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Review

Should We Have Selfish Microgrids?

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Abstract: Substantial breakthroughs in renewable energy have been made in order to reduce energy-induced climate change. Yet our reliance on these sources is still insufficient. The UK's objective of attaining net-zero emissions by 2050 is highly dependent on shifting to an electrical system that exclusively relies on zero-carbon generation. This entails integrating renewable energy sources, along with other low-carbon sources such as nuclear power, into the energy mix. However, the primary barrier to incorporating additional renewable energy sources into the grid is their intermittent and volatile nature. Therefore, there is a pressing need to stabilise the generation of renewables and manage this volatility by enhancing the balancing mechanism between microgrids and the national grid. This paper examines previous research on microgrids and smart grids, specifically from a supply chain perspective. It has been observed that the majority of the current literature focuses on documenting selfish microgrids that strive to optimise performance at the microgrid level. However, there is an alternative approach that draws inspiration from the field of supply chain management. Consequently, it is possible to enhance a microgrid's performance within the broader system that it belongs to by reconsidering the timing and location of storage utilisation.

Keywords: renewable energy; supply chain; selfish microgrids; energy storage system; balancing mechanism

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1. Introduction

Sustainability and climate change issues entered public conversation in June 1972 [1]. Since then, undeniable progress has been made in both areas, reflecting a culture shift in which economic development is no longer viewed as the primary and only objective. Stakeholders came together to work towards a low-carbon society, pursuing carbon neutrality through carbon capture or renewable energy. Governments, on the one hand, began to investigate methods to achieve a balance between these competing goals, while businesses, on the other hand, sought to incorporate social and environmental concerns into their economic operations.

Since the inception of energy systems, starting with the development of the first coal-fired steam engines in the 1700s, our consumption of fossil fuels has steadily increased. Using nonrenewable resources has hurt the environment, people, economy, and society, where carbon emissions are thought to be the main cause of climate change and global warming. In the following decades, if demand continues increasing at the same rate until 2050, these resources will be depleted, raising further concerns [2]. Due to these challenges, rising oil costs, and geopolitical instability, global decision makers are prioritising energy security. This includes geographical accessibility, energy availability, environmental protection for future generations, and financial feasibility [3]. Given that several nations depend on energy sources from possible adversaries, it is imperative to inquire whether a nation has the capability to sustain its own energy needs. Thus, a near-international consensus exists to cut fossil fuel consumption as soon as it is feasible, and transitioning to renewable energy is a key aspect of solving this problem.

The move to sustainable energy sources will impact future energy systems, requiring careful planning and resolution of challenges. There are three ways to approach future energy systems. First, evaluate the feasibility of a 100% renewable energy system. The Danish experience suggests that a radical redesign of the existing system is necessary [4,5]. The second method uses the current infrastructure and carbon capture and storage technologies to achieve carbon neutrality. The third option involves implementing a solution to enhance the current infrastructure and progressively increase the proportion of renewable energy sources while utilising the existing system for backup power generation. However, there are challenges in switching to renewables: their intermittent nature, energy storage cost, and the unpredictability and volatility of these sources [6]. For these reasons, countries that have committed to a net zero target, like the UK, for example, lack a clear and convincing plan demonstrating the ability to actively tackle the aforementioned difficulties. Formulating solutions to these challenges necessitates the utilisation of an engineering and management model, i.e., it is not only a technical matter. It necessitates some form of coordination to integrate all technologies into an integrated electricity network system in the future.

The energy business is rarely analysed as a supply chain since supply chains are usually portrayed as items passing via inventory nodes. Electricity storage is unusual; hence, its supply chain is unique. Converting burning heat into mechanical energy is the main way to obtain electricity. Even in an ideal frictionless system, the conversion efficiency is below 100% [7]. Due to the inevitability of efficiency losses in Carnot cycles, it is more efficient to generate and consume electricity than to produce and store it. This is especially true at the scale of national grids, as efficiency losses would be significant. Therefore, load balancing was the key challenge in original electricity supply chains (ESCs), and storage was ignored. Thus, existing electricity supply chains are all about flow, and they match a well-known supply chain management (SCM) tactical planning approach known as pure-chase demand. This approach seeks to avoid the use of inventory by adjusting supply to demand, as shown in Figure 1. It is the opposite of the pure-level production plan, which uses inventory to maintain a constant output level regardless of demand [8], as shown in the left-hand side of Figure 1. While a loss of efficiency is a difficulty when dealing with large-scale national grids [9], it becomes more controllable when considering smaller microgrids, making energy storage a viable solution. Furthermore, the potential of employing inventory management techniques to manage electricity storage has transformed the problem into a supply chain challenge.

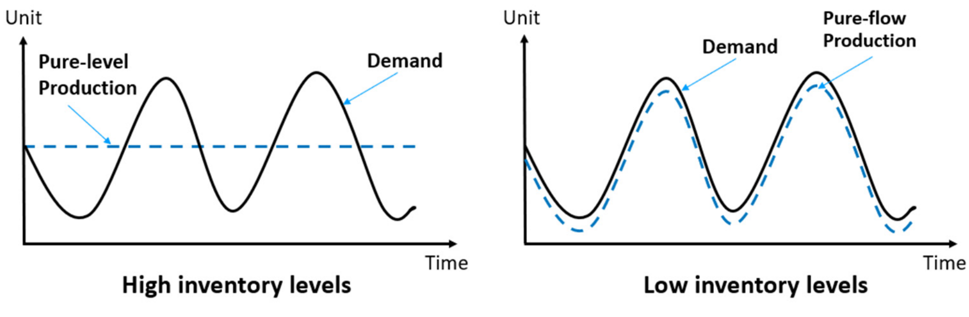

Figure 1. Pure-flow vs. pure-level production (adapted from [10]).

In recent years, several governments have implemented numerous programmes to enhance the proportion of power generation derived from renewable energy sources [11]. Nevertheless, several challenges hinder this transition in the UK, including the complexity of integrating renewable sources into existing systems and the substantial costs associated with abandoning the current infrastructure and implementing a completely new smart grid that operates solely on green energy. To illustrate the current situation in the UK's electricity system, Figure 2 depicts the output of the national grid from various sources over one month (April 2024), demonstrating the interplay between natural gas and wind in compensating for the intermittent generation of wind energy. Figure 3 displays the average use as well as the volatility of use of each source, further illustrating the very volatile nature of gas and wind supply when compared to other sources.

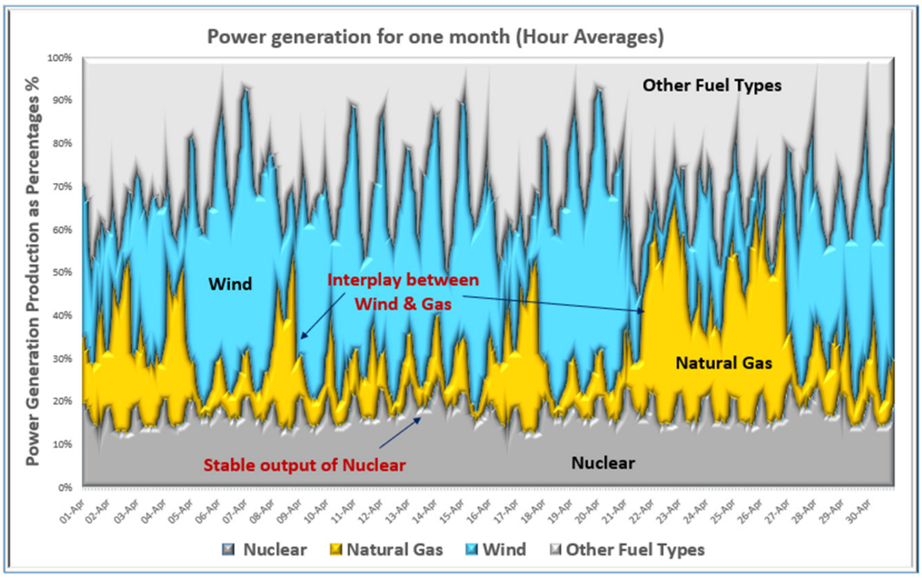

Figure 2. GB fuel type power generation output % (based on data from [12]).

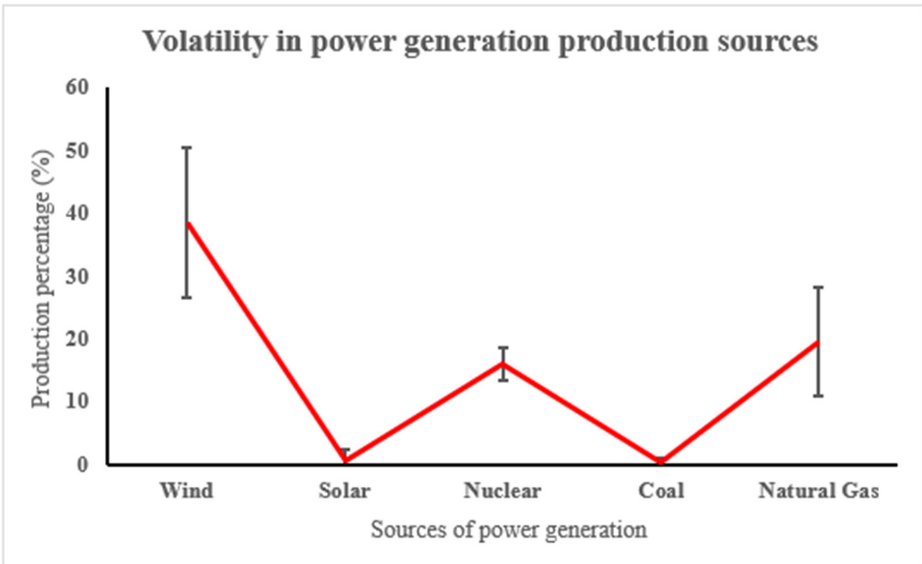

Figure 3. GB power average production and its volatility (range) (based on data from [12]).

The main hindrance to integrating more renewable energy sources into the system remains their intermittent nature. According to the 2021 report from the International Energy Agency (IEA), fossil fuels meet half of the annual growth in energy demand [13]. Consider a scenario where the national power system relies heavily on a large utility wind farm. In the event of consecutive days without wind, the most suitable alternative to compensate for the shortage would be natural gas, given its quick and efficient response. What would happen if we could stabilise the generation of renewables and effectively manage its volatility? Transitioning from gas to nuclear power as a low-carbon baseload will become feasible.

This review seeks to examine energy systems from the perspective of SCM. This involves the utilisation of SCM concepts and theories in the energy industry, with the primary goal of examining the existing gaps in the literature about the best practices of SCM and its implementation in the electrical sector, in particular by contemplating enhancements to the balancing mechanism between the national grid and microgrids. This review advocates for a transition from selfish microgrids to integrated microgrids that manage the volatile unpredictable demand for the national grid.

2. Electricity Systems from a Supply Chain Perspective

In the next section, we present a review of smart grids, microgrids, and their balancing mechanism from the perspective of SCM. It is thus crucial to start this section with the aim of providing an in-depth presentation of SCM and its most relevant theories and frameworks.

SCM's significance in operations management and management as a whole has only grown with time. Over the past three decades or more, researchers from a variety of disciplines have increased their focus on SCM, broadening the breadth and depth of knowledge and theory development in the field. In addition, professionals in SCM have begun implementing innovative strategies that increase company efficiency. The crucial role of SCM in the success of businesses is becoming increasingly apparent to both public and private sector organisations. Initially, academics argued that purchasing, as it was referred to at the time, should be a significant academic and practitioner priority [14]. Prior to the 1980s, the focus was exclusively on systems for managing inventory and inbound and outbound logistics. Kraljic's [15] use of the terminology "supply strategy" signalled a shift in attention from the narrower tactical and operational issues of purchasing to the larger strategic consequences of this corporate function, shifting the focus to the strategic character of supply.

The term "supply chain management" was first popularised by Keith Oliver in 1982 [16], and its initial definition highlighted the importance of top-level strategic decision making in order to effectively manage the supply chain as a whole. To provide optimal customer service, minimum inventory management, and low unit costs, in 1989, Stevens [17] argued that SCM should synchronise customer demand with materials flow. Later, several refinements were made to the SCM concept until Christopher, in 1992 [18], defined a supply chain "*As the network of organisations that are involved, through upstream and downstream linkages, in the various processes and activities that produce value in the form of products and services delivered to the ultimate consumer*".

In contrast to the main theme of the 1980s, which focused on the modernization of supply logistics management, the emphasis in the 1990s shifted towards making systems more globally competitive. This shift was particularly influenced by the revolution in information technology and the significant advancements in technology for communication during the mid-1990s [19]. As a result, increased research-and-development funding was allocated to the SCM sector [20].

The emergence of electronic supply chain management (e-SCM) may be ascribed to the transformative impact of the information revolution and the subsequent introduction of internet technology. According to Ross [21], e-SCM can be defined as follows: "*As a tactical and strategic management philosophy that seeks to network the collective productive capacities and resources of intersecting supply channel systems through the application of Internet technologies in the search for innovative solutions and the synchronisation of channel capabilities dedicated to the creation of unique, individualised sources of customer value.*" The integration of communication technologies into SCM has emerged as a crucial strategy for firms to enhance their agility and competitive advantage [22].

To this day, the definition of SCM published by the Council of Supply Chain Management Professionals (CSCMP) is the one most generally used and recognised. CSCMP defines SCM as "*encompassing the planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third-*

party service providers, and customers" [23]. In addition, CSCMP explains, SCM integrates supply and demand management within and across companies. However, scholars are sceptical that a universal definition of SCM will ever be commonly agreed upon. Changes in business practices and technologies have led to a variety of SCM theories and practices. Nevertheless, some SCM elements have not changed much since 1982. In this regard, we might consider such areas as managing resources, handling supplies, strategic connections, logistics, technological adjustment, the satisfaction of customers, and concise and clear interaction.

Scholars disagree on whether electricity is more like a service or a hybrid of the two because of its nature and need for grids. Since electricity is neither a material nor a fuel, some academics argue that it should be classified as a service instead. For the service industry, according to Kathawala and Abdou [24], a tailored definition looks like this: SCM in the service sector entails bringing products and services directly to the end user by streamlining distribution networks. Reactivity, efficiency, efficacy, and control, all of these factors—as well as more—are a part of the future-services supply chain. In service industries, the end user is a key source of inputs to the process for many service-based businesses. Thus, customers can also function as suppliers, a phenomenon known as "customer–supplier duality". The two-way nature of service supply chains is a direct result of this duality [25].

Identifying one definitive theory that laid the first groundwork for SCM is difficult due to the complex history of the discipline. The area of SCM has progressed throughout time by incorporating information and concepts from other disciplines such as logistics, operations management, and economics [26].

Yet, efficient inventory management is one of the most crucial aspects of SCM that has garnered significant attention from researchers. Since Ford W. Harris released his work on developing the economic order quantity (EOQ) model in 1913 [27], inventory modelling has given more significance to three primary areas: (1) Analysing inventory models that encompass numerous suppliers and various items, with a special focus on the first phases of the supply chain [28,29]. (2) Examining multiechelon inventory models that incorporate both producers and retailers in order to comprehend the internal framework of the supply chain [30]. (3) Examining inventory models that consider volatile demand for multiple products [31], with a special emphasis on the later phases of the supply chain. In contrast to the standard EOQ model, which assumes continuous and uniform demand, the marketplace in reality experiences dynamic and stochastic product demand, influenced by changes in price and time. Consequently, many methodologies were required to predict product demand, including econometric models [32], time series models [33], and stochastic demand models [34].

The "just-in-time" (JIT) theory is considered as another groundbreaking concept that has significantly influenced the development of SCM. It is one of the earliest and most essential theories in the realm of SCM [35]. Originally, it was a production revolution that originated in Japan during the 1950s. Following its adoption by prominent corporations like Toyota, it gained widespread recognition throughout the 1960s. The main objective of JIT is to guarantee prompt manufacturing and delivery of products, hence eliminating inefficiencies, reducing inventory levels, and enhancing overall operational efficiency [36]. From an SCM perspective, the adoption of JIT methodology centres around the concept of continuous flow, in opposition to the discrete-flow process of supply chains relying on inventory nodes. The goal is to maintain a constant movement of items and avoid keeping them in inventory while waiting for delivery [37]. Many contemporary SCM practices are based on the core notions of JIT. The significance of lean manufacturing in reducing inventory holding costs and ensuring a seamless flow of materials and goods from suppliers to consumers is the typical description of a modern, effective supply chain. Subsequently, total JIT (T-JIT) was implemented as a viable supply chain technique that impacts the total competence of the supply chain, hence improving organisational performance. It is an encompassing supply chain method that incorporates JIT-production, JIT-purchasing, and JIT-selling, along with a vital new element called JIT-information [38].

The existing electrical system's reliance on a 100% production flow plan has various implications. One of them is that customers perceive power as a readily accessible commodity through a plug [39]. Although there is some level of an awareness of the system, the understanding of electricity consumption management needs to be improved, and learning opportunities are rare. Smart metres, which are advanced devices capable of regulating power usage, are an exception, but unfortunately, their adoption in the UK has encountered resistance [40]. The implementation of these measures would have resulted in improved demand management and the promotion of efficient use of energy. Additionally, it would have increased reliability through reduced peak load using demand chain management and by facilitating the identification and resolution of power outages [41].

In the past, manufacturing supply chains used multiechelon inventory models, which resulted in a large amount of inventory (poor flow) being used. However, the current manufacturing supply chain, such as the one employed by Toyota, relies more on flow and uses less inventory. This shift towards enhancing flow has been the main focus of improvements in modern supply chains [37]. On the contrary, as shown in Figure 4, electricity supply has always been focused on the flow of electricity production due to the lack of storage capabilities and in order to avoid efficiency losses. Consequently, the whole issue goes back to chasing demand versus level production. Nevertheless, there is no empirical proof indicating that a 100% flow configuration is the most efficient design for the ESC at present or in the coming years, especially when incorporating additional renewable energy sources and increasing the volatility of demand for the national grid. The most straightforward approach to handle demand volatility is inventory, namely, by maintaining a consistent production level; the other solution is chasing demand (adjust supply to demand), but there are an infinite number of hybrid tactics in between. As the supply chain sector brings a new way to think about the problem, ESC could move along the pure-level/-chase spectrum. Therefore, it is essential to address the following question: if the proportion of renewable power sources increases in future systems, where would the future ESC be positioned in the schematic depicted in Figure 4?

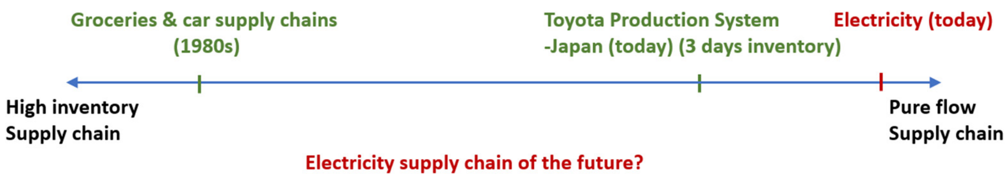

Figure 4. Evolution of different supply chains over time.

Figure 5 summarises the comparison between purchasing and SCM as an architecture model of SCM. The white layer captures traditional functions of purchasing management and of balancing supply and demand. A large number of technologies and frameworks have been deployed over time to transform purchasing management into today's overarching concept of SCM.

In this paper, we argue that an electricity network is one type of supply chain. As explained in Figure 4, it is unusual in that manufacturing supply chains have historically over-relied on inventory systems and are being improvement to achieve better flow. The history of ESC is the converse. The facts that modern flow supply chains have limitations, that system balancing is becoming more difficult because of the intermittence of renewable sources, and that electricity storage is becoming affordable all combine to make today an opportune moment to look at electricity systems from a supply chain perspective. As it was originally designed to be a pure-flow system, it can be argued that current ESC is still based on the purchasing management layer of Figure 5 and that much opportunity from improvements could come from SCM frameworks.

Before we begin the next review section on microgrids (the nodes in a network associated with loads and functions that make modern SCM applicable), it is worth stressing the importance of the foundation layer in Figure 5, that of supply chain design (SCD).

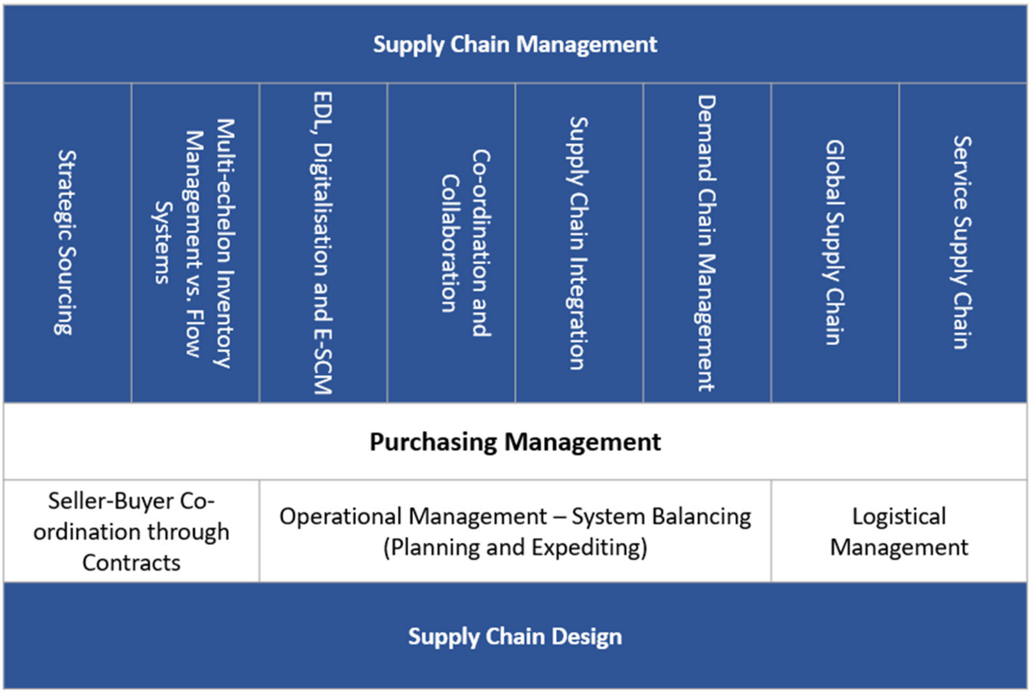

Figure 5. Architecture-based model of supply chain management.

In today's complex and rapidly evolving business environment, supply chain optimisation and competitive advantage improvement are under increasing pressure. SCD and SCM are two essential components of this optimisation process. In contrast to SCM's emphasis on the coordination and integration of numerous operations involved in the purchase, production, and distribution of products and services, strategic SCD entails the strategic decision-making process of organising and configuring the supply chain network, location, capacity, and shared systems if any. Most SCM work is performed to better the supply chain, which could be considered a short-loop improvement because it involves changing how the supply chain is managed (pure SCM), but sometimes it becomes clear that the constraint is in the design itself, necessitating a long-loop improvement to have the next generation design because, for instance, the number of suppliers needs to be increased or decreased. It appears odd to discuss SCM without framing it as a two-stage process, since neither long- nor short-loop improvements are distinguished in the literature, nor is the effect of SCD decisions on SCM practices and performance investigated Figure 6.

Understanding how to create a supply chain, as opposed to simply managing the current design, is crucial when thinking about the ESCs of the future. Having the optimal design is the first step, and knowing how to manage the supply chain is the next. For example, if the design lacks storage in an ESC design, the management approach may not be possible to apply. However, if storage is included in the design, a wider range of SCM strategies become available. It is therefore imperative to consider the possibility for optimising and relocating the storage in the supply chain so that there is an efficient balancing mechanism between microgrids and the national grid.

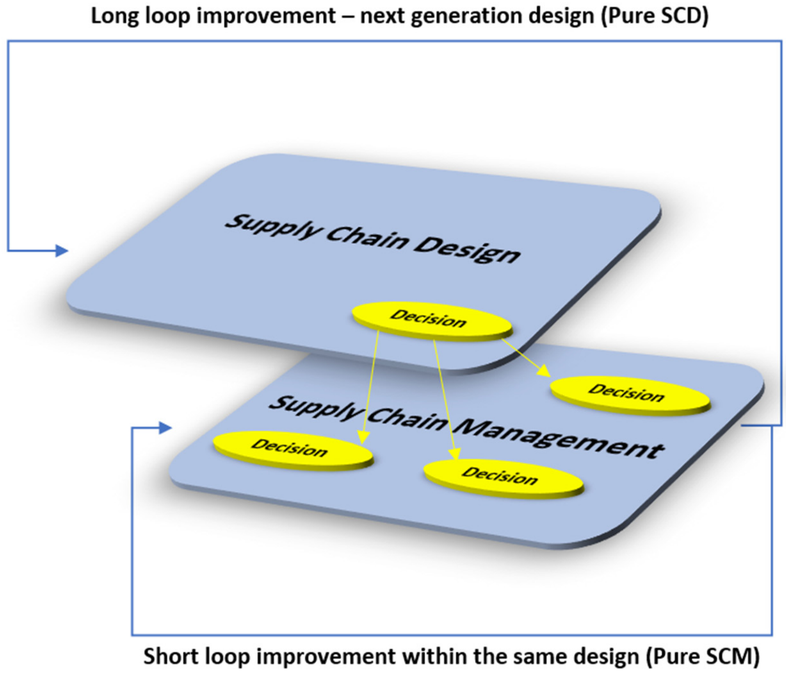

Figure 6. Two-level supply chain framework.

3. Microgrids Versus Smart Grids

3.1. Classification of Various Grid Types

The smart grid and microgrid concepts have been established in recent years to address the issues associated with integrating renewable energy sources into energy systems. Distributed energy sources (DESs), such as renewable energy sources and energy storage systems (ESSs), are classified as onsite generating sources [42], which are crucial for minimising transmission losses and enhancing the consistency of voltage in the supply network for large grids [43]. However, the usage of DESs has the potential to create just as many issues as they might fix. Adopting a system perspective that sees generation and related loads as a component of a system or "microgrid" is a better method to realise the promise of distributed generation, which is still in its infancy [44]. The past has been revitalised. The idea of the microgrid (MG) has been there since the inception of the energy business before the utility grid. The first implementation of electricity distribution was made possible by the use of decentralised MGs, which were subsequently interconnected to enhance operational effectiveness. When Thomas Edison inaugurated his Pearl Street Station in 1882, there was no established norm for an energy generation and distribution system. Consequently, he improvised and constructed the system as he progressed [42]. With the expansion of the network, electricity generation shifted from urban areas, resulting in communities losing their capacity for independent operation and the need for a more decentralised network.

There have been various definitions of an MG since then. An MG, as per the US Department of Energy's definition, is "a group of interconnected loads and distributed energy resources with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes" [45]. IEEE standard 2030.7 defines MGs as "loads, distributed energy resources (which include distributed generation, storage and load control), and the concept of operating with or without a grid" [46]. Many scholars provide similar definition [47,48]. Mohammed expanded upon the previous definitions by stating that an MG may be seen as a small-scale power grid comprising DERs, loads, and controllers [49]. Subsequently, the concept was broadened to encompass the notion that MGs can be operated in a regulated and synchronised manner, either while connected to the primary power grid and/or when operating autonomously [50].

MGs, as shown in Figure 7, are characterised by their smaller size and their capacity to operate autonomously from the main power grid. On the other hand, smart grids have been referred to by some scholars as a larger-scale power grid [51,52]. The IEA definition of a smart grid implicitly includes that it encompasses an extensive transmission and distribution infrastructure. As defined by the IEA, a smart grid is *"an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end users. Smart grids co-ordinate the needs and capabilities of all generators, grid operators, end users and electricity market stakeholders to operate all parts of the system as efficiently as possible, minimising costs and environmental impacts while maximising system reliability, resilience, flexibility and stability"* [53]. Nevertheless, it might be said that, as per the definition provided by the European Regulators Group for Electricity and Gas (ERGEG), every microgrid has the potential to be classified as a smart grid, and the latter is not necessarily required to function on a large scale. According to the ERGEG, a *"Smart Grid is an electricity network that can cost efficiently integrate the behaviour and actions of all users connected to it—generators, consumers and those that do both—in order to ensure economically efficient, sustainable power system with low losses and high levels of quality and security of supply and safety"* [54].

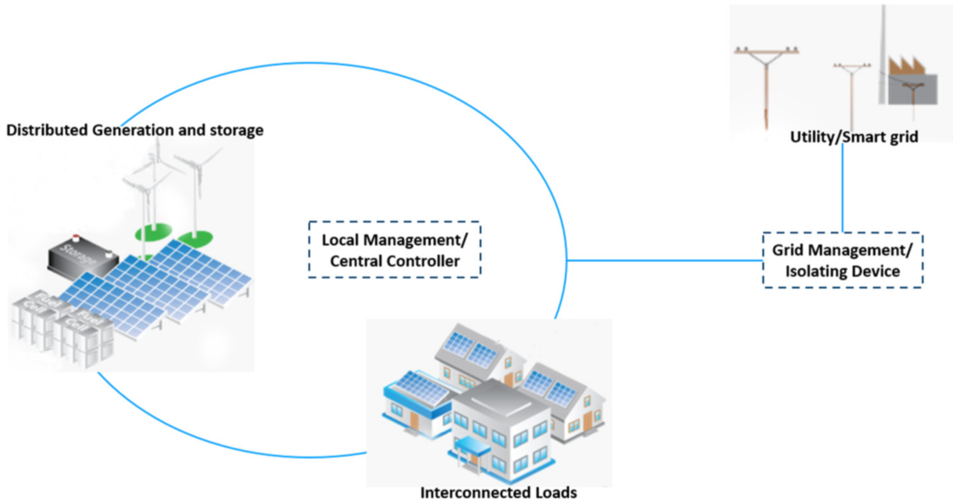

Figure 7. Architecture of a microgrid model.

The smart grid, despite its many advantages, is subject to several constraints. These include the need for two-way communication of information, integration of renewable energy resources into the grid, inefficient use of DESs, and insufficient network components and storage. Managing electricity generation, energy storage, and loads as a localised group is one way to achieve effective use of the DESs [47]. Therefore, the MG is an essential element of the concept of the smart grid. It is a scaled-down version of the utility grid, including almost all of its elements but in reduced quantities [55].

Frequency is critical to power system stability and resiliency. It measures power supply from sources like wind farms and gas plants and demand, especially during high-consumption periods like the evening. In the current electricity system in the UK, faster frequency response is needed due to the growing use of renewable energy and the grid's decreased inertia, which slows frequency deviations. The ideal electrical system would have a 50 Hz power network due to perfectly coordinated energy supply and demand. In actuality, the forces of supply and demand are continuously changing, and any variation in the frequency of the system can propagate rapidly over the whole network of Britain. Engineers in the UK's national grid are continuously controlling fluctuations in supply and demand to maintain a near-perfect balance and preserve the frequency within a one percent deviation from 50 Hz.

The Energy System Operator (ESO) for Great Britain recently implemented the Dynamic Containment (DC) frequency response service in the national control room. This service greatly enhances its capacity to swiftly address disruptions in the energy flow across the grid. DC is the first in a series of novel services that will enable operators to level frequency with greater speed and efficiency than before. The system is designed to respond quickly when it detects an error, such as the failure of a generator, to capture and control the subsequent change in frequency. This reaction is facilitated by agreements established with generators, ensuring their availability and prompt response when required. In addition, the speed and flexibility of batteries make them very suitable for doing the job [56].

In the UK, the energy system has employed DC as a method for more dynamic management of the national grid. This update would improve the system's efficiency and agility to handle the volatility of renewable energy sources, enabling it to handle a greater amount of renewable electricity. This progress aligns to attain carbon neutrality in the system by 2025. However, one might argue that reducing the volatility at a local level, such as in an MG, would also boost the performance of the national grid in a more straightforward manner.

3.2. Motivations for Implementing Microgrids

The concept of the MG has garnered significant interest from academics in the past decade because of its ability to effectively and efficiently integrate DERs into contemporary energy networks. MGs could be classified into two main categories based on their operation mode: grid-connected and isolated.

Since the introduction of MGs by Thomas Edison, there have been several compelling reasons to include them in energy systems. Initially, it was crucial to implement a "standalone microgrid" or "isolated microgrid" in distant areas where the distance and expense of transmitting and distributing power from a central energy source were prohibitive. They provide a solution for bringing electricity to rural populations in isolated regions and on tiny islands. This particular model is only designed for off-grid use and is not compatible with any external electric power network. The power is derived from several sources and is further supported by an ESS [57]. An isolated MG may efficiently include diverse DESs, particularly renewable energy sources.

Another form, known as a grid-connected MG, often functions in synchronisation with the conventional broad area grid (utility grid). However, it can operate independently in "island mode" based on technical or economic circumstances. This enhances the supply security inside the MG cell and enables the provision of emergency power, with the ability to switch between island and linked modes. The terminology used to describe these types of grids is "interconnected MGs". This review focuses on the advancement of an energy management system (EMS) for a grid-connected MG, as it can be considered a game changer in future ESC if it acts in an integrated way with the utility grid [58,59].

From the perspective of the utility grid, an MG may be viewed as a manageable unit inside the system that can be controlled as a single combined electrical load. This allows it to obtain favourable compensation, even if it is a modest power source or provides auxiliary services to support the network [50]. Grid-connected MGs could provide several benefits if they have the ability to upgrade the utility grid and integrate with smart grid arrangements. Including enhancing DERs utilisation and integrating renewable energy sources, they may effectively reduce peak load and minimise losses by generating power close to the point of consumption. Additionally, they supply energy to important loads, oversee power quality and dependability at a local level, and promote consumer participation through demand management and civic engagement in the distribution of electricity, improving the functionality of the utility grid through the local management of volatile loads and renewable energy fluctuations while also offering auxiliary services for the entire electric system [60].

3.3. Review of Microgrid Research

Energy management involves the methodical observation, strategic organisation, optimisation, and preservation of energy with the aim of creating an energy-efficient system. An MG may be regarded as a reliable and secure utilisation of DERs in a sustainable system. To attain optimum efficiency, it is crucial to have a well-functioning and efficient EMS in place given the unpredictable nature of renewable energy sources and changing electrical demand. An EMS is defined as "*a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost*" [61] by the International Electrotechnical Commission in the standard IEC 61970, which is related to the EMS application programme interface in power systems management. The EMS fulfils its mission by employing an advanced strategic thinking technique that is essential to its operations. By transmitting optimal decisions to each generation, storage, and load unit, the modules of DERs/load forecasting, human–machine interfaces, and supervisory, control, and data acquisition, among others, guarantee the effective implementation of EMS decision-making strategies [62]. Lately, some academics have concentrated their endeavours on developing sophisticated energy management methods for MGs, aiming to construct a self-sufficient MG.

MGs have challenges in terms of control and protection. This is because all ancillary services needed for system stabilisation must be generated inside the MG. The design of MG control systems follows a hierarchical approach as shown in Figure 8, which consists of three control levels: primary, secondary, and tertiary control. This method takes into account the various control tasks and time constants involved in the functioning of an MG [63]. In an isolated MG, there are two levels of control: primary control and secondary control. The primary control relies only on local measurements and consists of an output control stage that tracks voltage and current references, as well as a power-sharing control that ensures an appropriate distribution of power imbalances. The EMS, commonly referred to as the secondary control, is the top-level control responsible for ensuring the reliable and cost-effective functioning of isolated MGs. Further, the tertiary control oversees the synchronised functioning of various MGs and the utility grid, which is only applied in the grid-connected MGs.

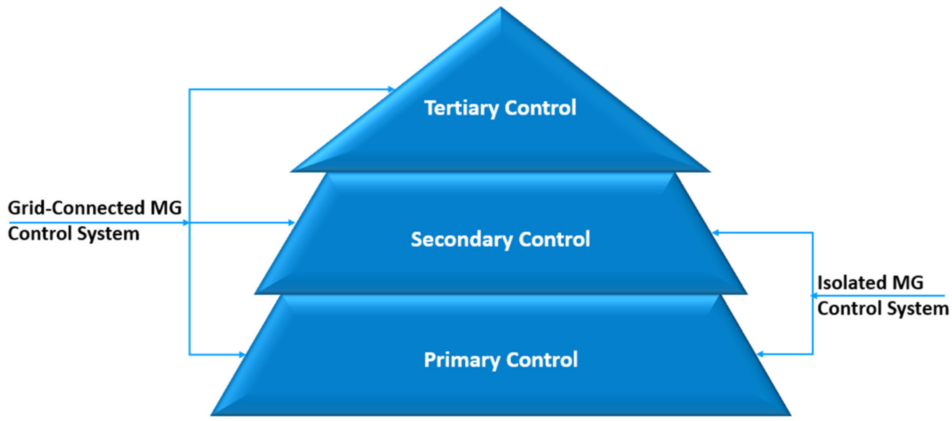

Figure 8. Hierarchical structure of MG control systems.

The methodologies used in EMS to optimise its performance may be divided into two main categories: EMS based on classical methods and EMS based on meta-heuristic approaches [64], as illustrated in Tables 1 and 2, respectively.

There have been several studies of isolated MG EMS [65–68], but the focus of this review is only on grid-connected MGs, as stated before.

Table 1. EMS based on classical methods.

Linear and Nonlinear Programming Methods	Dynamic Programming and Rule-Based Methods
Linear programming	Dynamic programming
Nonlinear programming	Approximate dynamic programming
Mixed-integer linear programming	Rule-based approach
Mixed-integer nonlinear programming	Battery SOC rule-based approach

Table 2. EMS based on meta-heuristic approaches.

EMS Based on Genetic and Swarm Optimisation	EMS Based on Other Meta-Heuristic Approaches
Genetic algorithm	Differential evolution
Memory-based genetic algorithm	Modified differential evolution
Matrix real-coded genetic algorithm	Ant colony optimisation
Particle swarm optimisation	Gravitational search algorithm
Regrouping PSO	Self-adaptive gravitational search algorithm
Guaranteed convergence PSO	Modified bacterial foraging
Particle swarm optimisation	Artificial bee colony
Self-adaptive modified θ-PSO	Modified artificial bee colony
Multiobjective PSO	Modified simulated annealing
Stochastic weight trade-off PSO	Modified crow search algorithm
	Imperialist competitive algorithm

The literary works included below pertain to EMS challenges that have been addressed using classical programming strategies, including linear, nonlinear, and mixed-integer programming methods. Linear programming (LP) is a method used to model a system with linear limitations and an objective function that aims to either maximise or minimise a value [69]. If the constraints in the system are nonlinear, it is possible to represent the system using nonlinear programming (NLP). If there is a need that some decision variables must have full integer values in the optimal solution, the issue is known as mixed-integer programming (MIP) [70]. Several researchers have suggested the use of EMS in grid-connected MGs, utilising LP and NLP techniques [71–73]. Sukumar et al. [74] developed an EMS for the MG that minimises operational costs using LP and mixed-integer linear programming (MILP) optimisation techniques. The EMS is created by integrating three suggested operational techniques, including the "continuous run mode", "power sharing mode", and "ON/OFF mode", throughout a 24 h time frame. In [75], a total cost minimisation methodology based on MILP for residential grid-connected MG energy management is suggested, including energy trading costs, customisable load shedding penalties, and EV battery wear costs, where critical, adjustable, and shiftable loads are examined. The implementation of several load profiles enables the proposed EMS to effectively regulate and operate the load within the optimal performance timeframe. More precisely, the load that may be shifted is assigned to the hours when there is less demand, resulting in reductions in total costs at both the utility and the MG level, which make the case a multiechelon optimisation. Similarly, the authors in [72] suggested an EMS that involves an optimisation issue to reduce running costs and encourage self-consumption. However, their fuzzy-based supervisory control unit adjusts for the mismatch in utility power by altering the references of the DERs. Therefore, it poses no harm to the utility grid. The authors in [76] developed an NLP approach to optimise the EMS of a grid-connected MG. Two market policies are suggested, where the primary goal of the first policy is to minimise the operational costs of the MG. The second policy focuses on maximising its profit by taking into account energy exchanges with the main grid. In the previous studies, day-ahead anticipated data are the most prevalent approach to address unpredictability.

On the other hand, dynamic programming (DP) is a method that involves breaking down a choice into many steps in order to simplify and optimise the decision-making process. DP reduces the computational solution time of a problem relative to techniques that do not utilise overlapping separate issues. An approximation DP method was introduced to address the issue of high dimensionality in the EMS model of a grid-connected MG [77].

The suggested model takes into account the volatility of wind speed, load demand, and surrounding temperature by generating several scenarios. It optimises the energy scheduling of the MG by using economic dispatch and unit commitment procedures. The efficacy of the suggested strategy is contrasted with myopic optimisation and dynamic programming techniques. The approach yields superior outcomes in minimising operational expenses but at the expense of increased processing time, in contrast to a myopic optimisation technique. Nevertheless, it accomplishes reduced computational time compared to the DP approach but at the expense of a greater objective function value.

Several traditional optimisation methods have difficulties when applied to real-world situations, such as having to disregard local optimum solutions, facing the possibility of divergence, encountering hurdles in addressing restrictions, or experiencing numerical difficulties in computing first- or second-order derivatives. In the early 1970s, heuristic and meta-heuristic methodologies were introduced to tackle these problems. Meta-heuristic algorithms are a collection of search algorithms that employ diverse and general heuristics to address intricate optimisation problems [78]. One of the most enticing features of meta-heuristic algorithms is that they may be applied without the need for any specific understanding of the optimisation problem at hand. Hence, they may be employed to elucidate the concept of a comprehensive problem-solving framework for optimisation difficulties or other associated matters [79,80]. The following is an analysis of some energy management methods that have been created using meta-heuristic methodologies.

In their study, Nikmehr et al. [81] introduced an EMS for a grid-connected MG that utilises particle swarm optimisation (PSO) to achieve the most efficient operation of the MG. The suggested problem is resolved by employing a bilevel algorithm. The primary purpose of the first level is to minimise the operational cost of each MG independently. On the other hand, the second level focuses on coordinating the activities of these individual MGs with the distribution network operator by using demand response programs. The authors determined that PSO is a very effective optimisation technique that offers cost-effective and environmentally friendly solutions when compared to stochastic programming. A genetic algorithm using an improved real-time energy management system for grid-connected MGs was developed by Elsied et al. [82]. This algorithm maximises renewable energy power while minimising operating costs and CO2 emissions. Each DER unit has a local controller to regulate current and power output. The authors used a realistic MG testbed to empirically verify the effectiveness of this real-time EMS. The majority of energy management techniques that are examined in this section consider the concurrent reduction of both operating and emission costs, where the integration of demand management is more successfully managed in energy management methods that utilise a meta-heuristic approach compared to classical optimisation approaches.

Other scholars have studied MGs through simulation studies [83]. Sato [52] performed research in Japan that focused on energy supply operations in a microgrid connected to a large grid. The study aimed to assess the performance of the system and develop strategies for achieving a stable supply into the MG. The results demonstrate that the connection to the large grid decreased the volatility in power supply feeding into the MG and successfully enables the implementation of Heijunka (level) production, which decreased the power shortage and its occurring frequency at the MG level. Nevertheless, the excess electricity exhibited by his results is seen as a waste in the MG system; even if the MG can sell it to the utility grid, a lot of power selling may lead to an increase in the peak load sources in the utility grid. Thus, he proposed the need for further enhancement in the management model to effectively decrease both power shortfall and surplus while avoiding an excessive storage capacity.

The storage system facilitates the seamless incorporation of renewable energy sources by stabilising the electricity supply during outages. It achieves this by storing energy during periods of low demand, resulting in cost savings [84]. Hence, many researchers have conducted a comprehensive investigation into the implementation of storage systems to integrate them with renewable energy sources to operate MGs [85,86]. In addition, several studies have asserted that the use of a hybridised approach, combining two or more storage systems instead of a single unified system, can enhance storage capacity, lifespan, and efficiency, especially in isolated MGs [87,88]. Shezan [89] states that incorporating renewable energy sources into the current energy system might provide significant technological challenges, mostly because of the unpredictable nature of renewables. This applies to both grid-connected systems and isolated MG systems. Nevertheless, his study contended that an alternate energy storage technology may be employed to address this issue provided the appropriate control mechanism is utilised.

3.4. Microgrid Research from a Supply Chain Perspective

In this section, we turn our attention to how microgrid research can be interpreted from a supply chain perspective. The key aspect of this critical analysis is supply chain planning. In a traditional supply chain, all nodes engage in their own planning activities. The challenge of supply chain planning is to achieve some sort of coordination between the different plans. The best practices are joint or/collaborative planning or, ideally, a complete integration of planning activities. Complete integration is in fact very rare as different echelons are reluctant to share competitive data and may have different objectives (for example, a manufacturer wants to minimise inventory, whereas a retailer wants an optimal inventory level). Table 3 presents the literature that has been discussed in the previous section, considering the interpretation of SCM in the proposed EMS in these studies.

Table 3 shows that aside from Sato, no studies specifically apply SCM techniques and concepts such as Heijunka to manage the balancing mechanism between MGs and the national grid. This approach is what we called the selfish microgrid approach: the primary objective of these articles is to improve the effectiveness of energy resource utilisation in MGs at the local level without considering the influence of the resultant design on the utility grid. When considering the problem from an SCM perspective, the MG may be seen as one echelon, while the utility grid can be seen as the infrastructure shaping the supply chain network. The notion of risk transfer to the utility grid, as shown in Table 3, involves enhancing the efficiency of an echelon (MG) by shifting the adverse effects of its design (e.g., increased volatility) to the remaining echelons of the supply chain (utility grid). However, it is crucial to prioritise the interaction with the utility grid in order to improve the overall supply chain performance while also adhering to a coordination guideline for supply chain echelons. Some researchers in Table 3 proposed an EMS that is focused on the MG performance; however, their results show no harm to the utility grid and do not benefit or optimise its performance [76,77,81,90,91]. Other studies have shown that implementing their EMS might represent a risk to the utility grid. This could be due to increased demand volatility [62,71,82,92] or an increase in peak load sources [52]. These effects are illustrated in Figure 9.

Table 3. Supply chain interpretation in managing grid-connected MG systems.

Study Ref	Year	Key Objective	Approach	Risk Transfer to Utility Grid	Selfish Microgrid Focus	Supply Chain Interpretation
[62]	2011	Operational cost reduction	Matrix real-coded genetic algorithm	✔	✔	Single-echelon operational cost minimisation
[76]	2011	Operational cost reduction MG profit maximisation	NLP	—	✔	Single-echelon multiple objective
[77]	2013	Operational cost reduction	Approximate DP	—	✔	Single-echelon operational cost minimisation

Table 3. *Cont.*

Study Ref	Year	Key Objective	Approach	Risk Transfer to Utility Grid	Selfish Microgrid Focus	Supply Chain Interpretation
[75]	2014	Total cost reduction	MILP	—	—	Multiechelon total cost minimisation
[92]	2015	Operational cost, pollutants emission cost, and power loss reduction	Imperialist competitive algorithm	✔	✔	Single-echelon multiple objective
[71]	2016	Operational cost reduction	MILP	✔	✔	Single-echelon operational cost minimisation
[82]	2016	Total electricity cost and emission reduction	Genetic algorithm	✔	✔	Single-echelon multiple objective
[74]	2017	Operational cost reduction	MILP and LP	✔	✔	Single-echelon operational cost minimisation
[72]	2017	Operational cost reduction promote self-consumption	MILP	—	✔	Single-echelon multiple objective
[52]	2017	Stabilising power supply operations into the MG	Simulation	✔	✔	Single echelon coordination constraint
[81]	2017	Operational and emission cost reduction	Particle swarm optimisation	—	✔	First, optimise performance at single echelon; second optimise multiechelon coordination
[73]	2018	Total electricity (from the utility grid) cost reduction	LP	✔	✔	Single-echelon electricity cost minimisation
[90]	2018	MG profit maximisation and energy balancing efficiency of home MGs	Multistage stochastic programming based on artificial bee colony algorithm	—	✔	Single echelon profit maximisation with coordination constraint
[91]	2021	Operational cost reduction Peak reduction	Quantum particle swarm optimisation	—	✔	Single-echelon multiple objective
[93]	2022	Operational cost reduction	Particle swarm optimisation	—	✔	Single-echelon operational cost minimisation
[94]	2023	Operational cost reduction	MILP	—	✔	Single-echelon operational cost minimisation
[95]	2024	Operational cost reduction	MILP	—	✔	Single-echelon operational cost minimisation

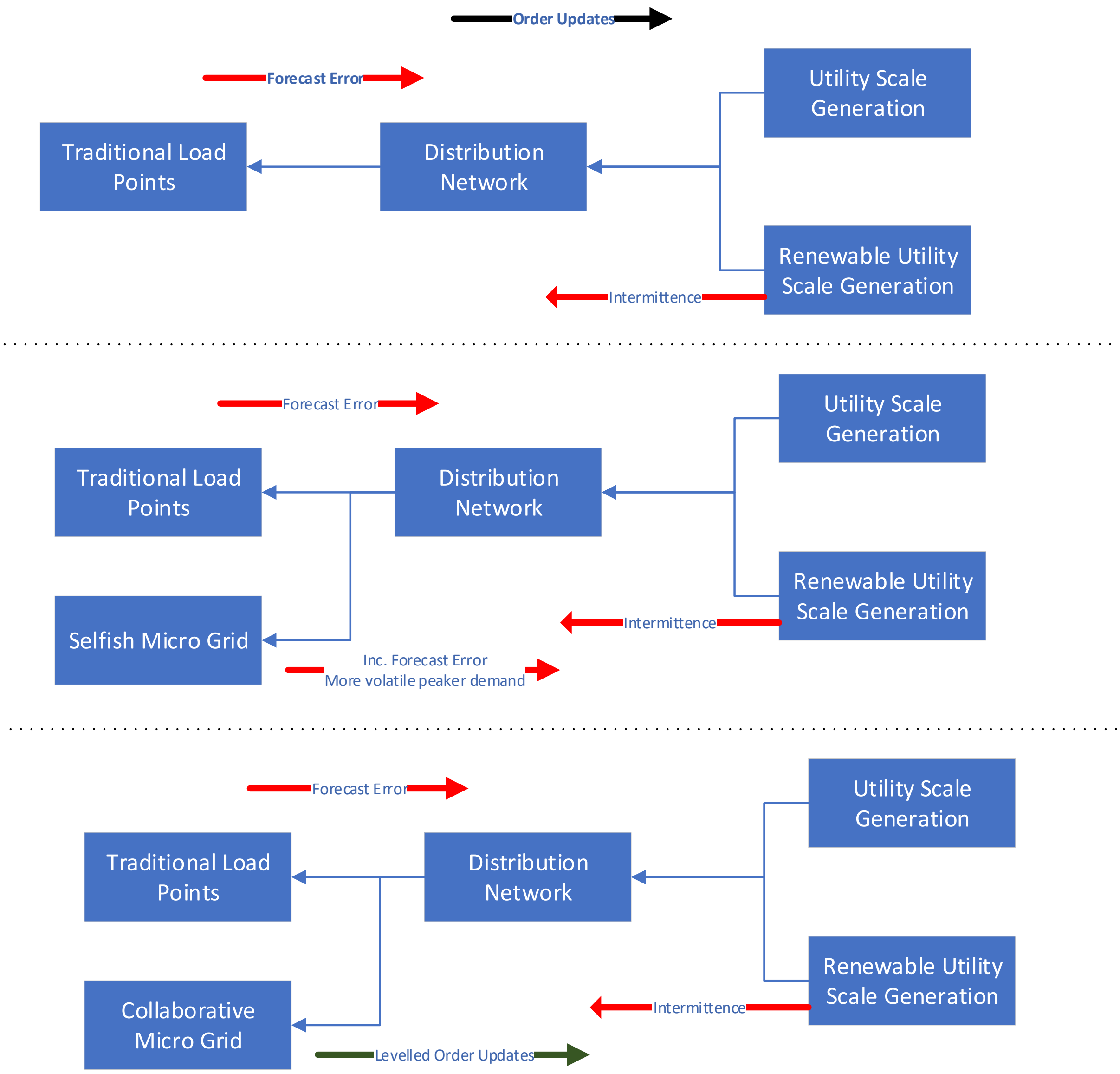

Figure 9. Electricity and volatility flows in electricity supply chains.

The top diagram of Figure 9 illustrates a traditional electricity system as a supply chain. The blue arrows represent electricity flows from generation to consumption, and the red arrows illustrate volatility flows, i.e., order updates that challenge the operation of the whole systems. Electricity supply chains cannot be fully responsive as they face update response constraints at the generation nodes as well as flows and regulation constraints at the distribution network level. The load balancing challenges reside in demand forecast errors (e.g., predicting when houseowners turn on their Christmas lights), but this is a well-known and managed problem by network operators, although system incidents and blackouts can happen. A more recent challenge is that of intermittence created by utility-scale renewable power generation. The situation gets more challenging with the introduction of selfish microgrids. They lower (and often eliminate) the average demand order updates to the network operator and only place these orders when they cannot generate that power or use storage to satisfy their demand. This results in an increase in volatility and the creation of potentially erratic order updates (as the underlying source of volatility is local demand and weather, it stands to reason that all selfish microgrids will place orders at the same time).

The energy system literature is well aware of the situation depicted in the central diagram of Figure 9. Current solutions that are explored are the introduction of utility-scale storage (to offset intermittence) or the redesign of the distribution network to have the capacity to deal with increased volatility. The gap in the literature that is revealed by this paper is shown in the bottom diagram. We found only one paper that shows that a microgrid could use a more collaborative approach to planning. In this approach, the microgrid uses its storage to handle the demand/supply volatility mix that it faces and places levelled order to the grid, making the operations of a utility-scale generator smoother and more efficient.

4. Theory Development

At the end of 2014, Ofgem's Low Carbon Network, UK Power Networks (UKPN), and others sponsored Europe's biggest battery at Leighton Buzzard for GBP 18.7 m [96]. It aimed to show that large-scale battery storage was feasible and cost-effective. This technology can balance network consumption efficiently by storing energy and using powerful algorithms to forecast and improve power delivery. They claimed that unlike demand response, it may immediately replace gaps with stored power rather than enticing heavy users to cut demand during peak periods. Long-term storage has several operational benefits, but it adds costs. The storage option requires over twice the capital, where the surplus is mostly related to the magnitude and uniqueness of the initiatives. The Smarter Network Storage Facility had obstacles during planning and design, including malfunctioning circuit boards and electromagnetic interference. UKPN later announced that it would sell the plant when Ofgem banned network providers from energy generating and storage. While all problems were surmounted and the process proceeded successfully, governance rules and economics had an impact on the practical value of storage. Europe has successfully charged its largest battery, but the question remains whether the market is prepared to embrace it [97].

Storing a significant amount of electricity, as seen at Leighton Buzzard, is a daunting problem. Similarly, managing inventories in MGs becomes hard when relying on intermittent electrical sources like PV panels. Integrating the MG with the national grid as a dependable backup source of power will simplify the balancing issue, allowing it to be addressed using conventional inventory management techniques and ensuring that a dependable power supply is guaranteed by the interconnection of MGs with the national grid, but more benefits can be sought from that interconnection. By effectively controlling the demand at the MG level, this system will not only provide a dependable power supply but also ensure that it is environmentally friendly. Enhancing the quality of instructions transmitted from the MG to the national grid would improve the integrated balancing mechanism between the two grids. To achieve Heijunka, the MG can use weather forecasts to estimate demand and give those instructions to the national grid. Additionally, an optimisation may be implemented in the storage system by utilising SCM techniques that optimise the inventory capacity, while minimising both surplus and outages. By implementing efficient energy demand management strategies at the MG level, such as installing smart metres, we can guarantee a reliable and environmentally friendly electricity supply. Consequently, it will progressively convert the national grid into a smart and effective grid.

Based on the information presented in Table 3, it could be argued that the majority of the research conducted on MGs in the academic literature mostly focuses on so-called integrated MGs, while the main purpose of these studies is to enhance only the local performance of the MG by achieving goals such as enhancing autonomy or minimising local expenses. MGs that prioritise their own advantage over the interests of the utility grid can be referred to as "selfish" MGs, as this selfish attitude results in an inefficient balancing mechanism that only serves the MG itself. Moreover, this self-centred behaviour has the potential to negatively impact the utility grid by exacerbating the volatile demand for the grid during times of renewable energy shortages or by unexpectedly unloading the system if it operates autonomously.

From a supply chain perspective, the current balancing method is a supply chain planning challenge related to load allocation. However, it should be handled through a supply chain integration approach, which brings us back to the concept shown in Figure 5. The majority of research conducted thus far has focused on the development of effective purchasing management, with a limited number of trials exploring topics related to SCM. However, there is currently no established framework for considering an ESC. A significant amount of research is now being conducted on the EMS of MGs and the utility grid. However, much of this research may be categorised as traditional purchasing management, lacking an in-depth understanding of the intelligent and dynamic capabilities of the smart grid. Only a few researchers have focused on accessing the data rather than exploring the underlying intelligence behind the smart grid's dynamic capabilities. There is a lack of coordination and integration in demand management. Due to the rising volatile demand on the grid caused by MGs, there has been an initiative from the grid to implement dynamic management like DC. However, this endeavour is limited to the grid side, while MGs continue to operate in a selfish manner. Nevertheless, it is more convenient to handle the unpredictability at smaller scales and local levels like MGs. How about implementing more integrated MGs that incorporate SCM principles and variables like optimal distributed storage and order updates? The unpredictability of renewable energy might be mitigated by using weather predictions to anticipate demand and proactively submit grid orders with a one-week lead time. Currently, the order rules of MGs are leading to fluctuating demand from the grid. This is because their primary focus is on utilising the renewable power they possess and only relying on grid power when necessary. By altering the priority of the order rules, it is proposed that MGs should first utilise the contracted grid power, which is ordered based on a demand forecast made one week in advance, and then utilise the available renewable power. By implementing integrated MGs, we can effectively manage the unpredictability and enhance the proportion of renewable energy inside the system, therefore progressing towards a more decentralised network. Additionally, enhancing the balancing mechanism of MGs and the national grid can lead to improved overall performance. To operate in a manner that is not driven by selfish motives, we propose the theory of a nonselfish MG.

By proposing nonselfish MGs, our contribution inscribes itself in the wider topic of planning an electricity network operations. This latter task is akin to the problem of aggregate production planning (APP) in operations and supply chain management. The main of contribution of this review paper is to highlight a gap in the literature about the relationship between microgrids and APP in the electricity sector, as explained in Table 4.

Table 4. Different aggregate production planning approaches in the electricity sector.

	Traditional APP	**Minimum Production APP**	**Current APP**	**Gap in the Literature**
Scope	Network of generators	Network of generators	Full network	Full network
Objective	Minimise cost subject to constraints	Minimise cost of baseload by maximising utilisation	Minimise cost of baseload and utilisation of green energy	Minimise volatility of orders to utility generators
Volatility	Is one of the constraints	Deals with responsive source	Deals with responsive source	Is part of the objective function
Principle	Produce electricity as cheaply as possible given demand	First, allocate baseload to nuclear. Allocate peak demand to gas.	First, maximise autonomy of microgrids. Second, use nuclear for baseload. Third, use gas for peaker demand and back up generation.	Optimise a portfolio of supply, storage, and demand nodes subject to constraints. Budget is a constraint.

Table 4 shows that the complexity of APP problems in the electricity sector has gradually evolved from a simple cost minimisation problem. In the current approach, microgrids are not part of the APP exercise as they perform a local optimisation (see Table 3). It is one approach, but not an intuitively appealing one: it decreases the load and therefore the efficiency of traditional utility-scale generators and increases the volatility of orders.

The column on the right-hand side illustrates where we found a gap in the literature, which consists of integrating microgrids in the larger APP problem in order to smooth out generation requirements, increase utilisation, and therefore lower cost whilst providing a solution to increasing the number of microgrids and green power generation points in the network.

5. Conclusions

This review utilises a supply chain perspective to address the issue of intermittent renewable energy by improving the balancing mechanism between MGs and the national grid, promoting cooperation rather than selfish motives. This is anticipated to be advantageous for both the electrical sector (utility grid and MGs) and the consumer.

Additionally, it is crucial to recognise that there might be constraints in implementing these techniques in real-life situations, therefore necessitating further investigation to tackle these obstacles. In summary, this study emphasises the significance of continuously investigating novel methods and strategies from the supply chain sector and using them in the electrical sector to guarantee the durability of future ESCs, especially with the increasing integration of renewable energy sources.

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Abbreviations

The following abbreviations are used in this manuscript:

APP	Aggregate production planning
CSCMP	Council Of Supply Chain Management Professionals
DC	Dynamic Containment
DESs	Distributed energy sources
DP	Dynamic programming
EMS	Energy management system
EOQ	Economic order quantity
ERGEG	European Regulators Group for Electricity and Gas
e-SCM	Electronic supply chain management
ESCs	Electricity supply chains
ESO	Energy System Operator
ESSs	Energy storage systems
IEA	International Energy Agency
JIT	Just in time
LP	Linear programming
MG	Microgrid
MILP	Mixed-integer linear programming
MIP	Mixed-integer programming
NLP	Nonlinear programming
PSO	Particle swarm optimisation
SCD	Supply chain design
SCM	Supply chain management
T-JIT	Total JIT
UKPN	UK Power Networks

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