.S. and A.A.A.; visualization, R.A.A., M.A., S.A.E. and A.A.A.; supervision, S.A.E. and A.A.S.; project administration, A.A.A.; funding acquisition, M.E. All authors have read and agreed to the published version of the manuscript.

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References

1. Hussain, S.; Lai, C.; Eicker, U. Flexibility: Literature Review on Concepts, Modeling, and Provision Method in Smart Grid. Sustain. *Energy Grids Netw.* **2023**, *35*, 101113. [CrossRef]
2. Qays, M.O.; Ahmad, I.; Abu-Siada, A.; Hossain, M.L.; Yasmin, F. Key Communication Technologies, Applications, Protocols and Future Guides for IoT-Assisted Smart Grid Systems: A Review. *Energy Rep.* **2023**, *9*, 2440–2452. [CrossRef]
3. Kesavan, P.K.; Subramaniam, U.; Almakhles, D.J.; Selvam, S. Modelling and Coordinated Control of Grid Connected Photovoltaic, Wind Turbine Driven PMSG, and Energy Storage Device for a Hybrid DC/AC Microgrid. *Prot. Control Mod. Power Syst.* **2024**, *9*, 154–167. [CrossRef]
4. Khan, K.A.; Quamar, M.M.; Al-Qahtani, F.H.; Asif, M.; Alqahtani, M.; Khalid, M. Smart Grid Infrastructure and Renewable Energy Deployment: A Conceptual Review of Saudi Arabia. *Energy Strat. Rev.* **2023**, *50*, 101247. [CrossRef]
5. Fakhar, A.; Haidar, A.M.A.; Abdullah, M.O.; Das, N. Smart Grid Mechanism for Green Energy Management: A Comprehensive Review. *Int. J. Green Energy* **2023**, *20*, 284–308. [CrossRef]
6. Oad, A.; Ahmad, H.G.; Talpur, M.S.H.; Zhao, C.; Pervez, A. Green Smart Grid Predictive Analysis to Integrate Sustainable Energy of Emerging V2G in Smart City Technologies. *Optik* **2023**, *272*, 170146. [CrossRef]
7. Javed, M.Y.; Asghar, A.B.; Naveed, K.; Nasir, A.; Alamri, B.; Aslam, M.; Al-Ammar, E.A.; Conka, Z. Improving the Efficiency of Photovoltaic-Thermoelectric Generator System Using Novel Flying Squirrel Search Optimization Algorithm: Hybrid Renewable and Thermal Energy System (RTES) for Electricity Generation. *Process Saf. Environ. Prot.* **2024**, *187*, 104–116. [CrossRef]
8. Dileep, G. A Survey on Smart Grid Technologies and Applications. *Renew. Energy* **2020**, *146*, 2589–2625. [CrossRef]
9. Olatunde, T.M.; Okwandu, A.C.; Akande, D.O.; Sikhakhane, Z.Q. The Impact of Smart Grids on Energy Efficiency: A Comprehensive Review. *Eng. Sci. Technol. J.* **2024**, *5*, 1257–1269. [CrossRef]
10. Mohammadi, M.; Mohammadi, A. Empowering Distributed Solutions in Renewable Energy Systems and Grid Optimization. In *Distributed Machine Learning and Computing*; Springer International Publishing: Cham, Switzerland, 2024; pp. 141–155, ISBN 9783031575662.
11. Jamal, I.; Elmorshedy, M.F.; Dabour, S.M.; Rashad, E.M.; Xu, W.; Almakhles, D.J. A Comprehensive Review of Grid-Connected PV Systems Based on Impedance Source Inverter. *IEEE Access* **2022**, *10*, 89101–89123. [CrossRef]

12. Hamid, A.K.; Mbungu, N.T.; Elnady, A.; Bansal, R.C.; Ismail, A.A.; AlShabi, M.A. A Systematic Review of Grid-Connected Photovoltaic and Photovoltaic/Thermal Systems: Benefits, Challenges and Mitigation. *Energy Environ.* **2023**, *34*, 2775–2814. [CrossRef]
13. Uddin, S.S.; Joysoyal, R.; Sarker, S.K.; Muyeen, S.M.; Ali, M.F.; Hasan, M.M.; Abhi, S.H.; Islam, M.R.; Ahamed, M.H.; Islam, M.M.; et al. Next-Generation Blockchain Enabled Smart Grid: Conceptual Framework, Key Technologies and Industry Practices Review. *Energy AI* **2023**, *12*, 100228. [CrossRef]
14. Andriyanov, N.A.; Dement'ev, V.E. Topology, Protocols and Databases in Bluetooth 4.0 Sensor Networks. In *2018 Moscow Workshop on Electronic and Networking Technologies (MWENT)*; IEEE: Piscataway, NJ, USA, 2018; pp. 1–7.
15. Lee, W.-H.; Kim, H.; Lee, C.-H.; Kim, S.-M. Development of Digital Device Using ZigBee for Environmental Monitoring in Underground Mines. *Appl. Sci.* **2022**, *12*, 11927. [CrossRef]
16. Jamshidi, M.; Yahya, S.I.; Nouri, L.; Hashemi-Dezaki, H.; Rezaei, A.; Chaudhary, M.A. A Super-Efficient GSM Triplexer for 5G-Enabled IoT in Sustainable Smart Grid Edge Computing and the Metaverse. *Sensors* **2023**, *23*, 3775. [CrossRef]
17. Khan, F.; Siddiqui, M.A.B.; Rehman, A.U.; Khan, J.; Asad, M.T.S.A.; Asad, A. IoT Based Power Monitoring System for Smart Grid Applications. In Proceedings of the 2020 International Conference on Engineering and Emerging Technologies (ICEET), Lahore, Pakistan, 22–23 February 2020; IEEE: Piscataway, NJ, USA, 2020; pp. 1–5.
18. Rao, S.P.C.; Sushama, M. An IoT-Based Sensor Technology for Improving Reliability and Power Quality in Smart Grid Systems. *Int. J. Electr. Electron. Eng. Telecommun.* **2023**, *12*, 264–271. [CrossRef]
19. Rostampour, S.; Bagheri, N.; Ghavami, B.; Bendavid, Y.; Kumari, S.; Martin, H.; Camara, C. Using a Privacy-Enhanced Authentication Process to Secure IoT-Based Smart Grid Infrastructures. *J. Supercomput.* **2024**, *80*, 1668–1693. [CrossRef]
20. Zahoor, A.; Mahmood, K.; Shamshad, S.; Saleem, M.A.; Ayub, M.F.; Conti, M.; Das, A.K. An Access Control Scheme in IoT-Enabled Smart-Grid Systems Using Blockchain and PUF. *Internet Things* **2023**, *22*, 100708. [CrossRef]
21. Ullah, Z.; Rehman, A.U.; Wang, S.; Hasanien, H.M.; Luo, P.; Elkadeem, M.R.; Abido, M.A. IoT-Based Monitoring and Control of Substations and Smart Grids with Renewables and Electric Vehicles Integration. *Energy* **2023**, *282*, 128924. [CrossRef]
22. Orlando, M.; Estebsari, A.; Pons, E.; Pau, M.; Quer, S.; Poncino, M.; Bottaccioli, L.; Patti, E. A Smart Meter Infrastructure for Smart Grid IoT Applications. *IEEE Internet Things J.* **2022**, *9*, 12529–12541. [CrossRef]
23. Saleem, M.U.; Usman, M.R.; Yaqub, M.A.; Liotta, A.; Asim, A. Smarter Grid in the 5G Era: Integrating the Internet of Things with a Cyber-Physical System. *IEEE Access* **2024**, *12*, 34002–34018. [CrossRef]
24. Rind, Y.M.; Raza, M.H.; Zubair, M.; Mehmood, M.Q.; Massoud, Y. Smart Energy Meters for Smart Grids, an Internet of Things Perspective. *Energies* **2023**, *16*, 1974. [CrossRef]
25. Malathy, S.; Sangeetha, K.; Vanitha, C.N.; Dhanaraj, R.K. Integrated Architecture for IoTSG: Internet of Things (IoT) and Smart Grid (SG). *Smart Grids Internet Things* **2023**, 127–155. [CrossRef]
26. Gooi, H.B.; Wang, T.; Tang, Y. Edge Intelligence for Smart Grid: A Survey on Application Potentials. *CSEE J. Power Energy Syst.* **2023**, *9*, 1623–1640. [CrossRef]
27. Touzene, A.; Moqbali, M. User Satisfaction-Based Genetic Algorithm for Load Shifting in Smart Grid. *Int. J. Comput. Appl.* **2023**, *45*, 444–451. [CrossRef]
28. Razzak, A.; Islam, M.T.; Roy, P.; Razzaque, M.A.; Hassan, M.R.; Hassan, M.M. Leveraging Deep Q-Learning to Maximize Consumer Quality of Experience in Smart Grid. *Energy* **2024**, *290*, 130165. [CrossRef]
29. Elmorshedy, M.F.; Essawy, I.J.A.; Rashad, E.M.; Islam, M.R.; Dabour, S.M. A Grid-Connected PV System Based on Quasi-Z-Source Inverter with Maximum Power Extraction. *IEEE Trans. Ind. Appl.* **2023**, *59*, 6445–6456. [CrossRef]
30. Mamodiya, U.; Tiwari, N. Dual-Axis Solar Tracking System with Different Control Strategies for Improved Energy Efficiency. *Comput. Electr. Eng.* **2023**, *111*, 108920. [CrossRef]
31. Kabeyi, M.J.B.; Olanrewaju, O.A. The Levelized Cost of Energy and Modifications for Use in Electricity Generation Planning. *Energy Rep.* **2023**, *9*, 495–534. [CrossRef]
32. Rusănescu, C.O.; Rusănescu, M.; Istrate, I.A.; Constantin, G.A.; Begea, M. The Effect of Dust Deposition on the Performance of Photovoltaic Panels. *Energies* **2023**, *16*, 6794. [CrossRef]
33. Dkhili, N.; Eynard, J.; Thil, S.; Grieu, S. A Survey of Modelling and Smart Management Tools for Power Grids with Prolific Distributed Generation. *Sustain. Energy Grids Netw.* **2020**, *21*, 100284. [CrossRef]
34. Ateya, A.A.; Muthanna, A.; Koucheryavy, A.; Maleh, Y.; El-Latif, A.A.A. Energy Efficient Offloading Scheme for MEC-Based Augmented Reality System. *Clust. Comput.* **2023**, *26*, 789–806. [CrossRef]
35. OpenWay Riva CENTRON Meter. Available online: https://na.itron.com/products/openway-riva-centron-meter (accessed on 25 June 2024).
36. Landis+Gyr E450. Available online: https://www.landisgyr.eu/product/landisgyr-e450/ (accessed on 25 June 2024).
37. Gridsense Line IQ. Available online: https://www.powerandcables.com/product/product-category/hv-power-grid-monitoring-gridsense-line-iq/ (accessed on 25 June 2024).
38. EPM 7100—Legacy. Available online: https://www.gevernova.com/grid-solutions/multilin/catalog/epm7100.htm#dimsmount (accessed on 25 June 2024).
39. Cisco IR829 Industrial Integrated Services Routers Data Sheet. Available online: https://www.cisco.com/c/en/us/products/collateral/routers/829-industrial-router/datasheet-c78-734981.html (accessed on 25 June 2024).

40. UTX-3117. Available online: https://www.advantech.com/emt/products/bda911fe-28bc-4171-aed3-67f76f6a12c8/utx-3117/mod_9a201cd3-1416-4282-9fc4-de8ca1e6bcbc (accessed on 25 June 2024).
41. FETMX8MM-C System on Module. Available online: https://www.forlinx.net/product/imx8mm-system-on-module-28.html (accessed on 25 June 2024).
42. SIMATIC S7-1200. Available online: https://www.siemens.com/global/en/products/automation/systems/industrial/plc/s7-1200.html (accessed on 25 June 2024).
43. Jetson Xavier NX Series. Available online: https://www.nvidia.com/en-sg/autonomous-machines/embedded-systems/jetson-xavier-nx/ (accessed on 25 June 2024).
44. Intel® MovidiusTM MyriadTM X Vision Processing Unit. Available online: https://www.intel.com/content/www/us/en/products/sku/204770/intel-movidius-myriad-x-vision-processing-unit-0gb/specifications.html (accessed on 25 June 2024).
45. Cisco Catalyst IE3400 Heavy Duty Series. Available online: https://www.cisco.com/c/en/us/products/switches/catalyst-ie3400-heavy-duty-series/index.html (accessed on 25 June 2024).
46. Solar Panel PV System Dataset. Available online: https://www.kaggle.com/datasets/arnavsharmaas/solar-panel-pv-system-dataset/data (accessed on 1 May 2024).
47. Ateya, A.A.; Muthanna, A.; Vybornova, A.; Darya, P.; Koucheryavy, A. En-Ergy-Aware Offloading Algorithm for Multi-Level Cloud Based 5G System. In *Internet of Things, Smart Spaces, and Next Generation Networks and Systems*; Springer: Cham, Switzerland, 2018; pp. 355–370.
48. Ateya, A.A.; Vybornova, A.; Samouylov, K.; Koucheryavy, A. System Model for Multi-Level Cloud Based Tactile Internet System. In Proceedings of the International Conference on Wired/Wireless Internet Communication, St. Petersburg, Russia, 21–23 June 2017; Springer: Cham, Switzerland, 2017; pp. 77–86.