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Review

Microgrid Emergence, Integration, and Influence on the Future Energy Generation Equilibrium—A Review

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Abstract: Microgrids are emerging throughout the world as a means of integrating decentralized, renewable energy power generation. The flexibility of this customer-driven, behind the meter solution allows it to address unique challenges. This variability that drives microgrid adoption is the same thing that keeps them from being categorized and repeatable. This lack of specific modeling leads to a stalling in financing and wide-scale adoption. By analyzing the microgrid system development, evolution, architecture, integration zones, technological advances, and business models, a clearer picture of how these entities are intertwined emerges. Several case studies of deployed microgrids will showcase the cutting-edge solutions they apply. The future implications of this new energy revolution will be highlighted and shown to create an energy generation equilibrium and the significant role played by microgrids in this new energy revolution. Although many compilations of research work on microgrids have been previously presented by various reviewers, most of them are specific to an electrical or power quality-related issue, which addresses a discrete audience. This work only includes within its scope a general outlook of microgrids and the present-day challenges in its use of rural/urban renewable energy production and distribution. The results allowed for the researchers to conclude that microgrids have emerged as a great solution in situations where energy has to be transmitted from a decentralized system to a centralized system. Challenges will arise in the microgrid management and government laws and regulations if rectified microgrids can lead to an equilibrium between decentralized and centralized bulk energy networks.

Keywords: microgrid integration; microgrid management; energy equilibrium

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1. Introduction

Most power generation systems worldwide have been designed to provide energy in a centralized distribution manner, regardless of how the energy is derived. New and more advanced systems are beginning to take shape throughout the world, which are laying the foundation for decentralized and distributed energy systems. The main platform of how these are taking shape is through the creation of microgrids. The idea behind this type of grid is that it is a group of smaller generation, storage, and load management systems that are either linked to the main electricity grid or islanded from it.

The definition of a microgrid is overarching and they have been utilized in varying capacities and technologies by the energy sector for 30 years [1]. It is only recently through the advancement of technology and software, the lowering of the cost of energy generated by these systems, and a motivated customer-driven demand for solutions that microgrids are increasingly being deployed. In the United States, research by the Department of Energy led to the Modern Grid Initiative of 2005, which spearheaded the development of a system-wide view of the modern grids in the United States [2]. To generate this report, energy industry experts were gathered to evaluate the current infrastructure, energy systems, and trends. The goal was to create an overview of a modern grid. Instead of haphazardly adopting advances in technology as they emerge, they set out to create the vision first, and work backward until they reached their current situation in the overall picture. To reach their goal, five primary elements of a modern grid emerged. Through analysis of these elements, they developed an overview of what the grid of the 21st century should be capable of doing by integrating the trends arising within the industry. They concluded that the (energy) business was technologically advancing, incorporating digital components and solutions, thus creating an informed and invested customer base. An important insight was that the industry identified that an open grid architecture, where all components interacted in a two-way dialogue, was needed to address the trends. Distributed energy resources were becoming more common, and with the increased installation along with the new trends, the current grid would not be able to keep up with the changes this new energy revolution was bringing. They highlighted that individual tailoring of solutions was possible, and over time, helped drive market production, reduced the costs of products, and expanded the services provided.

As smart grids and microgrids began emerging at an increasing pace, the Modern Grid Initiative emphasized the importance of not specifically defining what each one was, but what each should be able to do. The authors in [1] explained that by 2010, this beast of an energy solution was causing too much confusion and essentially growing uncontrollably. The Department of Energy gathered experts, and over the course of a year, defined what a microgrid is. Over the past 15 years, the idea of approaching a microgrid in this way has led to the following areas that are addressed by these solutions: improvement in sustainability, improvement in reliability and resilience, and better long-term cost predictability. If all three are met, the system is defined as a microgrid. If only one or two of these are met, it is considered as a distributed energy solution [1]. Adefarati and Bansal found that the microgrid system had a few benefits such as enhanced reliability, less transmission and distribution losses, auxiliary voltage support, improved efficiency from waste heat recovery, and low power interruption rate [3], which makes it suitable for renewable energy distribution. Eid et al. [4] contemplated the various attractive features of microgrids that enable their worth as a research topic and their competitive nature in being used in renewable energy. The researcher also mentioned that a well-controlled microgrid guarantees a continuous flow of power to and from the main grid, making it a flexible power system. According to Bracco et al. [5], the main research challenges of microgrid based technologies can be looked at from two different viewpoints: (i) the development of novel groundbreaking technologies, or (ii) the testing of current systems. Wang et al. [6] reiterated in their review paper that there is a need for the modern microgrid to become intelligent and flexible enough to handle modern-day challenges with the aid of telecommunication technologies and new generation information technologies. Alonso et al. [7] were of the opinion that for microgrids to be widely used in the renewable energy sector, they needed to become smart, where the use of the latest communication technologies and automatic control systems are used extensively, without ignoring the security and reliability features. Bliek et al. [8] mentioned a project in the Netherlands where about 25 households are interconnected using a local energy market consisting of various energy generation units such as micro-cogeneration units, hybrid heat pumps, solar photovoltaic, wind farms, etc.

To refine the focus of this work, only renewable energy microgrids were considered as the main driving force behind this work was to understand the significant role played by microgrids in decentralized renewable energy production. Under such instances, various novel micro-related technical ideas were not included in this work. The emergence of this new approach to energy generation and management is still in its infancy, but themes between worldwide systems are beginning to emerge. The global context of these and how the economics of these will lead to an equilibrium between centralized and decentralized energy systems will be analyzed.

2. Microgrid Emergence

Microgrids are increasing in number throughout the world. The 16th edition of the Microgrid Deployment Tracker in 2019 found 4475 projects totaling 26,769 MW of planned and installed power capacity [9]. By 2020, the 17th edition identified 6610 projects representing 31,784.6 MW of planned and installed power capacity [10]. The adoption of these solutions over time has proven that they are feasible, but not financially affordable without external support [1]. Early renewable technologies mirror microgrids in their evolutionary history; they are achievable, but only over time and further integration will they become affordable. Microgrids are emerging as behind the meter solutions, but since each challenge they address is unique, each solution is different. The variability that drives microgrid solutions is the same thing that keeps them from being categorized and repeatable. This lack of a specific model leads to a stalling in financing and wide-scale adoption. Thus, these grids are customer-driven, small government projects of all different types, and are seen more as an additional energy tool to utilize [1].

When assessing electricity power systems, the generation, distribution, transmission, storage, and management of energy is traditionally accomplished via a centralized system. Since energy management is one of the key pinnacles of countries around the world today, new approaches to provide this crucial resource have emerged. To aid centralized distribution, compact generation units such as combined heat and power (CHP), landfill biogas, and renewable energy (RE) have been decentralized and placed closer to customers. This type of generation is referred to as distributed generation (DG) and the resources providing it are distributed energy resources (DERs) [11]. The Energy Management Handbook states that these DERs are categorized as smaller scale generating units [12]. The operation and control strategies of integrated distributed energy resources explain that DERs, when integrated into modernized power systems, decrease emissions and resistive losses while increasing the reliability and security of electric networks [11]. Each country faces diverse challenges with centralized infrastructures such as:

- High amounts of emissions;
- High generation costs;
- Voltage deviations;
- Overloaded lines;
- Static, dynamic and transient stability problems;
- High levels of resistive losses; and
- Service interruptions [11].

By adopting distributed generation resources and new architectures, many of these issues can be assuaged. The drawback of adopting this type of renewable energy generation is that it is intermittent and thus needs to be integrated into the existing electricity network to provide high-quality electricity and meet the load demand. To manage the DERs, they can be classified into two categories: dispatchable and non-dispatchable energy resources. The dispatchable resources' power output can be regulated by utility operators and managers, thus most of these are fossil fuel-based sources. Renewable energy generating resources can be grouped as non-dispatchable power since it is not adjustable by the system operators [11].

The main task of managing all these in the context of cities can be broken into five intervention areas:

- Generation;
- Storage;
- Infrastructure;
- Facilities; and
- Transport [13].

Microgrids can help ease and aid the incorporation of these five components into a plan for a sustainable energy system of the future. They can provide the scaffolding between each section to make the concept of a smart city a reality.

3. Microgrid Evolution

In the 1990s, the U.S. and Europe started looking at ways to be able to integrate vast amounts of distributed energy resources into their already developed and aging grid infrastructures [14]. To undertake the level of research needed for a development program of this magnitude, the U.S. created CERTS and Europe developed the MICROGRIDS consortium. Both were pioneers in defining a solution—a grid architecture divided into sub-sections that could manage the generation and demand at a local level and could also be disconnected from the "macrogrid" (the main electricity grid), should the need arise. The term they coined for the solution to the challenge was microgrid.

As these early solutions began to be conceived in laboratories and test sites, each microgrid had to meet the following three requirements:

1. They had to be identifiable as a distinct subset of the distribution network;
2. The resources attached to it were controlled in concert with each other instead of with resources further from it; and
3. That it could operate on its own if disconnected from the macrogrid [14].

The functional needs of this type of smaller grid were the result of the initial motivation for these systems. Their earliest inceptions were to assist during times of natural disasters, central grid attacks, or major cascading failures. The grid architecture and topology of the 20th century had reached their maximum ability and usefulness, and the time for evolution and progress was beginning with smaller, distributed energy, and power systems [14]. The broad concept and definition of a microgrid stated nothing about the size requirements or the types of technologies that it could use though, so the possibilities were almost endless as to what could transpire.

4. System Development

Today, there are numerous ways to classify, categorize, and develop microgrids. It can be based on size, type, function, operating mode, technology attached to it, or architecture. As energy management evolved from the early 1990s to 2015, the realities of optimizing the five intervention areas began to emerge as a multifaceted undertaking. When analyzing how cities can deal with energy operation and control, a research team created a modeling system that could successfully design solutions that could benefit all sectors involved. This is outlined in Figure 1.

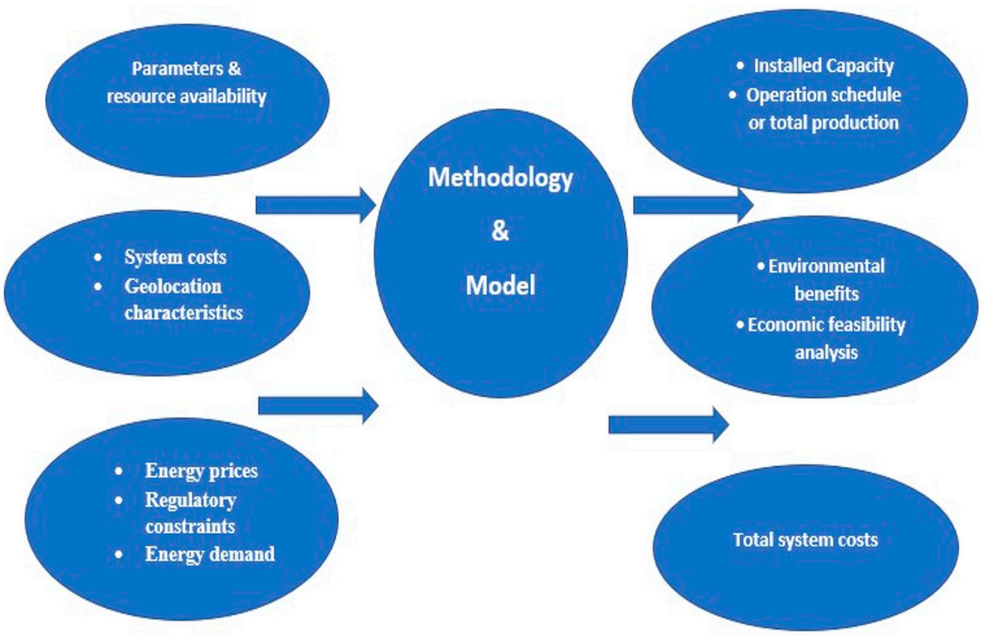

Figure 1. Energy system design model [13].

When analyzing various methodologies that can be inserted into the model, the most promising, overarching solution is a microgrid. It creates an energy cycle that is no longer linear, but circular and decentralized. Each specific geolocation, load demand, operation schedule, or other components of the system will influence the optimal microgrid creation response. A review paper on microgrid technologies and key drivers stated a list of reasons for why electricity companies are shifting to DERs [14]. The range of benefits of these types of resources can also be applied to microgrids. Furthermore, depending on what challenge or challenges the microgrid is mitigating will influence what type and size it is.

5. Ways of Classification of Microgrids

5.1. Microgrid Sizing

The first way to categorize microgrids is by size. What has evolved are smaller nano and picogrids being established around the world. These tie into microgrids and support either buildings or homes, respectively. Microgrids are now classified as neighborhood or community-sized systems. This allows for a purer classification of the function of each grid, based on its size, as can be seen in Figure 2. Once you understand the position of each type of grid in the layer of the system, you can choose the appropriate size based on the end goal of the system provider.

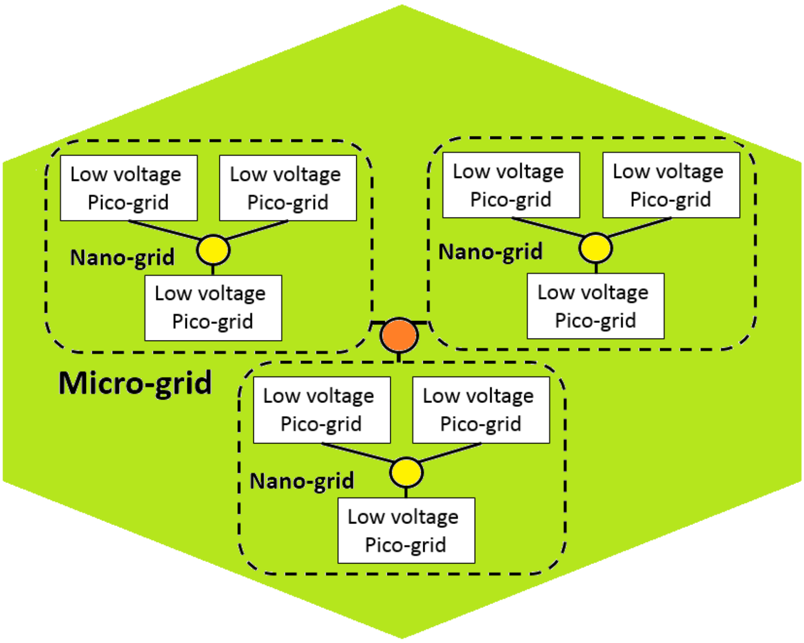

Figure 2. Breakdown of functions of smaller grids.

5.2. Microgrid Topology

When viewed based on the way a microgrid distributes electricity, three distinct models emerge: radial, mesh, and network, as seen in Figure 3 [15,16]. The most complex of them is the network system. Some later studies have suggested that to implement a fully decentralized network, each house could be its own micro source that can interface with the utility via its current meter, which creates a behind the metered approach that could ease regulatory or legal complications [8]. Radial and mesh systems are more commonly researched and established throughout the world. Another microgrid type that has emerged in the last five years is a looped and a mixed loop topology. However, due to the current grid operation and protection strategies, the radial distribution system has been identified as the one with the least negative impacts [17].

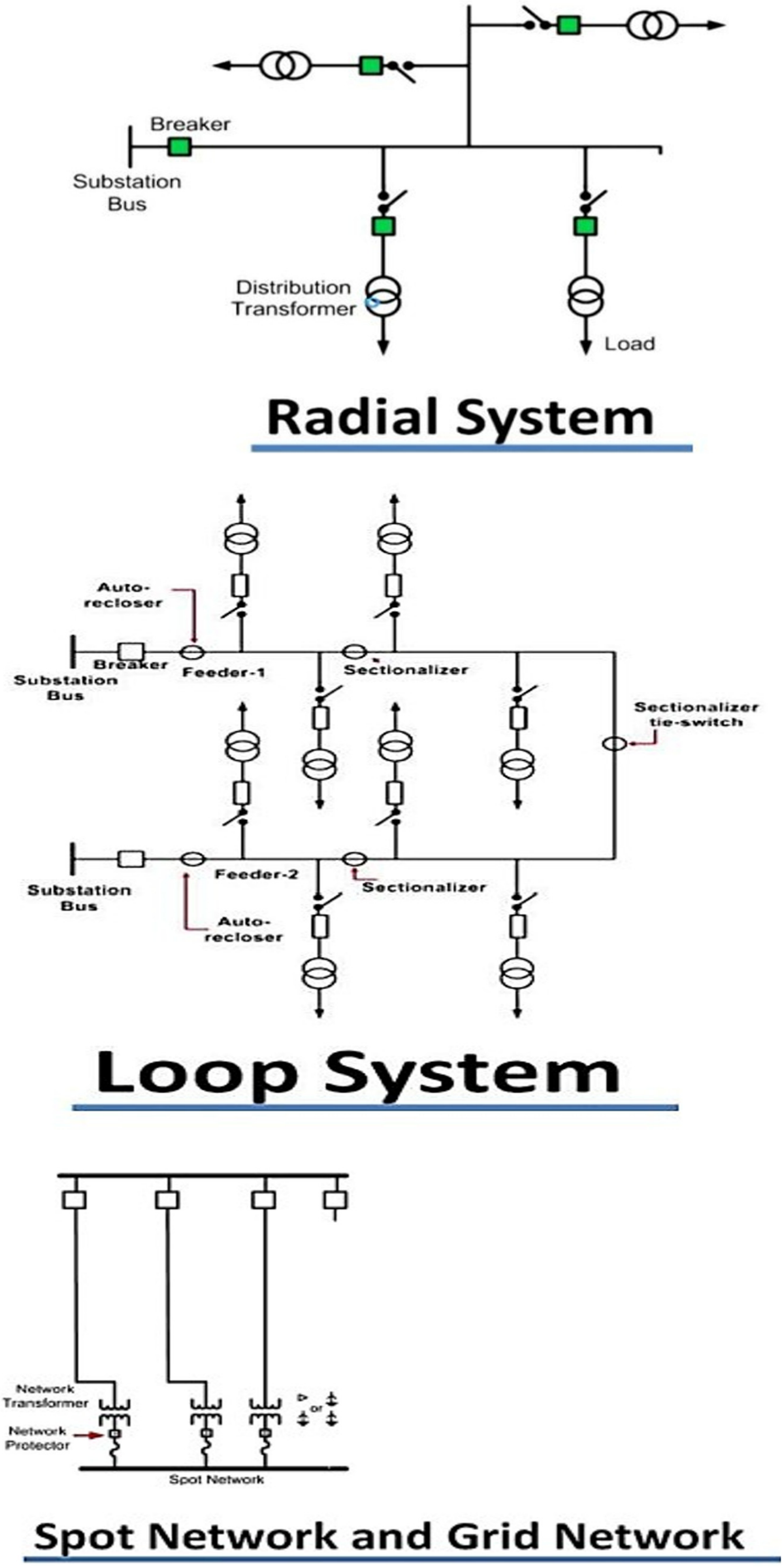

Figure 3. Electricity distribution schemes.

5.3. Sectors of Installation

Adam Hirsch et al. [14] identified six main segments of a nation, city, or community that utilize microgrid systems. As of Q1 2016, they had identified the following percentage of sectors where microgrids were employed:

- Remote locations (54%);
- Commercial/Industrial (5%);
- Community (13%);
- Utility distribution (13%);
- Institutional/Campus (9%); and
- Military (6%) [14].

They further identified that residential grids could be aggregated to optimize benefits based on sizing and integration levels.

- Community microgrid—where multiple houses (multiple micro sources) are connected to form a smaller microgrid that has a single utility interface with the main grid;
- Customer microgrid—each house serves as its own micro source that interfaces with the main grid, forming multiple utility interfaces; and
- Nesting microgrid—a neighborhood level or building level system with its master controllers to manage the DERs, share community energy resources and loads such as communal lighting, and has one interface with the macrogrid [14].

5.4. Current Type

There are three configurations used to connect microgrids to the electric infrastructure, AC, DC, and a hybrid AC/DC form. An overview of microgrid practical operations analyzed the two most common topologies: radial and mesh. It was found that AC, DC, and AC/DC configurations were present in radial topologies, but that AC was only present in mesh topologies [17].

5.5. Mode

Microgrids exist in two distinct modes, off-grid (islanded) only or on-grid/off-grid function. Islanded grids are typically in remote areas that lack an electrical network. On-grid and off-grid systems occur where an existent network is present that the microgrid can incorporate into. In this instance, the microgrid can either use a bumpless or non-bumpless transition between being connected to the grid or islanded mode. Some areas utilize off-grid systems to complete what is commonly referred to as the 'last mile connectivity', the area where the expansion of an electricity grid has yet to reach.

6. Layers of a Microgrid

Microgrids can be viewed from a top–down functional layering system or vice-versa. In November 2012, a task force, established via a mandate laid down by the European Union (EU), studied Smart Grid models that began to emerge in their countries [18]. The case studies helped create a standardized approach to microgrids and identified key layers in the architectural framework of these systems.

As it could be manifested from Figure 2, a later study updated and refined the architectural layers from that report into a more concise model that also incorporated the newer microgrid sizing. After analyzing the microgrid testbeds, installed microgrids, and published papers relating to them, some basic key similarities between the architectural structuring have been identified. Each one has a physical, hardware layer, commonly referred to as the infrastructure or component layer. Next is a communications layer. Depending on the complexity and size of the microgrid, this can be a simple converter or an entire network of protocols dealing with over 1000 system variables that must be conveyed through a hardwired high-speed communication channel capable of processing real-time data [17]. This is the case for the PrInCE Lab microgrid in Italy. Earlier microgrids had what is referred to as an information layer [18]. By 2016, identified this information layer as a more sophisticated intelligence layer, which was needed to manage the resiliency, reliability, efficiency, and quality of service or electricity that was provided or being moved between the macro- and microgrid. From 2016 until 2020, this layer has grown to encompass online management PLCs and security features needed to make microgrids a reality in power systems throughout the world. The original idea that microgrids could be managed via the intelligence systems that controlled the centralized, one-way power distribution systems, worked for simpler, picogrid sized systems. The amount of data needing to be processed to balance loads, voltage, frequency, renewable energy generation systems, and storage options has proven to bottleneck the networks. To overcome this, a new layer was added to the architecture, the System Control and Data Acquisition Systems (SCADA), as seen in Figure 4 [17].

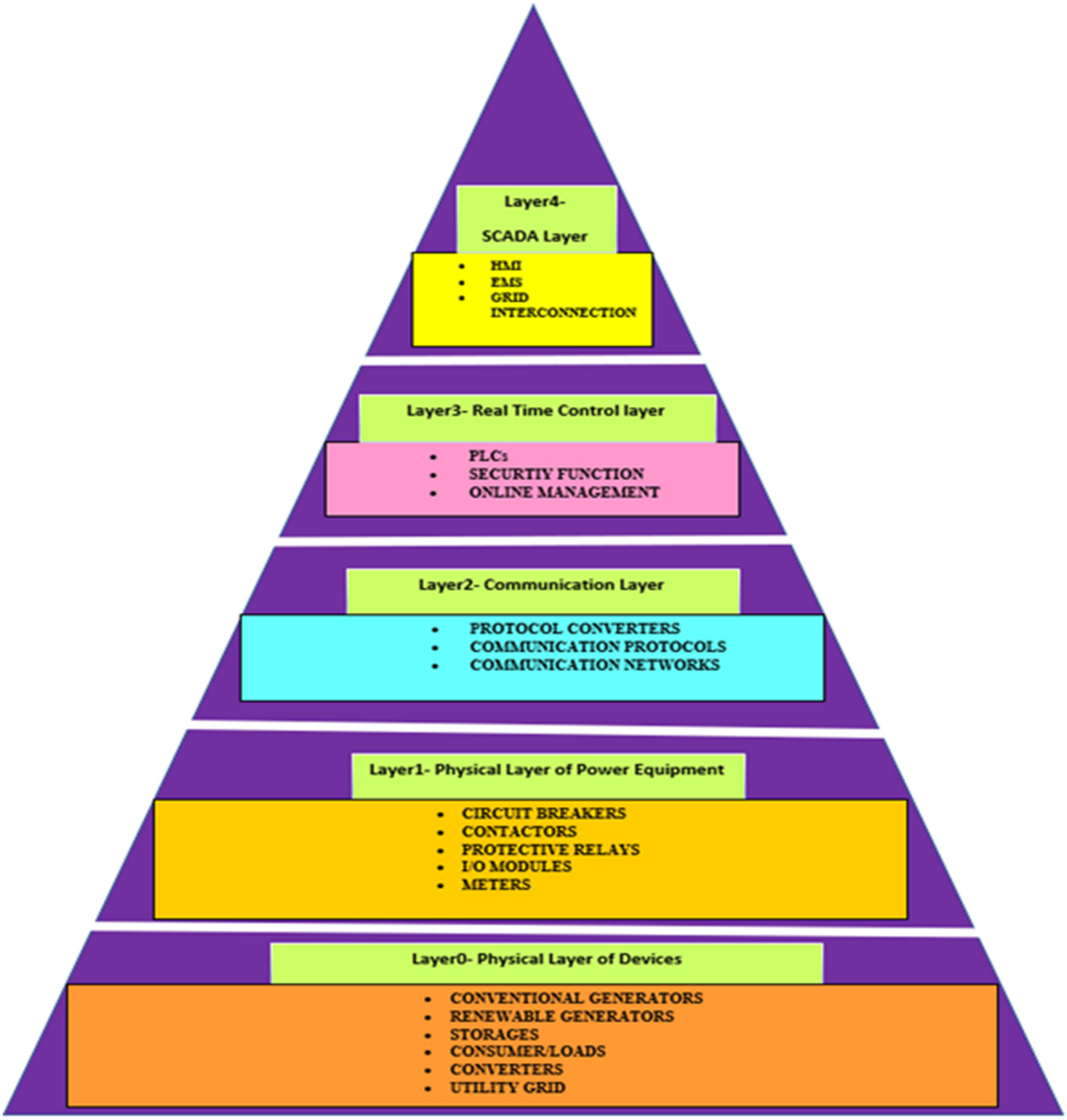

Figure 4. PrInCE Lab microgrid management layers.

The PrInCE Lab microgrid needed two servers in the hot standby configuration to achieve the level of control and management needed to optimally run the system. The servers processed the data through a custom-made human–machine interface (HMI) software package designed specifically for this microgrid. This layer also included an energy management system that allowed operators to control the operating states, modes, and other relevant systems. The earlier designed microgrids of the 1990s to early 2000s simply added a business and/or regulatory layer instead of SCADA. The SCADA intelligence and real-time control layers should ideally be intertwined throughout each layer to optimize the overall power system. The goal of everyday operations, extended over weeks and months, minimizes losses, maximizes efficiency, and establishes a balanced system. It is influenced by regulations, but it can also influence the change in energy policies as time goes on. Having separate business and policy layers is not needed as they should be threaded through the background of each layer. The most basic, one-size-fits-all layering system derived from the literature is the following:

1. Physical Equipment and Infrastructure;
2. Device Integration;
3. Management and Market Clearing; and
4. SCADA (if big data are involved).

Communication streams through all layers.

7. Related Technology and Development

7.1. Functional Control of Microgrids

The hardware used in microgrids has been well studied over the last ten years. The future of microgrid functionality in energy systems depends on the current research being conducted on the control strategies and functions needed to achieve robustness, resilience, and security in all operating states and transitions [17]. This includes the power electronics, control features, protection layers, communication methods, and intelligence systems that interlink the microgrid to the macrogrid.

7.2. Power Electronics

Of all the components of microgrids, this is the most established in the industry.

When incorporating RES into microgrids such as DC power solar or high-frequency AC power microturbines, the need for DC/AC or DC/AC/DC converters is required to connect the generation sources to the electrical grid. The inverters play key roles such as voltage and frequency control in islanded mode and assist with black start policies [8]. The use of static disconnect switches (SDS) is a crucial function for islanding and synchronization. They can be set to trip rapidly if the following occurs:

- Overvoltage or undervoltage;
- Over frequency or under frequency; and/or
- Directional overcurrent.

An AC microgrid has the advantage of ease when it comes to connecting with the main grid through a synchronous AC connection. DC microgrids, on the other hand, use an asynchronous connection utilizing a DC-coupled electronic power converter [8]. The converter can manage frequency, voltage, and harmonics by isolating the microgrid from the utility when needed.

The control features exhibited by the microgrid will be different when it operates in an island mode. In a grid connected mode, the DERs operate in a frequency control mode during which it is highly essential that the frequency is maintained constant, although the change in the voltage is permissible whenever there is a fluctuation in the loads. In an islanded mode, the separate island, also known as a microgrid, is formed, which becomes a standalone without any grid support. During such time, DERs normally operate in droop control, where a slight variation in frequency is permitted and the voltage is held constant despite the load fluctuations. When there are multiple DERs in the microgrid, one takes the lead and others follow. Fast load shedding schemes are also associated with the controllers to ensure that a source load mismatch is not present. Furthermore, the protective relays are made to be operated by the controllers to protect them from power surges.

Multifunctional breakers and microgrid master controllers are employed to perform such coordinated control, which are inbuilt with the inverter based DGs. Therefore, it is essential to maintain the voltage and frequency all the time and based on the priority.

7.3. Control Features

As stated previously, microgrids can be controlled similarly to the main utility grid. The more complex the microgrids become, the more robust and diverse the control features must become to handle them. The study in [14] presented this type of control as a three-layered hierarchy. The primary control layer manages the frequency and the secondary layer deals with voltage regulation. These two layers accomplish this via a microgrid central controller (MGCC) that commands the DERs. If the microgrid is more advanced, has batteries, larger generation amounts, or multiple DERs, it will need a third control layer consisting of storage utilization, generation scheduling and dispatch, and management of the electricity being exchanged across the grid network. This third layer allows for the overall control of each section of the utility to achieve the best possible benefits from the integration of all aspects of the energy system. For this to occur, the control features must deliver the following operations:

1. The microgrid (independent of size) is presented as a separate entity to provide frequency control;
2. Avoid power flow that exceeds line ratings;
3. When in islanding mode, the voltage and frequency must be kept within the allowable range;
4. Dispatch resources as needed to maintain energy balance;
5. Navigate between on-grid and off-grid modes smoothly; and
6. When reconnecting and resynchronizing with the utility infrastructure, it must do so smoothly [14].

7.4. Protection

The eight main protection schemes were tested and found applicable to microgrids, as outlined in Figure 5. Based on the analysis of these protection schemes, the choice of method for protection is up to the designer and is influenced by the layout of the microgrid with respect to its larger function in the overall grid network. The most ideal protection for a microgrid that can operate either in on-grid or off-grid mode is a decentralized adaptive protection method that is capable of secure, high-speed communication protocols. If the operation is in islanded mode only but has a communication link, then a voltage-based scheme is acceptable.

7.5. Communication

The way a microgrid or several microgrids transmit information between each other and the electricity grid is a vital factor in the optimization of the whole system. This key element is how real-time data are dispersed and monitored, in addition to how management decisions are disseminated throughout the network. Depending on the microgrid size, type, topology, mode options, type of control structure, protection schemes, DERs and network requirements, choosing a means of communication can be challenging. It is common practice to use the same protocol as the main controller.

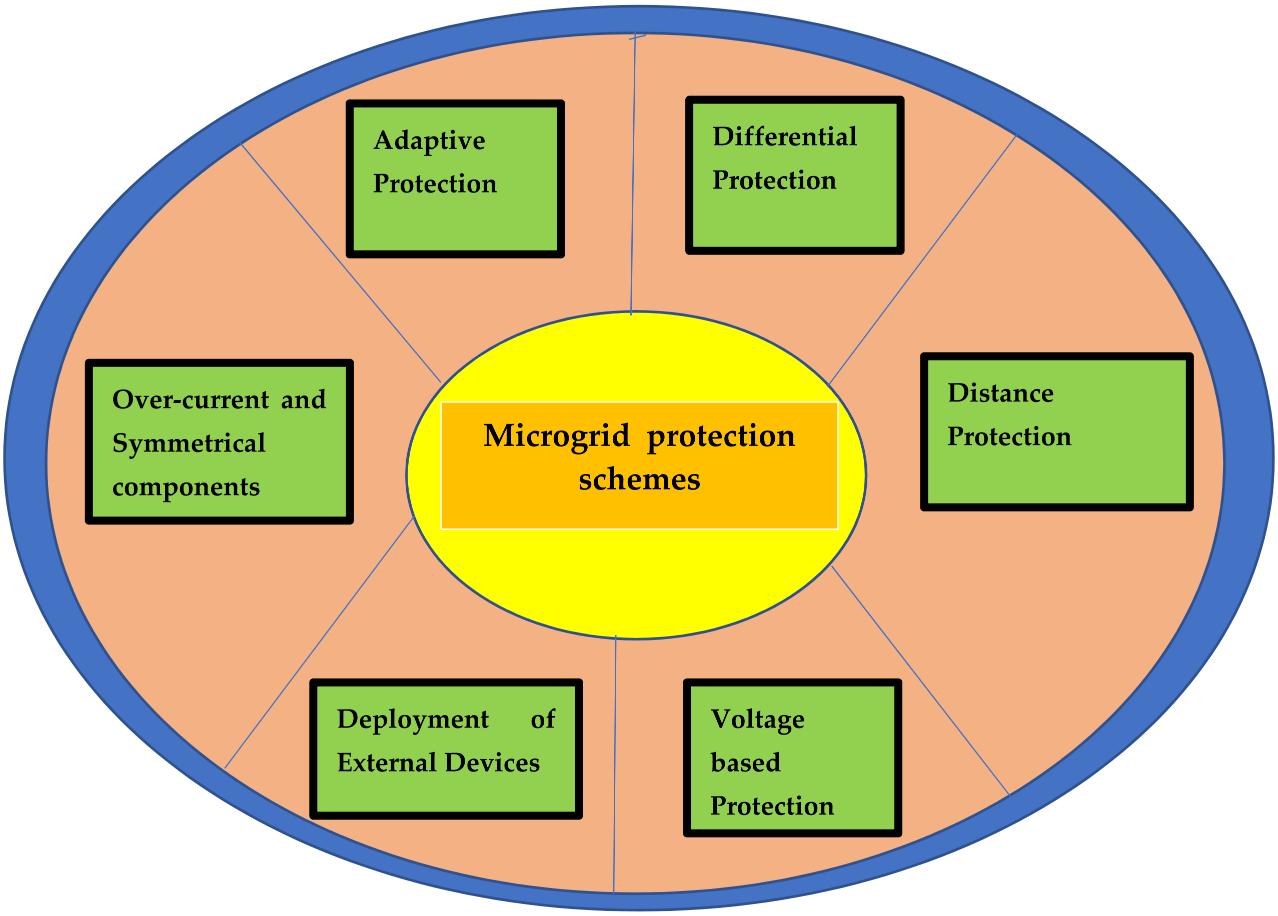

Figure 5. Protection schemes of microgrids.

Existing microgrids use multiple methods of communication such as

- Optical fibers;
- Wireless;
- GPS;
- Global System for Mobile Communications (GSM);
- XLM;
- Power lines;
- Telephone;
- LAN; and
- Combinations of the above [17].

The most common proprietary and open standard communication protocols used for communication are:

1. IEC 61850;
2. Distributed Network Protocol 3.0 (DNP3.0);
3. Modbus;
4. Profibus;
5. Wi-Fi; and
6. TCP/IP [17].

Ethernet and XLM-RPC were also utilized in the CESI Ricerca DER test facilities in Italy, at the National Technical University of Athens in Greece, and DeMoTec microgrids at ISET (in collaboration with the University of Kessel's Institute for Electrical Energy Technology). These were earlier experiments in collaboration with the European MICROGRIDs project. Since then, it has become apparent that upgrading the communication networks used by devices in most microgrids to high-speed, secure systems capable of handling vast amounts of data is quickly becoming the standard. If cost is a factor, then a wired communication structure can be utilized.

8. Case Studies

The deployed microgrids in Table 1 were chosen to highlight the breadth of solutions that microgrids can give. These are a mixture of grid-connected and islanded systems, have a variety of generation sources, and the breakthrough design that the microgrid was created for is explained. These systems prove that it is technologically possible to utilize microgrids for a multitude of energy challenges throughout the world, regardless of size or location.

Table 1. Highlights of deployed microgrids with breakthrough concepts.

Name	Location	Size	Output	Breakthrough Idea	Success
Yackandandah Community Microgrid	Northern Victoria, Australia	14 houses	550 kW solar, 110 kWh of battery storage	Grid-connected transactive energy. 169 Victorian-made Ubi energy management system monitoring units installed	The goal was to power the community with 100% renewable energy. It was successful and there are now 3 microgrid projects being commissioned for the larger community [19,20].
Koh Jik Microgrid	Jik Island, Thailand	400 people	40 kW solar, 50 kW diesel Genset, 240 kWh lead-acid batteries	Rural islanded DC/AC hybrid microgrid intends to create a reliable energy reserve to mitigate intermittent renewable energy sources and account for a 0.5% annual load increase. Researched the financial indicators comparing lead-acid and Li-ion batteries, rooftop vs ground-mounted PV, payback periods and renewable energy system fractions	The wind turbine failed and is still non-functional. The hybrid system can mitigate the variability of solar generation and provide power for the community. Determined that as Li-ion prices continue to decrease then you can achieve higher renewable fractions as you decrease the use of the diesel Genset [21].
Brooklyn Microgrid	Brooklyn, NYC, USA	60 rooftop solar PV sites and 500 people participating in transactive energy	Unknown	Grid-connected transactive energy. Installed TransActive Grid smart meters and tested the Exergy platform for peer-to-peer trading.	The microgrid is providing local and hyper-local energy to the community involved in the trial. Since it is connected to the grid, the question arises as to whether they are truly providing this power to the neighborhood since it is still passing through the macrogrid [22–24].
Ilse of Eigg Microgrid	Isle of Eigg, Scotland	31 km^2 island, 38 houses and 5 commercial properties	54 kW solar, 24 kW wind, 119 kW hydro, 160 kW gas/diesel, 212 kWh storage	First 3-Renewable microgrid in 2008. Off-grid hybrid system. Each property has an energy monitoring unit and droops control of the system based on the battery state of charge and frequency.	Electricity is provided 24 h a day and 95% of it is from renewables. Demonstrated that a microgrid based on renewable energy can reliably provide electricity for 24 h a day [25,26].

Table 1. *Cont.*

Name	Location	Size	Output	Breakthrough Idea	Success
Bornholm Island Microgrid	Bornholm Island, Denmark	28,000 customers	16 MW biomass CHP, 2–1 MW biogas CHP, 37 MW wind, 23 MW PV, when islanded has 58 MW reserve in conventional units	The system is electrically coupled to the Nordic power system via an underwater cable to Sweden. The grid is 60 kV medium voltage (MV). It is a multi-microgrid, MV network that can island. Demonstrates that it is possible to interconnect and communicate between multiple local microgrids and large-scale REG units.	It can provide local supply restoration abilities when operating in islanded mode. The main control room uses two SCADA systems and due to this level of control, the distributed generation resources can be integrated into the microgrid and the EU Mega-grid [27–29].
Banggi Island Microgrid	Banggi Island, Sabah, Malaysia	7 remote villages	1200 kW solar, 1350 gas/diesel, 4300 kWh battery storage	The largest hybrid power, islanded system in Malaysia. Uses a Hybrid System Control Command Unit (HCCU) and is remotely monitored and controlled.	The telemonitoring system can display real-time system data which assists in maximizing operation [30].

9. Business and Economics of Microgrids

9.1. Overview

As more renewable energy resources are being installed, microgrids, smart grids, and virtual power plants are a few of the proposed solutions to the challenge of integrating these distributed energy generation units. As it stands, the existing vertical management utility system is unable to support these changes [30]. These new systems are intermittent, have high capital costs, site-specific availability of resources or technology that can be deployed, are dependent on time-sensitive weather forecasting, and are leading to an increase in self-consumption. The associated markets will need to adjust and transform to incorporate these new ventures. What many researchers state is that due to a lack of standardization, particularly in microgrids, each project is viewed as a unique system. This diversity of techniques leads to costly implementation and non-repeatable deployment, thus higher financial risks, lack of investment, and ultimately lower integration of projects. The overall development of microgrids is reliant on a blend of technical, economic, and regulatory factors [31,32]. A review of microgrid management found that it can be divided into two main categories: control and energy [33]. On the control side, frequency and voltage were statistically discussed the most and seen as a dominant factor. The cost was the most dominant factor when viewed from the energy side [33].

9.2. Vertical vs. Tiered Management Models

At present, most utilities are large, central markets that have a vertically integrated management. The ability for small-scale producers of energy to participate within this market is typically restricted. Assimilation mechanisms such as feed-in tariffs and net-energy-metering are strategies that allow for renewable energy technologies to be incorporated in a controlled manner. As these mechanisms reach their limits or are discontinued in countries, the utility operator still needs a way to maintain grid stability while these distributed generation units are injecting energy into the system. As self-consumption increases and transactive markets are being realized, the fear of losing revenue further drives regulation to limit the integration of this energy. Support for microgrids varies between countries, states, and even jurisdictions. According to [34], high connection fees, extended wait times, and even bans on these types of systems occur. Current research shows that a layered or tiered management approach is best embraced, where the challenge of managing the complex system of DERs is shared [35]. This creates load diversity, and if managed properly, creates a balance between annual production-to-demand ratios. This occurs in community microgrids in Switzerland where new legislation supports a tiered, bidding prosumer market, and studies have found the 'optimal point' where self-consumption and self-sufficiency are equal and create a net zero energy [36]. By experimenting with various sized microgrids and different prosumer–consumer ratios, it was found that the ideal ratio for this optimal point to occur is within a 60% prosumer to consumer ratio in community microgrids [36]. The energy generated is then utilized and sold through a tiered market.

9.3. Local vs. Central Energy Markets

As DEG and DER installed capacities are increasing in countries around the world, local energy markets are emerging. The question is, how do these local markets interact with the central energy market? The authors studied cross-provincial energy market trading in China. DEG units were installed outside the major metropolitan areas where energy demand is lower than generation capacity. They proposed a two-level power transaction market that allowed for the trading of energy and concluded that this segment bidding method, based on the minimum dispatch interval, led to less renewable energy abandonment and a lowering of the real-time balancing costs. This expanded trading space can be implemented in other community microgrids to balance energy generation and load needs across varying local and provincial markets.

Local energy markets support prosumers, community energy, and tiered markets where the regulatory framework encourages energy consumption in the following order: self, local bidding, and when there are no buyers, it is sent to the grid. At this point, the central market becomes the owner, operator, and manager. A long-term solution for this integration will be needed in the form of market mechanisms, regulation changes, and management system upgrades. These local markets create new resources for energy service companies, the TSO, the DSO, and the country. Since countries, regions, and utilities already have tariff charges and structures in place, the central market has a way of channeling this energy for integration via policy intervention.

9.4. Intervention and Integration of Market Drivers and Business Models

The microgrid market is projected to reach USD $30.9 billion by 2027 and Frost and Sullivan forecast that USD $846.12 billion will be invested into the distributed energy resources market between 2020–2030 [37,38]. Finding steps to integrate environmental drivers, economic benefits, and business models will allow these two markets to reach their full potential.

The environmental drivers seek to lower CO_2 emissions by installing renewable energy technologies, and the economic drivers are the cost–benefit analyses of the energy and business models seeking to maximize investment returns, energy savings, and improved reliability. These drivers influence the types and sizes of distributed energy resources to meet the goals of all involved. The components of each system are linked when load and demand data across various system configurations are compared and optimized with levelized costs of electricity, levelized costs of energy, annual energy costs, financial markers such as payback period, profitability index, and internal rate of return and policy goals are met through a reduction in greenhouse gas emissions.

New markets are emerging in the United Kingdom, Germany, France, U.S., Sweden and the Nordic regions to manage and trade these flexible energy resources, as seen in Table 2.

Table 2. Emerging markets in response to distributed energy integration via microgrids.

Time Frame	Technical Management	Market
Short-Term (few seconds to 2 h)	Frequency and voltage control, network restoration, network congestion, portfolio balancing	Ancillary Services Market System Balancing Market
Medium-Term (~15 minutes to 48 h)	Balancing and network congestion management, day-ahead and intraday trading	Network Planning Marketplace Spot Market Energy Trading
Long-Term (Year ahead)	Mitigating network investment, diversification of energy portfolio and peak and baseload management	Generation Capacity Trading

The technical needs of the overall energy system are becoming more complex, but the mitigating options are increasing with DERs. Time of use and electricity quantity tariffs, known as dynamic pricing, as seen in Figure 6, are currently used in industry settings. Some countries also implement them in residential settings. These same pricing schemes can be applied to users connected via microgrids and the electricity generated from DERs. By prioritizing the renewable generation units in the pricing schemes, even further support for clean energy is provided.

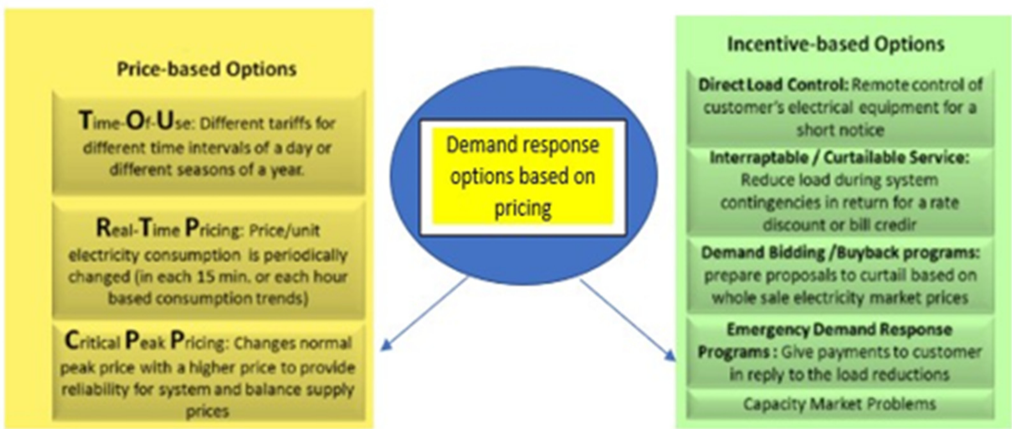

Figure 6. Electricity industry tariff options.

Studies states that to create "bankable" microgrids, an industry-standard advanced software program that can effectively deploy these systems is needed. This standardization tool could reduce development costs by 20–30% [39–41]. The optimization algorithm they presented takes the load data, generation data and site weather, along with costing, emissions, and grid management goals to obtain the optimal DER scheduling and structuring. This type of algorithm is needed to analyze the millions of options when incorporating all key aspects to distributed energy management and integration. Tools such as these may be able to standardize the approach to microgrids and lead to financial backing and investment, project auditing, and the creation of a new financial asset class that this technology can belong to [41].

9.5. Energy Equilibrium

Many drivers influence the adoption of microgrids. A key to their success is that they can be designed to address the specific objectives of the customer, as outlined in Table 3 [1].

Table 3. Drivers and impacts of microgrid adoption in the energy industry.

Drivers	Change Agents	Results
Sustainability	Individuals, Communities, Corporations, Cities, States, Countries	Increased renewable energy via decentralized grid architectures and decreased emissions
Lost Value (mismatched ESAs and PPAs)	Commercial and Industrial Entities	Increased microgrid deployment for real-time, true asset lifetime realization
Resilience	Communities, Corporations, Cities, States, Countries	Quantitative and qualitative importance of service utility provider becoming more relevant
		due to power outages that affect public relations and brand value. Increase in microgrids that can island.
Under-Utilization of Assets	State and Country	Shift away from single asset sizing based on peak demand to economically sized microgrids.
Diversity	Individuals, Communities, Corporations, Cities, States, Countries	Country-wide investment for multiple energy generation resources leading to security. Microgrids solve specific challenges of all sizes.
Cost	Individuals, Communities, Corporations, Cities, States, Countries	The shift in investment from utility upgrades (maintenance, transmission and distribution) to microgrids and prosumer transactive energy.

Advances in technology such as cloud-based and Internet-of-Things platforms are facilitating the integration of the physical, communications, and intelligence layers of a microgrid. As policy and regulations continue to change, the business sectors will begin to create models that are more specific and repeatable. The study in [1] explains where the microgrid market is today. Currently, the types and sizes of these projects are varied, with industry researching ways of scaling these up to meet greater energy demand in a decentralized manner. This new technology is an investment risk for private capital, and traditionally, financiers do not invest in novel technology. The diversity of the projects adds to the risk factor as there is no specific sector that microgrids fit into, nor are there repeatable models that can be used for investment and economic comparisons. The electricity network and utility companies view the wide-scale adoption of these systems as competition for-profit and the capital required is diverted to utility upgrades. Commodity costs of electricity have not increased significantly in the past 15 years, but in the U.S., there is a steady annual increase of 3% in transmission and distribution charges [1].

As time elapses, [1] explains that the market between decentralized and centralized energy becomes a supply and demand S curve. As the demand for bulk energy decreases, investment in it follows suit by decreasing. Similarly, the demand increases for decentralized energy systems and so does investment in it. Eventually, the two reach an equilibrium point by 2035 [1]. The authors in [1] go on to further explain that this can be accomplished through integrated resource planning (IRP) and analysis of the distributed energy supply curve. This is possible in countries that place a higher value on renewable energy integration and government-backed regulatory changes. It may take longer for this reality to form, but if the demand is there, the market will adjust accordingly.

10. Future Implications

10.1. Motivation for Change

Many organizations and studies have supported the need for electricity systems all over the world to decentralize, decarbonize, and democratize. EXERGY, a LO3 Energy Innovation, lists these 3Ds as "decentralizing, decarbonizing, and digitizing" [42]. The level of development of a country, its current energy outlook, future policies and governing agencies will mold the level of decentralizing, decarbonizing, and democratization through the level of digitalization that is possible within the entire system. A country may decide to decentralize its' energy system for security purposes, lower greenhouse gas emissions, aid in infrastructure repair, add diversified energy storage options, increase power quality, and control or integration of renewable energy generation options. For example, the U.S. is more focused on resilience and reliability and Europe is motivated by climate change mitigation and the integration of renewable energies. In 2019, the United Nations projected that 68% of the world's population will reside in urban areas [43]. The energy needs of cities across the globe are increasing, as are the citizens' desires that the increased energy demands be met in a sustainable manner that leads to an increased quality of life index [44].

10.2. Smart Cities

The concept of a smart city has increased in popularity in the past ten years. Communities around the world are expressing a desire for renewable energy generation to lower greenhouse gas emissions, and increased climate change is pushing for secure, reliable electricity that can still be operated as more violent storms are becoming the norm [45]. Countries are also realizing the benefits of more efficient use of energy. To create an infrastructure capable of all these benefits, a multi-disciplinary approach and engineering tools for the development and implementation of this paradigm are needed [46]. Smart city is a holistic approach to synthesizing environmental and energy concerns while optimizing economic and societal impacts [47].

The four general themes or pillars of a smart city are: societal, economic, environmental, and governance or institutional [48]. It is proposed that there are five, as seen in Figure 7, with governance threading through them all. Energy plays a key role in these as the physical, electrical, and digital characteristics ties each theme to the others. It creates a circular, smart energy economy. The progression toward a smart city requires a smart grid, something that perfectly aligns with distributed renewable energy integration via microgrids, smart meters that allow for bi-directional energy flow and communication, energy storage adoption, and effective energy management [49].

10.3. Electric Vehicle Based Microgrid

Most recently, few utilities have started to test the interaction of vehicle-to-grid (V2G) projects to assess whether the stressed grid could be supported by plug-in-electric vehicles, thereby converting them into mobile microgrids. The ultimate idea of introducing EVs is to make them available as a mobile microgrid to help generate power to the grid as well as to reduce the stress on the grid during peak loading hours. This would also facilitate and support the other renewable-based DGs in the microgrid such as PV and wind, considering their stochastic nature. The U.S. has been actively involved in such pilot projects and in the forthcoming years, the contributions from EVs will become the quintessence of the overall smart grid system [50]. Electric vehicles inverters also act as smart inverters for ancillary services, playing a major role as a reactive power compensator apart from the exchange of real power [51–54]. Electric vehicle technology has thus become the need of the hour that could provide both real and reactive power support in a microgrid environment.

Figure 7. Proposed five pillars of smart city design.

11. Conclusions

This work, as mentioned earlier, mainly focused on microgrids and related technical factors applied in renewable energy generation and transmission. Hence, many new aspects belonging to core distribution may not have been discussed in this work. One of the main challenges of decarbonizing an energy system is integrating non-dispatchable resources that are generating power intermittently and then transmitting that electricity from a decentralized location via a grid that was designed for a one-directional flow of energy. Microgrids are fast becoming the solution. A smarter grid can link markets, service providers, customers, operations, generation, transmission, and distribution [51]. This notion was first conceptualized by the CEN group, as seen in Figure 8.

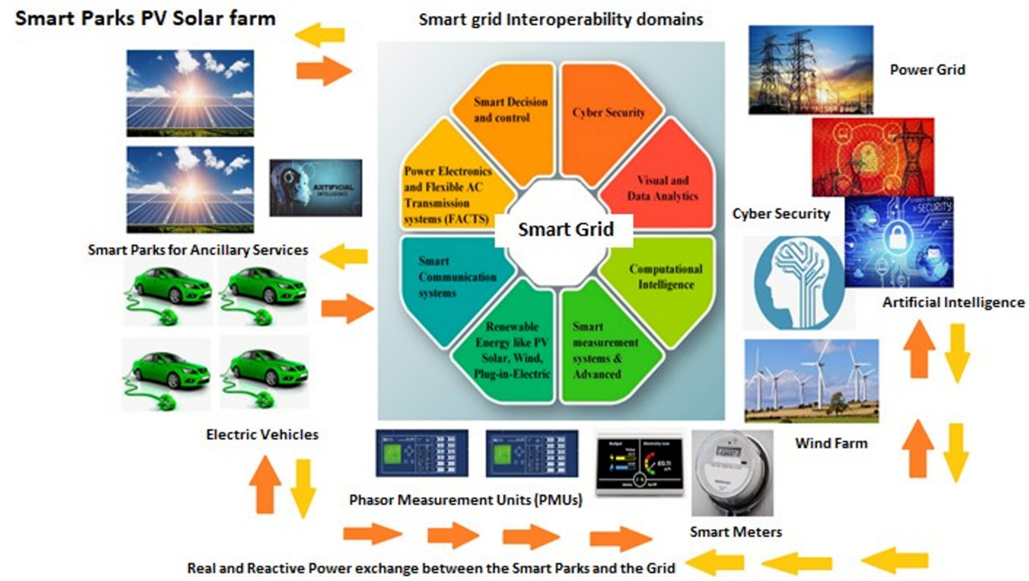

Figure 8. Smart grid conceptualization model.

This model has been used as a guide for research laboratories and microgrid testbeds around the world. What has been realized and proven through experimentation is the need for the standardization of interoperability via communications, security, safety standards, device advancement, terminology, and general guidelines for development. After more than 20 years of the research and development of microgrids, their infrastructures have been well studied. The means of communication between all layers of the system have mostly focused on smart grids, but a relatively small number of microgrids have been established worldwide and the case for standardization is well documented. Intelligence systems have historically been studied from the approach of quality of power, reduction in overall losses, and improving reliability and resiliency. Only in recent years has the intelligence layer been a possibility to provide economic benefits through the buying and selling of energy generation. Furthermore, the U.S. and Europe have started to examine what a customer-side and utility-side business model would look like that can join local energy and central energy markets. This work, along with the intelligence systems and regulatory frameworks necessary to allow this, is still in its infancy. The areas of research for this have been limited to developed countries with legacy grids and high socio-economic leveled communities. It was identified that the main bottleneck in microgrid management were constraints placed on the energy side of the sector [33]. Where changes in legislature and government commitment (even at the local level) support a decarbonizing, digitizing, and democratic system, it motivates and drives change from the utilities, financial, and economic sectors. This will lead to an energy equilibrium between centralized bulk energy and decentralized systems.

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