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Smart Grids as product-service systems in the framework of energy 5.0 - a state-of-the-art review

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Abstract

Aim: This work explores the opportunities and challenges associated with the integration of Product Service Systems (PSS) into Smart Grids (SGs) with the aim of improving manufacturing and production systems' sustainability under the Society 5.0 framework.

Methods: A bibliometric analysis was conducted to examine the existing bibliographic material and identify the primary scientific directions for this research area. The aim was to provide a thorough understanding of the research problems and perform an in-depth analysis of the distinctive aspects of development of the scientific research in this field and visualize the results with VOS viewer tool.

Results: Industry, society, and academia are being reshaped and reorganized to integrate new information and communications technology (ICT) to enable complete digitization and digitalization of their infrastructures. This trend is driven by the need for more resilient, environmentally sustainable, and human-centric systems, as indicated by the terms Industry 5.0 and Society 5.0. Electrical power generation and distribution currently are critical issues for society. In this context, SGs are examined from the perspective of product-service systems (PSSs). The key enabling technologies are discussed and a technical discussion based on presentation of implemented frameworks follows.

Conclusion: Intelligent societies will become the new reality. It is necessary to adapt existing infrastructures toward human centricity, resilience, and sustainability. SGs require further development, with several challenges still to be addressed. However, engineers have several technologies available, including blockchain and PSSs, to promote client activity in societal infrastructures.

Keywords: Energy 5.0, smart grid, product-service system, PSS, Society 5.0, sustainability

INTRODUCTION

Climate change has been an open challenge in recent decades, creating pressure on governments, companies, and the international community to adopt cleaner energy strategies and improve the energy efficiency of their systems and processes/operations[1]. Production and manufacturing are among the most energy-intensive activities in modern society and by extension, their energy consumption has been subjected to extensive research over the last few years because of increasing public awareness of key environmental issues, including the greenhouse effect and global warming, the strict legislation about permitted emissions, and rising energy costs. As a result, enterprises are moving toward efficient manufacturing[2]. Furthermore, energy efficiency has been recognized on a global scale as a major policy priority to achieve a carbon-neutral society. More specifically, energy efficiency represents one of the cornerstones for several initiatives, including the EU energy and climate policy[3], the United States policy called "Getting to Zero: A U.S. Climate Agenda"[4], and China's path toward a carbon-neutral society by 2060[5].

In light of the recent advances in Industry 4.0[6], the upcoming Industry 5.0[7], and Society 5.0[8], engineers are now focusing on the design, development, and implementation of strategies to enhance their productivity and remain competitive while also ensuring that the environmental impact of their activities remains as low as possible. Among the possible solutions for energy and waste management, business models have also been transformed by following the servitization paradigm to provide models such as product-service systems (PSSs) and industrial product-service systems (IPSSs), which promote selling of services rather than tangible goods[9]. According to recent reports[10], an increase in global electricity demand has been noted that is estimated to hit a 40% increase by 2040. From the latest European Union (EU) market analysis, it has become evident that under current circumstances, the costs of electric energy production and distribution are now a critical issue[11]. Consequently, energy suppliers are faced with the challenge of producing even more electrical energy to meet market demand, compensate for the production cost of this electrical power, and follow new environmental initiatives for greener and more sustainable power production as well. The solution to this challenge lies in the design and development of frameworks to support power generation from renewable and distributed energy resources, which by extension should also be integrated into the outdated, inflexible, and overstressed centralized electrical grids. Essentially, it has become apparent from the most pertinent literature that energy distribution, beyond the existing environmental challenges and the concerns raised by communities, should be democratized. Consequently, energy distribution in modern SGs is accompanied by a constant exchange of information between the energy suppliers and energy consumers. Therefore, with the proposal and integration of PSSs in SGs, new opportunities for creation of suitable communication channels between the clients and the producers will be established. The resulting communication among the stakeholders will allow the volatility of demand, which remains an ongoing challenge, to be tackled more efficiently[11]. Furthermore, with constant tracking of energy demand *vs.* energy production *vs.* the production resources (e.g., fossil fuels, renewable sources), energy producers will be more capable of utilizing the potential of their renewable sources fully while minimizing the environmental footprint of their operations. Another important challenge is addressing the stability of the networks and preventing power outages, which in many cases are related to increased and uncontrolled demand from the clients. Similarly, the decentralization model of the SG offers additional benefits to society as a whole since new opportunities can be created for energy companies, while their competitiveness is maintained. In addition, this model means that energy consumers can also play a more active role in energy production. More specifically, rather than the classic consumption model, consumers can contribute to the SG by generating electrical power (via utilization of individual devices) that can be stored and then delivered to meet demand in peak energy consumption periods. Therefore, by using digital technologies such as blockchain, distributed ledgers can be implemented to maintain a complete record of the energy transactions, set up virtual contracts between clients and producers, and provide a space for implementation of a client reward system. The generation of more efficient production schedules that focus on rebalancing energy supply and demand, driven by the ever-increasing need to reduce costs, is thus an imperative.

Ultimately, in an attempt to address the challenges mentioned and the literature gaps identified in the preceding paragraphs, this work presents and discusses the latest developments in the field of PSSs (including IPSSs) and the servitization of energy distribution that takes advantage of the cutting-edge digital technologies that were introduced in the Industry 4.0 framework.

The remainder of this work is structured as follows. In Section 2, the most pertinent and relevant literature in the SG field and the accompanying technologies and techniques are investigated. Then, in Section 3, technical details are provided through presentation of frameworks that were mainly developed in the industrial domain but are expandable to the SG concept. In Section 4 the key research challenges for the near future are summarized, possible solutions are discussed, and a conceptual solution framework is presented. Finally, in Section 5, conclusions about the research are presented, and aspects of future work are discussed.

STATE OF THE ART

Review methodology

A bibliometric analysis was conducted to examine the existing bibliographic material and identify the primary scientific directions for this research area. The aim was to provide a thorough understanding of the research problems and perform an in-depth analysis of the distinctive aspects of development of the scientific research in this field. The sequence for the bibliometric analysis is presented in Table 1.

The initial search returned a total of 181 scientific literature articles. These articles comprised 51 journal articles, 92 conference papers, 10 book chapters, two books, and 26 conference reviews. In addition, with regard to the relevant topics, the majority of these publications fall into the categories of engineering, energy, computer science, mathematics, and environmental science.

Next, the results dataset was converted into the comma-separated values (CSV) format for further processing. VOSviewer software was used in an effort to visualize the results and analyze their bibliometric form as presented in Figure 1. Specifically, VOSviewer provides the functionality required to create a keyword map based on shared networks, and it can thus create maps with multiple items, along with publication maps, country maps, journal maps based on networks (co-citations), and maps with multiple publications. Less relevant keywords can be removed, and the number of keywords that is used can be adapted by the users. In summary, the functionalities of the VOSviewer software extend to the support of data mining, mapping, and grouping of articles retrieved from scientific databases. Topic mapping is essential for bibliometric research[12].

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Table 1. Review methodology

Database	Scopus
Article type	Scientific articles published in peer-reviewed journals
Search query (TITLE)	("Smart Grid") and ("product service systems" or "PSS") and ("energy")
Time frame	2012-2022
Identification of publication type	Journal articles only; conference papers, books, and book chapters
Language	English
Choice of the field of publication	Engineering and manufacturing relevant domains
Screening & paper selection procedure	Full paper available; article in English; article in the manufacturing domain; article related to maintenance
Results	181

PSS: Product-service systems

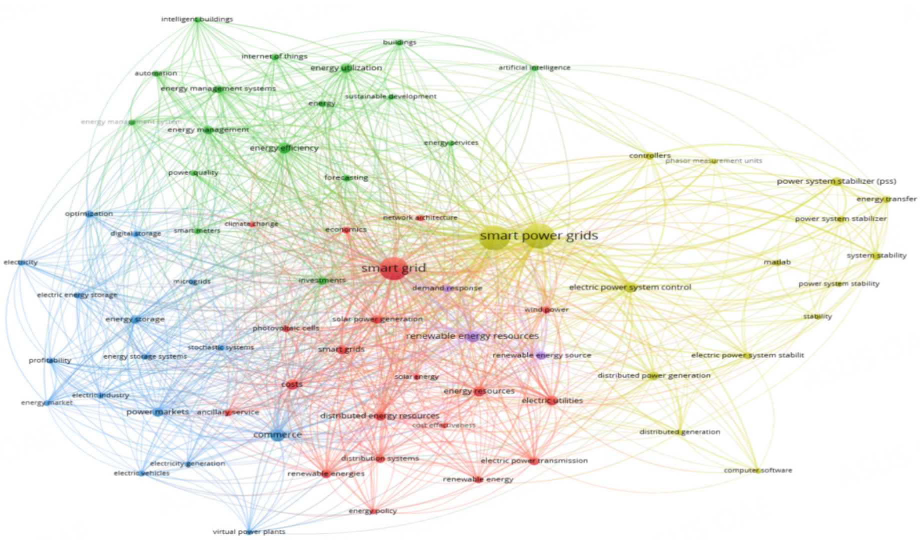

Figure 1. Network visualization of the literature topic areas.

From Industry 4.0 to Energy 4.0 and beyond

Technological advancements and the adoption of the Internet of Things (IoT) in business have sparked the Industrial Revolution 4.0 and the rise of Energy 4.0. This section discusses the advantages and the difficulties that the digital revolution has brought to the energy sector. Energy usage contributes significantly to global emissions and thus to climate change. Additionally, the associated energy costs are rising globally. As a result, there is growing pressure to address both the volume and the type of energy consumption across all sectors by implementing new and creative solutions[13]. New electricity sources such as wind and solar energy have now been demonstrated to be mature and dependable technologies, but there are still related difficulties. The next step will be to tailor these new forms of energy generation to the users' consumption patterns. Because industrial users account for more than 40% of the global total energy consumption, there is a significant opportunity to increase energy efficiency by taking advantage of important trends in industry[14].

In Figure 2, the correlation between industrial revolutions and energy is illustrated. More specifically, when mechanical production began to replace manual labor in the late 18th century, the first major industrial revolution occurred. Chronologically, the second industrial revolution took place a century later, following the widespread electrification of industrial processes. Subsequently, electrical grids began to be developed

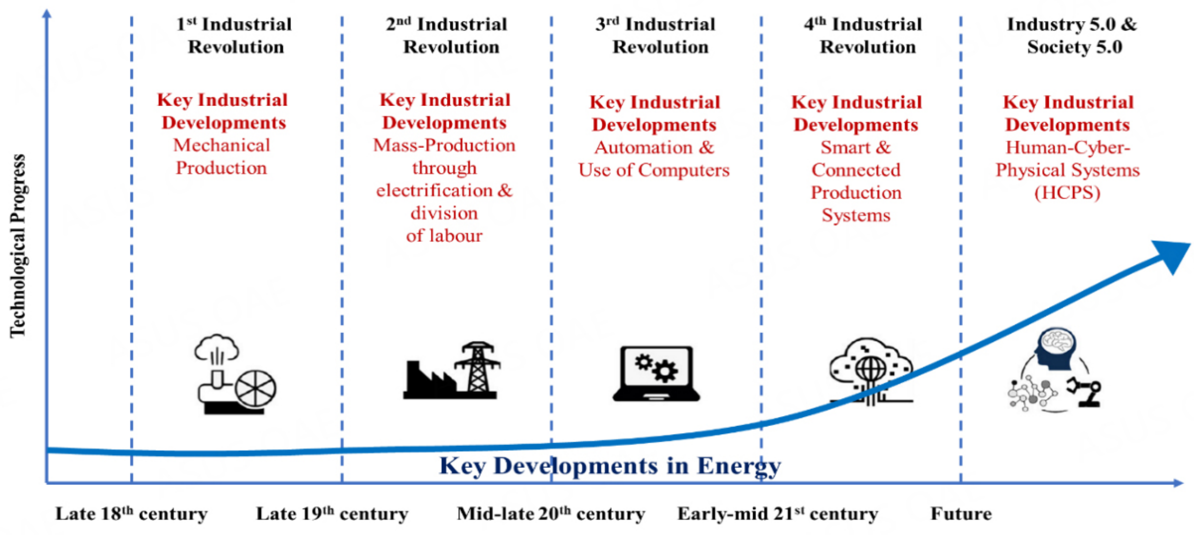

Figure 2. Key developments in energy in parallel with industrial revolutions[15].

on a global scale. In the third industrial revolution, which began in the middle of the 20th century, process automation and computers were introduced to enable further optimization of the production process. The fourth industrial revolution, which is also known as Industry 4.0, is currently using new smart and connected systems to boost the flexibility and overall productivity of industry. By extension, the interconnectedness of machinery, larger systems, and devices both within and between industrial sites and users has led to increased manufacturing intelligence. The sustainable energy transition and Industry 4.0 thus share important characteristics that can be interconnected to pursue a sustainable energy transition toward the realization of Industry 5.0[16].

Some fundamental guidelines for incorporation of Industry 4.0 tools that will enable Internet connectivity and usage in operational and industrial processes to aid in the implementation of Energy 4.0 are summarized in the following points[17]:

- Interoperability: Through use of the Internet and its services, interoperability represents the connection of various components and human resources.

- Virtualization: Information from sensors, simulation models, back-office systems, and other resources can be made into virtual copies.

- Real-time capability: The capacity to gather data, conduct analysis, and reach decisions immediately with near-zero latency.

- Modularity: The ability to replace, add, or remove components as needed.

Consequently, through the implementation of Industry 4.0 and Energy 4.0, engineers have laid the foundations for the realization of Energy 5.0. More precisely, developments falling within the framework of Energy 4.0 have also been defined in the literature as Smart Grid 1.0 (i.e., the first-generation SG). Similarly, the imminent changes and advances that are being made towards Energy 5.0 are defined as the second-generation SG, i.e. Smart Grid 2.0, and will be discussed in the following paragraphs.

Energy 4.0 definition

Energy 4.0 is a concept that was introduced within the framework of Industry 4.0, which refers to the digitization of the energy sector[18]. A detailed definition of Energy 4.0 is necessary here, because Energy 5.0 is heavily correlated with this concept as it essentially represents the next stage in its evolution[19]. It should be stressed here that in the energy sector, key areas including energy generation, distribution, storage, and marketing, among other aspects, are all included. The reasons behind these changes include the fact that the physical world is changing at an unprecedented speed, with significant issues to be addressed in intermittent renewables, nuclear power, and new transmission and distribution grids, among other areas. Additionally, the commercial energy world is changing (e.g., unbundling, trading, and new products). Finally, another significant reason is the constantly growing collection and flow of big data sets.

Cyber-physical systems (CPSs) are essential elements of Energy 4.0[20]. CPSs are composed of physical entities and are controlled or monitored using computer-based algorithms. The energy industry can also be considered to be one huge and highly complex CPS. As a result, the energy industry is likely to be seriously affected by cutting-edge Industry 4.0 technologies[21]. Figure 3 illustrates the concept of the CPS in the energy sector as the convergence of energy law frameworks and information and communications technology (ICT) law frameworks, as presented by the global community during recent years.

Benefits of the electricity digital revolution

A plethora of new technologies has been developed as a result of the digital revolution occurring in the electricity sector, along with exponential increases in both data processing and storage capacity. Many advantages have accompanied this change and are summarized in the following[22]:

1. Electricity utilities have further aided in addressing the grid instability and imbalance issues that have been partially exacerbated by the introduction of intermittent renewable energy sources. Widespread adoption of pre-emptive processes and much faster corrective actions have been made possible by implementation of real-time data monitoring.

2. The related interoperability of the various asset types, including renewable generation resources, energy storage facilities, and flexible loads, has been essential to this digital transformation.

3. The detection of process inefficiencies and equipment malfunctions at industrial sites has also been made possible using these data and monitoring-based approaches. Changes in business practices and replacement of outdated technologies with newer, more effective models are only two components of the solution. Artificial intelligence (AI)-based software applications with higher levels of sophistication can also be used actively to optimize energy flows.

4. Reductions in energy consumption ranging from 13% up to 29% have been enabled by use of new technologies and waste reduction. This has resulted in a remarkable 4% reduction in total global CO_2 emissions.

5. Placement of major technological innovations is helping to improve the efficiency and sustainability of the energy sector.

6. Increased flexibility has been realized in operational procedures.

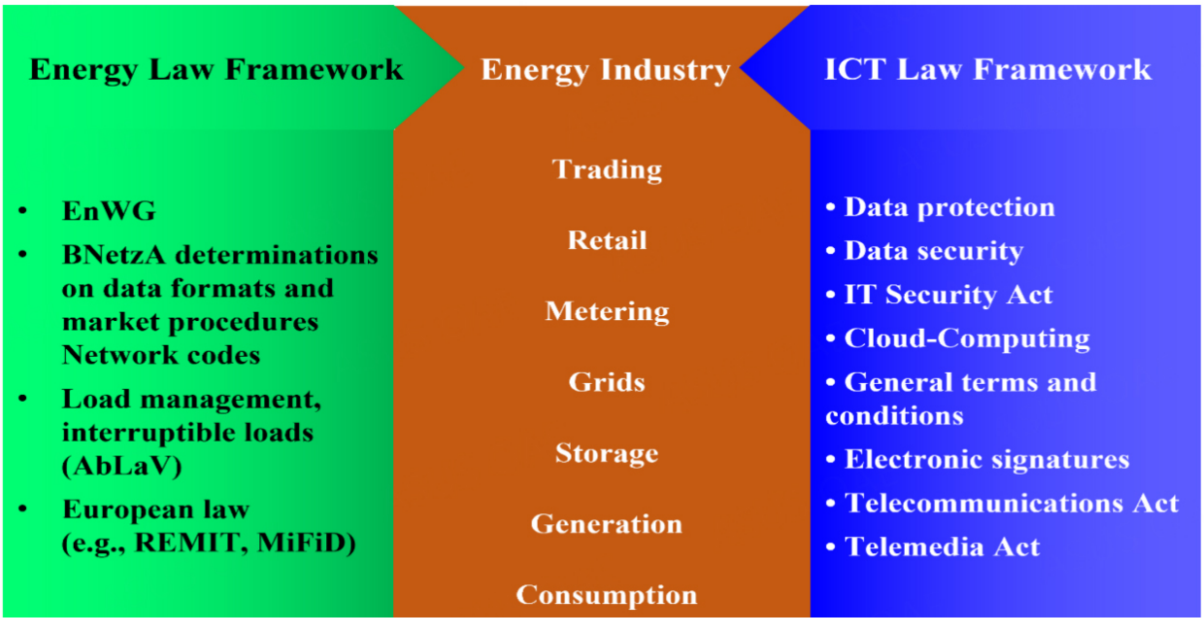

Figure 3. Energy 4.0 business models as a basis for development of the Energy 5.0 business model. AbLaV: Load management, interruptible loads; BNetzA: German Federal Network Agency for Electricity, Gas, Telecommunications, Postal Services and Railways; EnWG: ESA (European Space Agency)-NASA (National Aeronautics and Space Administration) working group; IT: information technology; MiFiD: markets in financial instruments directive (2004/39/EC); REMIT: regulation on wholesale energy market integrity and transparency.

7. Increased levels of personalization have been introduced into the services in an attempt to meet the requirements of customers.

8. The capability to obtain real-time, accurate information has been realized.

9. Accurate and thorough monitoring of the entire supply chain, including generation, transmission, distribution, and commercialization, has been enabled.

10. Process automation has improved the operational effectiveness of businesses.

11. Real-time supply and demand adjustments can aid in reducing the number of inefficient operations.

Challenges of the electricity digital revolution

Developed countries have reliable electrical infrastructures and minimal growth rates that allow them to focus on grid standardization, smart meter implementation technology development, and the interoperability of grid-connected and distributed renewable energy generation[23]. The business model for Energy 4.0 offers various advantages, but there are also several challenges that must be addressed to enable a successful transition toward a more sustainable and human-centric Energy 5.0 business model. Therefore, the key challenges and issues that must be addressed by both the developed and developing countries to realize the full range of benefits of SG implementation are discussed hereafter[24]:

1. **Technology Development:** Over the past decades, ICT has advanced significantly[25]. However, to make the grid smarter, a brand-new communication infrastructure that is highly reliable and attack-resistant must be constructed, either separately from or integrated into the existing World Wide Web. Advanced sensor

systems will be created and implemented in both smart buildings and the grid to measure phases, collect consumer consumption data, control automatic circuit breakers to ensure minimal disruption, and perform peak shaving of electrical appliances. It is thus necessary to develop and implement cutting-edge components, including smart appliances, smart meters, effective energy storage devices, high voltage DC transmission devices, and flexible AC transmission system (FACTS) devices[26].

2. **Quality Power to All Households:** In the coming years, significant expansion of the power system network will be required to ensure reliable supply of electrical energy to all households. To realize the vision of the SG, the quality of the supply must also be guaranteed. Therefore, to ensure that a high-quality supply to all households is maintained, the current grid will have to be upgraded and expanded. In addition, to reduce the supply gap during peak hours and peak energy costs, distributed renewable energy generation and the ability to save money by shifting loads from peak periods to off-peak periods should also be encouraged[27,28].

3. **Reduction of Transmission and Distribution Loss (T&D):** T&D losses will be minimized to meet international standards. Technical losses caused by a weak grid, financial losses, and a decline in collection efficiency are the main factors that influence the T&D loss[29].

4. **Interoperability and Cyber Security:** An advanced metering infrastructure (AMI) and SG end-to-end security, a revenue metering information model, building automation, inter-control center communications, substation automation and protection, application-level energy management system interfaces, information security for power system control operations, and phasor measurement unit (PMU) communications are among the interoperability standards that have been created by the National Institute of Standards and Technology in the United States (including intelligent electronic devices or IEDs)[30].

5. **Consumer Support:** The lack of consumer awareness of problems in the power sector is one of the main obstacles to the implementation of the SG. Therefore, to reduce peak load consumption and encourage distributed renewable energy generation, consumer support for SG implementation will be essential. Intelligent grid implementation will raise the quality and consistency of the power supply. It will also ensure that utility customers will have an easy-to-use and transparent interface, additional options, including green power, and the ability to save money by shifting their loads from peak times to off-peak hours. Nevertheless, to benefit from the SG on both individual and national levels, consumers must be aware of new technologies and support their utilities[31].

Industry 4.0 technologies and electrical industry

Industrial Internet of Things (IIoT) sensors can be used by electric companies to collect behavioral data about their assets. Machine learning (ML) algorithms and big data techniques can then be used to analyze this information along with the data acquired from the rest of the power network to predict problems and assist operations managers in determining when to maintain or replace a network asset. Knowing when to perform equipment maintenance increases the equipment's lifespan and reduces the number of truck rolls, the numbers of field personnel deployed, and the material stock, thus contributing to financial savings. Electric companies are familiar with use of sensing equipment to monitor their assets and have used sensors in their operations for many years. These sensors are used to monitor a variety of parameters, including load, voltage, phase, temperature, and oil viscosity, and they also give Supervisory Control and Data Acquisition (SCADA) system operators advance notice of equipment failure. However, there are two main distinctions between the IIoT devices suggested by Industry 4.0 and the existing sensing and actuating devices that are present in the power grid[32].

First, IIoT devices are much simpler to deploy in larger quantities in any piece of equipment or at any point in the network because of their smaller sizes, lower power requirements, and lower costs when compared with the current devices. IIoT sensors represent the best way to gather the data required for predictive maintenance plans for older assets and for areas in the network that were not previously monitored because most legacy equipment does not contain embedded sensing devices[33].

The second distinction is that the data from the sensors are now delivered using the Internet protocol rather than through private area networks (PANs) or local area networks (LANs). This quality is essential for rapid and economical deployment of these devices across the entire power grid. It has been predicted that the investment required to upgrade an existing communication network will be at least 60% of its initial cost to compensate for the number of sensors and the amount of data required for an application on this scale. By relying on Internet service providers (ISPs) for management of the communications and utilities, the enormous costs associated with the development, upgrading, and maintenance of private communication networks are shifted to an outside company who have a core competency of communications and can thus provide better service at lower cost[34,35].

Therefore, when moving onto predictive maintenance plans, electricity providers have the best available options because of emerging technologies such as IIoT and ML. A typical conceptual framework for enabling predictive maintenance in the electric industry via use of Industry 4.0 technologies is depicted in Figure 4.

Sustainable development goals for sustainable energy & industrial development

The 2030 Agenda, which is the main document intended to direct global efforts in sustainable development until 2030, was adopted at the UN Sustainable Development Summit in September 2015[36]. The agenda lists 169 additional specific targets in essential development areas, including poverty, water, energy, education, gender equality, economy, biodiversity, climate action, and many others, in addition to 17 goals that are known as the Sustainable Development Goals [Table 2]. More specifically, with regard to SG development, the following SDGs, and 7, 9, and 13 in particular, are relevant.

A detailed overview of the Smart Grid

The introduction of the SG signals the beginning of a new era of energy industry dependability, availability, and efficiency, which will be beneficial for both the economy and the environment. Several benefits will follow the creation and implementation of the SG[37], and one of these benefits is more effective electrical power distribution, which is made possible by using algorithmic approaches that consider current and future demand along with energy production and consumption. Energy providers will be better able to track and predict grid malfunctions and act rapidly as a result of their close monitoring of the grid components, thus minimizing power disruptions (e.g., power outages). The cost of power for the consumers can then be reduced as a result of the reduced numbers of operations and management expenses required for the utilities. Additionally, better energy management and distribution among the grid users can reduce peak demand, thus enabling energy providers to lower electricity prices further. In addition to the benefits listed above, the SG encourages integration of extensive renewable energy systems (e.g., solar, wind, and hydrogen resources). When the IoT is integrated, it becomes essential to integrate renewable energy systems for two reasons. Distributed power generation comes first (i.e., decentralized power generation). Second, because customers contribute actively to the development of power consumption plans, they are more effectively integrated into and involved in the power distribution process. Finally, one critical issue that will require careful design and implementation is security against cyberattacks. To manage cyberattacks against safety-critical systems, engineers can develop and implement security frameworks with the aid of an SG. Based on the authors' recommendations in reference, the DO-178B aviation standard may be helpful[38].

Table 2. Relevance of SDGs for sustainable energy and digital industrial development[23]

SDG	Description
SDG 7. Affordable & clean energy	SDG 7 encourages the use of clean, affordable energy. By 2030, it wants to make sure that everyone has access to modern, sustainable, affordable energy. This entails significantly raising the proportion of renewable energy sources in the world's energy mix as well as doubling the rate of energy efficiency growth everywhere. With a focus on least developed nations, small island developing states, and landlocked developing nations, SDG 7 specifically aims to develop infrastructure and sustainable energy services for all in developing countries
SDG 9. Industry innovation & infrastructure	SDG 9 is concerned with business, innovation, and infrastructure. It aims to create robust infrastructures, advance inclusive and sustainable industrialization, and encourage innovation. The promotion of inclusive and sustainable industrialization, as well as increasing the share of manufacturing employment and the proportion of manufacturing value added to the gross domestic product, are specifically highlighted as goals under SDG 9. A specific goal of SDG 9 is to increase access to Information Communication Technologies (ICTs) and provide universal, accessible, and affordable Internet access to the least developed nations by 2020
SDG 13. Climate action	SDG 13 is focused on addressing climate change, including stepping up efforts to both mitigate it and adapt to its effects. The Paris Agreement, which went into effect on 4 November 2016 and represents a significant turning point for international efforts to mitigate and adapt to climate change, is closely related to the implementation of SDG 13

SDG: Sustainable development goal.

Industrial product service system

Europe is the region that has the highest energy consumption among manufacturers, accounting for approximately 25% of global energy consumption[39]. This category includes two different business types: small and medium-sized enterprises (SMEs) and large enterprises, with SMEs making up 99.8% of all businesses in Europe[40]. To satisfy customer demands and requirements while also increasing product value, manufacturers have recently been moving away from pure manufacturing via mass production toward a more flexible and personalized production approach for their customers. The evolution of manufacturer servitization is strongly correlated with the IPSS model, which is a hybrid dynamic system that combines the physical products and services of a single company[41]. The following two factors have had an impact on successful adoption and use of IPSSs:

1. The long-term relationship between the supplier and the customers, which is essential because the services rely on two-way interactions between the customers and the supplier; and

2. the ICT that will support appropriate use of the available services[42].

Digital twin of Smart Grid

With a potential market size of $15 billion by 2023, the Digital twin (DT) was first used by Grieves (2015)[43]. The DT has been rated strategically as one of the top ten technologies of 2018 (subject to predictions on future research trends)[44]. The DT, as one of the technological pillars of Industry 4.0, is a virtual representation of a valuable or physical asset, e.g., a service, product, or machine, with models that can alter behavior using real-time data and analytics supported by visualization tools and human-machine interfaces linked to the condition of the monitored object (e.g., a machine)[45,46].

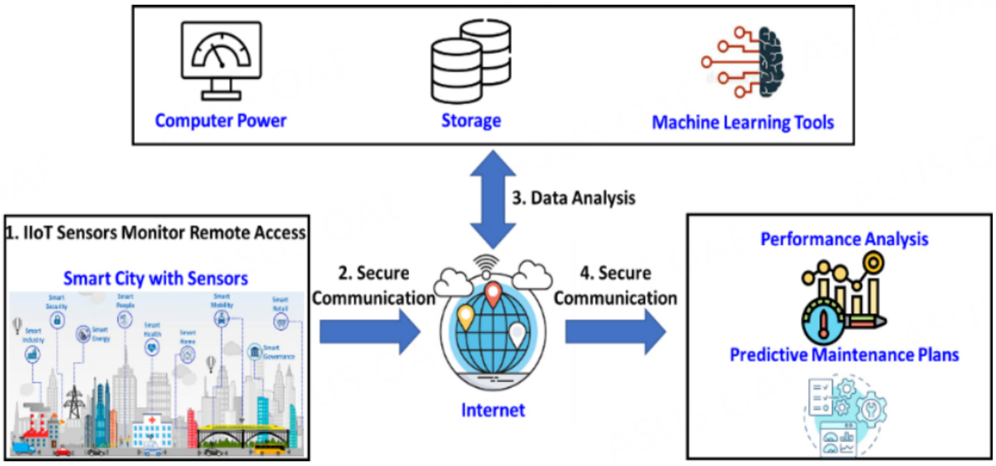

Figure 4. Migration of Industry 4.0 digital technologies to Energy 5.0 to enable predictive maintenance in the electric power industry.

With regard to the existing research, the authors in created a DT for real-time analysis of complex energy systems by simulating the grid states and then assessing the grid's effectiveness using ML algorithms[47]. A DT-based platform for smart city energy management has also been presented in the literature[48]. To benchmark a building's energy efficiency, smart meters are used to gather asset data that is then fed into DT virtual building models. Frameworks for energy demand management based on DTs have also been presented and discussed in the literature[49,50].

The literature investigation indicates that Industry 4.0 has greatly improved advanced simulation technologies and techniques such as DTs. Additionally, DTs are being incorporated into power distribution grids, which will make it easier to manage and regulate the energy supply network[51].

IPSS business models of the energy sector

Modern society and the economy are dependent on energy. Much of the current industrial sustainability agenda is defined using eco-initiatives, eco-innovations, and eco-efficiency. Decarbonization, increased decentralization, and increased digitalization of energy systems are driving the current rapid changes in the energy sector. Larger consumers such as manufacturing firms are also involved in this effort, which is intended to create more sustainable energy production and consumption systems through implementation of service-oriented business models[52]. Energy providers are altering their IPSS business models to add value to their offerings and increase their competitiveness and sustainability[53]. IPSSs are business models for reliable product and service delivery that allow for cooperative product and service deployment and consumption. However, PSSs have now been integrated into a wide range of scientific disciplines, including business management, ICT, and manufacturing. Energy companies use cloud systems, IoT, and big data analytics to combine their centralized and distributed energy systems into a more complex system. To maintain the high fidelity of constant energy supply while ensuring that the electricity supply remains competitive and affordable, energy sales companies (ESCs) must also become more digitalized. The manufacturing sector (demand) and the energy sector (supply) must therefore work together more closely. Additionally, creative approaches will be required to adapt the electricity market to distributed energy generation while also enabling the industrial sector to switch to energy-efficient manufacturing. The main goals are to place the consumers at the center of the energy system and to ensure that they can then take advantage of the cutting-edge energy services that are available.

Business models address how an organization defines its competitive strategy through the design of the goods or services that it provides to its market, how it sets its prices, how much it costs to produce its goods or services, how it sets itself apart from rival organizations through its value proposition, and how it connects its value chain to those of other organizations to form a value network[54].

The history of PSSs, the current state-of-the-art, and potential directions for future PSS research were all presented well by Meier *et al.*[55]. The authors also stated that the market proposition, customer requirements, and environmental impact are major defining factors. Reduced environmental impact, differentiation, attainment of competence, and production efficiency are some of the main advantages of PSS adoption. The PSS value proposition strategy is regarded as one of the innovations that will be required to advance society toward more sustainable futures as a result of extensive research[56].

Production scheduling in the energy sector

There is growing interest in application of manufacturing scheduling as a way to reduce energy costs. One important but difficult situation is the case of scheduling of an industrial facility that is subject to real-time electricity pricing[57]. The manufacturing sector faces new challenges that these contemporary products and systems are unable to address successfully[58]. Energy-efficiency techniques and services that regulate electricity demand and optimize power consumption have thus been proposed to meet these challenges. To change the amount and/or timing of the energy consumption, industrial energy demand management (EDM) involves systematic actions being taken at the interface between the ESC and the industrial consumer[59].

On the industrial consumer's side, the EDM activities include responses to energy price signals and production adjustments that result in energy demand flexibility (EDF). The advantages of EDF include lower power consumption costs and greater room for intermittent renewable energy sources. Energy demand response (EDR) represents shifting of energy consumption to a different point in time or to different resources, in contrast to energy efficiency, which is intended to reduce overall energy consumption[60]. Explicit and implicit schemes are the two main complementary approaches to EDR. In the first scheme, customers are rewarded specifically for their flexibility (e.g., free consultancy). An actual energy cost reduction is provided in the second scenario. Effective scheduling tools are essential for industrial EDM, where complex manufacturing processes are involved, because of the strong correlation between energy availability and energy price. Planning and running energy-efficient and energy-demand-flexible production systems necessitates in-depth understanding of the energy consumption behavior of the system components, the energy consumption of the production processes, and techniques to evaluate system design alternatives[61]. In addition, a personalized-real time pricing (P-RTP) system architecture structure has been proposed[62]. Only users who initiate the P-RTP would receive an equal distribution of the energy cost savings. As a result, the proposed system reduces energy costs significantly without sacrificing the welfare of the electricity users. It is concluded that all the approaches mentioned above have a common goal: the generation of flexible, adaptable, and practical production scheduling. The electricity grid typically provides the energy required to run industrial machinery. However, the ways in which the machinery uses materials and energy can be wasteful[63]. Studies have therefore been conducted on energy-supply-oriented production planning[64]. Similarly, Biel and Glock[65] presented a literature review of decision support models for application to energy-efficient production planning and described how taking energy consumption into account during production planning can lead to more energy-efficient production processes. It is evident from the available literature that integrated approaches would be advantageous for all parties involved[66].

Consumer vs. prosumer

Conventional electrical grids are based on functional integration of the energy producers and consumers. However, the new characteristics of SGs offer the possibility of development of sustainable, economical, and efficient energy supplies to the customers[67]. This model thus encourages the consumers to engage in the grid's operation and management, and to contribute to the energy distribution process by producing, selling, or sharing through the grid. This means that they represent important components for the grid's functionality and transform into "prosumers", who optimize their economic-energy decisions based on their individual energy requirements[68]. A prosumer is an energy user who produces energy from renewable sources such as photovoltaic arrays or wind turbines, rather than counting on the power plant's supply alone, and shares this energy with the grid's other consumers. Therefore, a prosumer can be recognized as a stakeholder who uses electrical power and also contributes to the grid by generating power at a certain point in time. The grid follows the bidirectional data flow and energy flows between the stakeholders, analysis of which may provide important information for the electrical grid function and for energy distribution optimization[69]. Overall, prosumers, smart information, bidirectional communications, and advanced analytics are regarded as the basic components of the SG. The main characteristics of the prosumer's profile can be summarized as (i) energy production; (ii) energy storage and sharing; (iii) energy consumption; and (iv) peer-to-peer transactions.

However, prosumers are differentiated from consumers because they are considered to be an advanced version of the latter and provide significant advantages for both their energy management and the entire grid. Table 3 highlights the main differences between the two energy client profiles described above.

Smart Grid 1.0 and Smart Grid 2.0

In the literature, two generations of SGs have been proposed. Both generations share the same goals, i.e., improving power distribution architectures to support real-time operation and thus achieve greater resilience and adaptability for an SG within a smart city environment. However, the two generations are differentiated by the fact that Smart Grid 1.0 mainly focused on technological evolution of the existing infrastructure based on the recent technological advances from both Industry 4.0 and digital technologies, including ICT. In contrast, Smart Grid 2.0 is mainly focused on the involvement of the customers in a variety of SG operations, including power generation, storage, distribution, and marketing. Therefore, as part of the framework for Smart Grid 2.0, the use of a peer-to-peer (P2P) architecture is imperative. Furthermore, Smart Grid 2.0 also focuses on distribution automation (DA) and an AMI. The DA can provide a self-healing, digitally controlled network to ensure reliable electric power delivery. The concept also encompasses demand response, smart home automation, distributed generation, distributed storage, and automated control. It is stressed that Smart Grid 2.0 is regarded as the energy Internet (EI) from an information technology perspective[70]. Although the current electrical grid is being transformed into an SG, open energy or EI is rapidly gaining popularity. An EI is an example of this trend, which is also being referred to as the Smart Grid 2.0 era[71].

Consequently, the role of the intermediaries is eliminated. Furthermore, the second generation of SGs supports improved data acquisition and cybersecurity mechanisms to ease the development of more robust and precise decision-making tools. In Table 4, the key differences between Smart Grid 1.0 and Smart Grid 2.0 have been compiled and categorized based on their domain of interest.

Blockchain in Smart Grid operation

Among the challenges listed in the Introduction, it has also been proposed that the integration of blockchain technology, because of its advantages and its development during Industry 4.0, will enable

Table 3. Consumer *vs.* prosumer energy profiles

Consumer	Prosumer
Consumes energy	Consumes, produces, shares, stores, and sells energy
Has limited access to static data	Has access to real-time data
Deploys non-renewable energy sources	Deploys renewable energy sources
Physical presence is required for device utilization	Remote utilization of applications and services
Increased vulnerability to grid malfunctions and instabilities	Safer against grid malfunctions and instabilities
Limited to non-existent electricity cost management	Increased insight in energy patterns and support for self-management of consumption
Limited to non-existent environmental consciousness	Increased environmental consciousness

Table 4. Smart Grid 1.0 *vs.* Smart Grid 2.0 as derived from the literature[72-74]

Domain	Smart Grid 1.0	Smart Grid 2.0
Energy production	Centralized or distributed production including renewable energy and battery storage	
Energy transmission	Routing to geographically diverse locations	Routing to geographically diverse locations, integrated with asset management and fault prognosis and recovery
Energy distribution	Limited types of energy resources at the distribution level, including prosumer energy production and storage	Integration of heterogeneous energy sources, increased grid resilience and efficient asset management for distribution networks
Energy consumption	Self-management of energy consumption patterns utilizing smart meter data	Autonomous demand response initiatives for sustainable energy consumption patterns
Marketing	Intermediaries heavily involved	Self-energy generation and peer-2-peer trading are promoted (democratization of energy)
Operations	Energy trading and information flow between the providers and the customers	Energy trading and real-time information exchange over the Internet
Information transfer	Domains are connected to power and communication networks, whereas market and operations operate via two-way communication channels	The Multi-layer architecture enables peer-2-peer communication over the Internet Protocol

engineers to provide additional functionalities in the SG. Therefore, in this Section, the challenges and opportunities of blockchain technology are discussed, along with the steps required for implementation. Briefly, blockchain is based on the creation and constant updating of a distributed ledger following a common consensus policy. Essentially, the adoption of such a technology will make it easier for multiple stakeholders within a network (independently of the network's size) to maintain a common track of the exchanges that take place within the network. The process above can easily be paralleled and implemented within an SG [Figure 5].

In the work of Dehalwar *et al.*, the authors proposed a methodology for integration of distributed ledger technologies and techniques in an attempt to improve the management of an SG by building a trust management policy[75]. Similarly, Guo *et al.* also investigated the topic of blockchain within the SG environment[76]. Among the key findings of this literature review, the authors stated that this technology will enable additional managerial functionalities by focusing on the decentralization of SG management, and it may be extended beyond infrastructures to be used in electric vehicles as well[77]. Figure 4 presents a generalized roadmap for a blockchain SG.

One of the most important aspects of blockchain technology is smart contracts, which can enable energy providers to encode market rules and by extension to ease automation of the pricing process at the individual prosumer and microgeneration levels[78]. As a result, with the adoption of a smart contract policy,

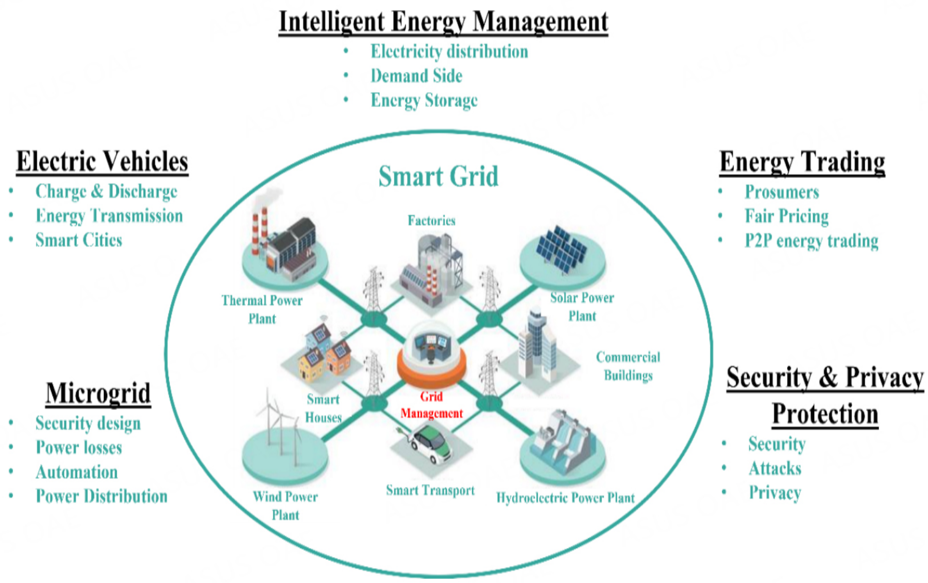

Figure 5. Roadmap for blockchain technology integration within the Energy 5.0 framework.

complex power distribution networks and their modules can be segmented with respect to direct participants to promote independent operation while also maintaining supervision and coordination without the need for third-party involvement.

FRAMEWORKS AND CASE STUDIES TOWARD ENERGY 5.0

Integrating AI into the renewable energy domain

The SG concept is one of the most challenging aspects of the realization of the smart cities of the future. In general, AI has proven to be a useful tool for imitation of human intelligence in machines and computers. Similarly, AI is useful in the energy sector, enabling processing of the vast amounts of data produced within an SG, and also coping with the grid's increasing complexity. In particular, in the renewable energy (RE) sector, AI provides better monitoring, operation, maintenance, and storage of the electrical energy produced. Consequently, the contributions of AI to the RE sector can be summarized in the following, and are illustrated in Figure 6[79,80]:

- Energy generation while considering supply volatility
- Grid stability and reliability
- Grid demand and weather forecasting
- Grid demand-side management
- Energy storage operations
- Market design and management

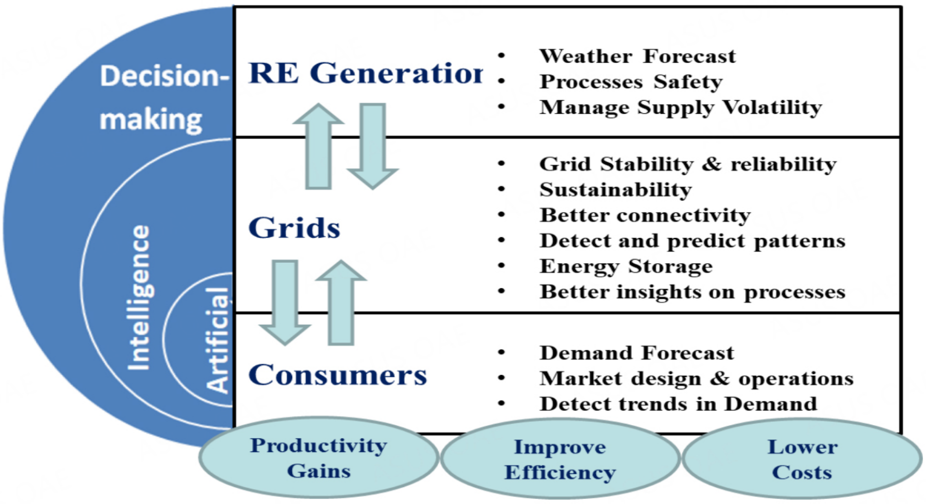

Figure 6. Artificial intelligence (AI) applications in smart grids. RE: Renewable energy.

The key applications in RE systems are summarized as follows:

- Smart matching of supply and demand[81]
- Intelligent storage[82]
- Centralized control systems[83]
- Smart microgrids[84]

Overview of AI techniques for the energy 5.0 distributed model

Future power systems can support the incorporation of renewable energy resources (RERs) by using SG technologies. With high penetration of distributed generation into power systems and advancements in ICT associated with customer data, the electric power grid can be transformed[85]. AI-enabled smart energy markets can make it simpler to establish effective policy incentives and allow both consumers and utility companies to make decisions about their own consumption and generation in a way that reduces CO_2 emissions. Designing automation technologies for heterogeneous devices that can learn to adjust their consumption *vs.* pricing signals with user constraints, creating a means of communication between humans and the controllers, and creating simulation and prediction tools for consumers are among the challenges that face AI in electrical power systems.

Intelligent tools and methods are required to manage the system appropriately and to make timely choices as the energy sector becomes more complex. The problems of classification, forecasting, networking, optimization, and control methods can be solved using artificial neural networks (ANNs), reinforcement learning (RL), genetic algorithms (GAs), and multi-agent systems[86]. Because of the lack of sufficiently sophisticated automatically controlled resources, many system operations are still conducted manually or with only the most basic automation. However, introduction of AI into the grid system would lead to breakthroughs and provide new directions for development of the electrical grid. Figure 7 illustrates the entire distributed SG concept with AI methods and the use of techniques to provide cost savings and perform optimization. To optimize the controllable loads, Atef and Eltawil[87] described a GA for

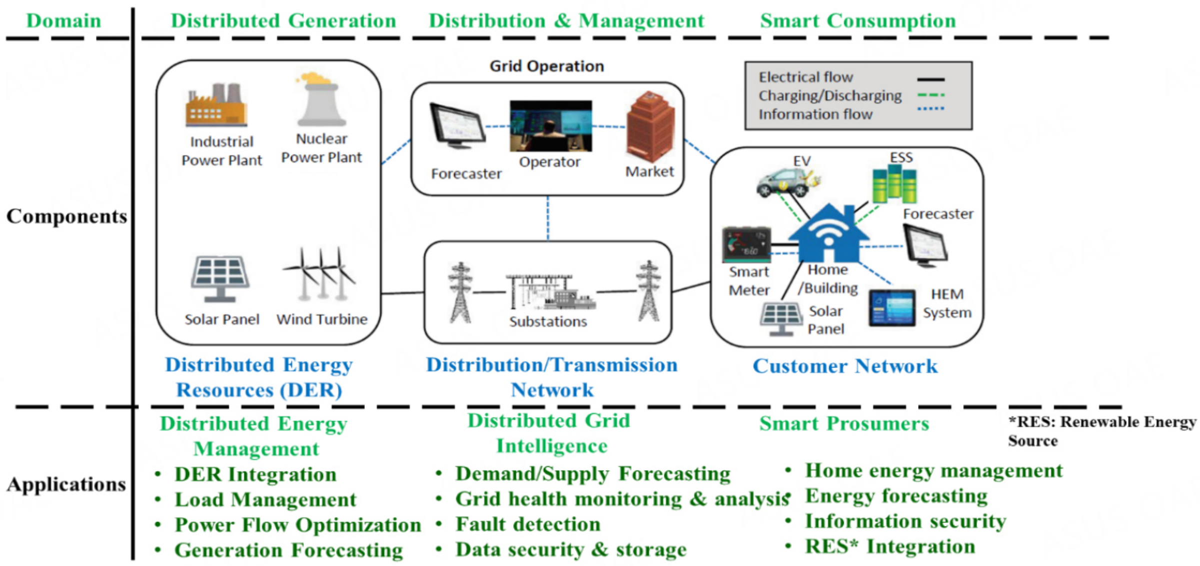

Figure 7. Architecture of the Energy 5.0 distributed model.

management of standalone microgrids (MGs). AI techniques are now providing considerably more effective and powerful ways to deal with the limitations of conventional grid systems as a result of advancements in computer power and the ready availability of data storage. Additionally, several security issues have arisen as a result of the application of distributed computing algorithms in SGs. Threats including physical attacks and cyberattacks can result in infrastructure failure, privacy breaches, service disruption, and denial of service (DoS)[88].

Energy management system

As a result of the availability of sufficient customer data, computing power, and potential training algorithms, AI has now developed to the point where it can even predict customer electricity prices in complex environments. A comparative analysis of such intelligent schemes that concentrated on deep learning (DL) and support vector regression (SVR) has been presented in the literature[89]. In addition, demand response (DR) represents the deviation of the end users' normal electricity consumption patterns from those suggested by the utility, or the use of financial incentives to prevent the reliability of the power system being jeopardized as a result of peak demand[90]. Recently, several research works available in the online literature have concentrated on the use of AI techniques to predict energy demand patterns[91,92]. To overcome the uncertainty in future electricity prices, Al-Fuqaha *et al*. proposed an hour-ahead DR algorithm that used RL and an ANN and also took user comfort and consumption behavior into account[93]. The various energy management system types for use in SGs with the enabling techniques discussed in this paper are summarized in Figure 8.

Integration of the Smart Grid with other smart elements

It has become challenging for grids to control the demand for electricity for both household and industrial uses as a result of rapid population growth and the expansion of various industries. Short circuits and transformer failures are two issues caused by the increased demand for electricity at specific times of the day. To deliver electricity effectively, it is necessary to predict the customer consumption patterns to address the problems with traditional grids for electricity transmission. To that end, the concept of the SG has been introduced. An SG can transmit electricity based on the anticipated demand by using its intelligence to predict electricity demand. An SG can address many of the issues faced by traditional grids, including

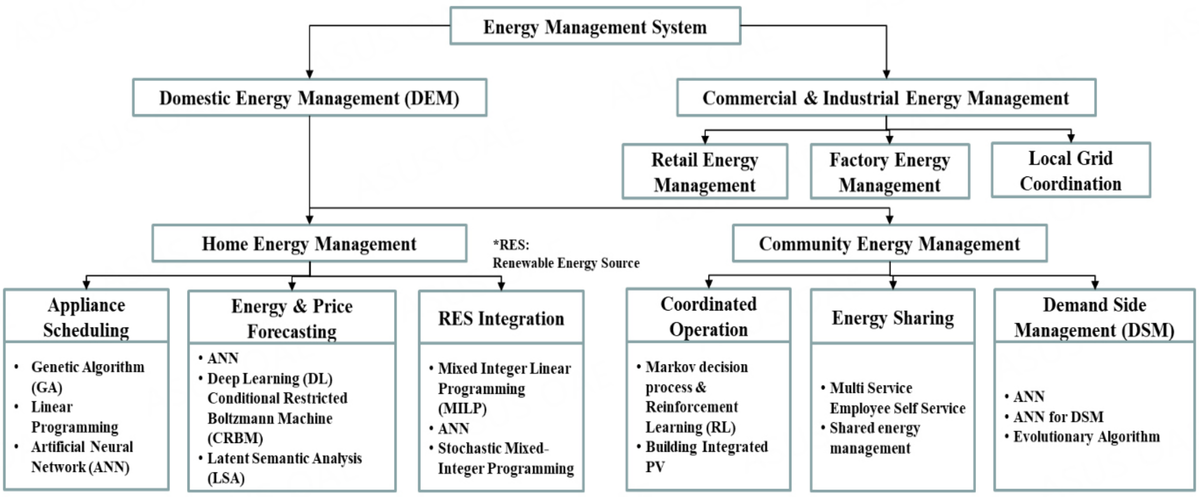

Figure 8. Taxonomy of AI techniques for each management sector in smart energy.

demand forecasting, reduction of power consumption, and reduction of the risks of short circuits, thus preventing the loss of lives and property[94]. The true potential of SGs has been unlocked by technological advancements such as the IoT[95], fifth generation wireless networks and beyond (5G)[96], big data analytics[97], and ML[98].

As shown in Figure 9, an SG has multiple stakeholders and can be connected to several other smart areas, including smart cities, buildings, vehicles, and power plants.

Energy trade market effect on production scheduling: an IPSS approach

Hardware, software, and services can be integrated into a distribution platform known as "energy-as-a-service" (EaaS). Such a solution should promote use of decentralized supply sources and renewable energy, provide demand control and energy storage technologies, and maximize the equilibrium between supply and demand[99,100]. This business model can also be applied to the SG. Customers can use the electricity and also generate, distribute, and trade resources with other consumers thanks to the SG, which enables bilateral communication and data transfer between electricity customers and the power grid. Cost and capacity are the two factors that define energy production. However, a rise in the price is often seen when the demand exceeds certain capacity thresholds. A trade-off between capacity, price, and consumer demand-satisfaction results from taking rising worldwide demand into account and using the available capacity in the best possible way at the lowest possible cost. As a result, energy demand consumption optimization, or smart usage, becomes crucial. Additionally, energy utilities are altering their business models by providing clients with energy-related services via energy service contracts, and thus raising the value provided. The business model used in this approach, which is based on the current business-to-business (B2B) strategy, is the provision of an energy-oriented IPSS[101]. Provision of energy can be regarded as a product service, with the contract acting as both a tangible good and a collection of intangible services. Through this collaboration, the energy provider and the customers gain mutually beneficial outcomes[102]. To that end, a system architecture proposed in the literature is depicted in Figure 10[103].

In this architecture, an ESC has a particular pricing strategy with distinct tariffs and is seeking to build an ecosystem to offer dynamic energy pricing. An EDM service, which is fed with the "production-consumption profiles" of each individual industry within the ecosystem, is necessary to accomplish that

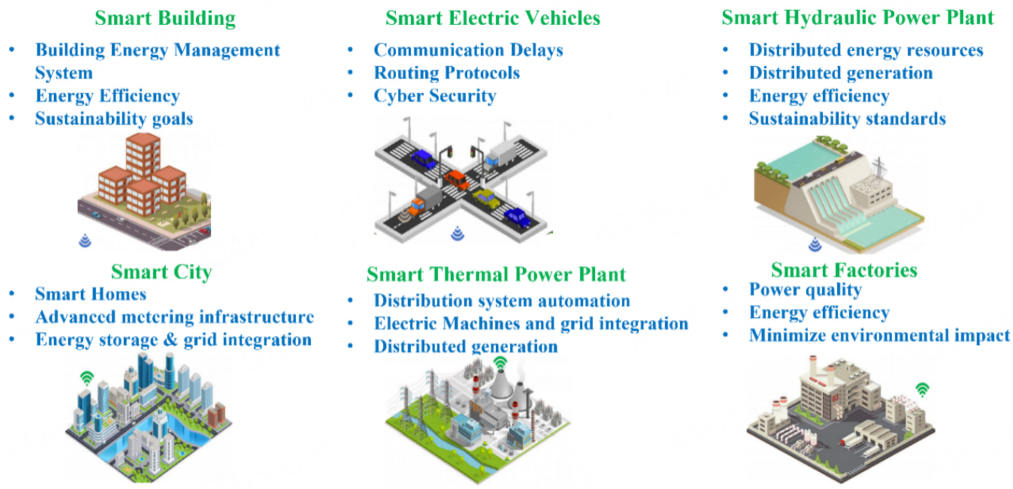

Figure 9. Energy 5.0 as part of a smart and intelligent society.

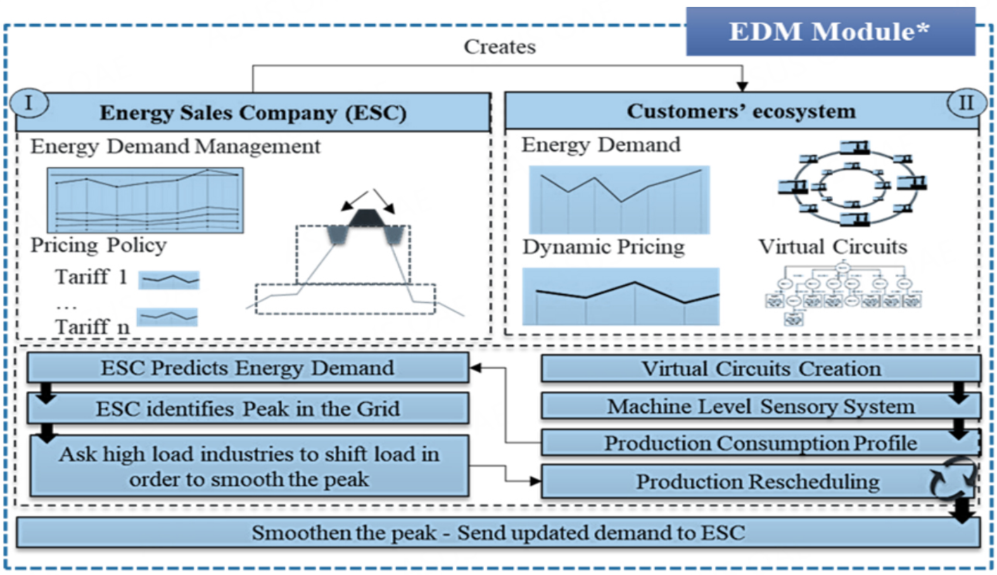

Figure 10. Proposed IPSS architecture for intelligent energy management[104]. EDM: Energy demand management; ESC: energy sales company.

aim. Visualization and monitoring of the manufacturers' infrastructures, or the virtual circuit, through a wireless sensor network (WSN) that allows the EDM to know when, where, and why energy is consumed represents an innovation point of the proposed methodology. The production equipment is equipped with wireless data acquisition devices (DAQs) that transmit data to a cloud server. This part of the service's primary function aims to offer insights into the energy consumption of the machines and to connect that information to the energy consumption profile of the corresponding customer. As a result, data from the machines can be used to predict future energy demand, thus enabling identification of energy grid peaks. An alert is sent then to a specific group of high load industries as soon as a peak has been identified, requesting that they shift their load to smooth the estimated peak. However, if a company disregards the alert, they will be charged according to a high demand period tariff until they follow the suggested instructions for the method. As a result, an adaptive scheduling algorithm is activated on the manufacturer's

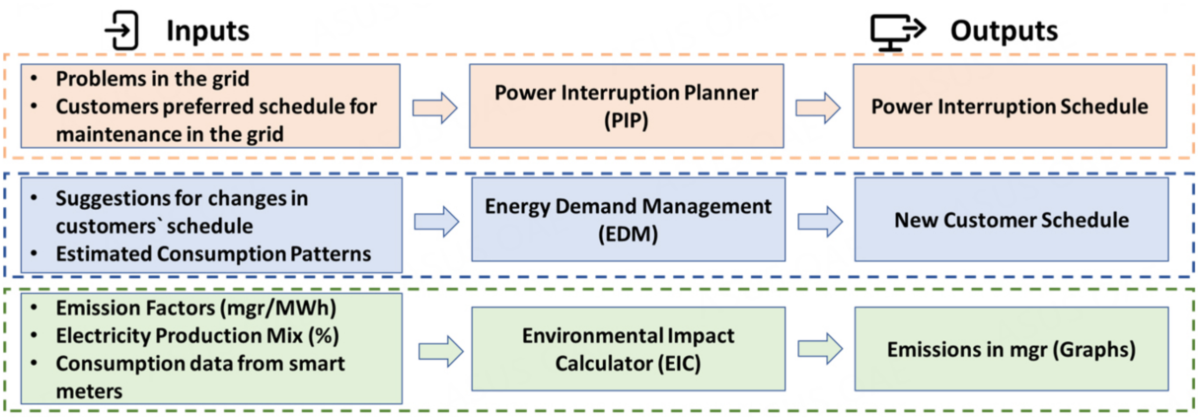

Figure 11. Energy services framework system architecture.

side to guarantee grid stability and reduce the necessary energy consumption during peak demand periods. The data collected from the customers not only helps ESCs produce better predictions of their customer needs and increase the system's efficiency, but it also helps them to cut costs by managing the energy demand directly. The proposed IPSS system architecture shown in Figure 9 summarizes and presents the relevant steps.

A collaborative approach to energy-based offered services

Mocanu *et al.* proposed an IPSS framework for the energy sector to create a smart service-based energy ecosystem, as illustrated in Figure 11[105]. The proposed framework was validated by performing a real-world case study with a European electricity distribution company.

The framework above is based on utilization of energy services that can be used by both the energy suppliers and their customers. The proposed services are as follows: a power outage planner, an energy demand manager, and a calculator for the Environmental Impact (EIC). To enable operation of these services, customers must provide real-time and historical consumption data. The data are gathered from smart meters that have been installed in the customers' facilities. Depending on the embedded sensors, e.g., in the lighting virtual circuit, the cooling virtual circuit, or a machine virtual circuit, all the customer facilities are discretized into virtual circuits that represent some of the factory structures. Every customer will have a smart meter that measures their consumption in kWh and this meter is installed at the enterprise level and on every virtual circuit. The virtual circuit meters take their measurements in real time, while the enterprise lever meters take measurements every 15 min. The virtual circuit is a branch of the customer passport for each customer. The architecture is divided in two flows: one that is based on the information about electricity use from the smart meters, and another that is based on information about the grid power outages obtained from interactions between the suppliers and the customers. To generate an image of each customer's environmental impact, the EIC service converts each customer's consumption into emissions. Diagrams that show the quantities of the emissions from each customer can also be generated by this service. The supplier then notifies the customers of any power outages caused by grid issues through the power interruption planner and schedules scheduled maintenance in conjunction with the customers who will be affected. Every customer provides an estimate of how much energy will be used by each virtual circuit. When a submission is made, the supplier then verifies that the combined consumption of all customers in each individual grid segment is less than the peak level. If it is not, the supplier then alerts the customers of that section, suggests a schedule change, and then asks them to recheck to see if the power consumption has fallen below the peak level. If so, the supplier does not offer any additional

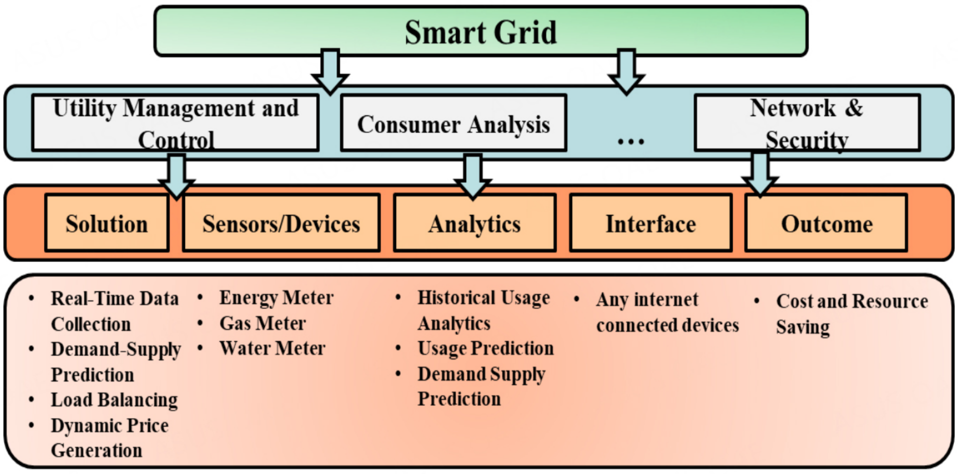

Figure 12. ML and IoT integration for utility management and control in a smart grid.

recommendations. The third service, which is called EDM, is composed of these actions. The web-based platform on which all services are built relies on communication between the ESC and the energy consumer-industrial SME customer. Because the services are dependent on customer input, ongoing customer involvement, and the permission to install meters in their facilities, customer cooperation is essential. The electrical system of the energy client, the installed sensor systems, and an IT system infrastructure that gathers the data from the sensor systems comprise the energy IPSS.

Smart Grid based on IoT services

According to Gartner, 20.8 billion connected devices were in use worldwide in 2020 and this number is predicted to hit approximately 29 billion by the end of 2022, with approximately 18 billion of these devices being related to the IoT[105]. The SG, as a major consumer of autonomous connected devices, not only uses millions of IoT devices but also processes enormous amounts of data to improve its understanding of the SG network. On a global scale, approximately 23 million smart meters were installed and used in 2019 and this number is projected to reach 188 million by 2025, representing a compound annual growth rate (CAGR) of 6.6% during the forecast period. To increase the effectiveness of power networks, SGs are being implemented worldwide[106]. IoT and big data analytics are essential components of the SG. Therefore, it is imperative to integrate ML with IoT sensors and devices at various levels in the SG to enable analysis of the entire ecosystem and optimization of the important parameters, e.g., cost and energy resource balance, and ultimately to form an intelligent SG, as shown in Figure 12.

Application of the IoT in the SG may fall into one or more of the following categories:

1. IoT is applied to use different IoT smart devices for monitoring of the equipment status

2. IoT is applied to collect information from equipment with the support of its linked IoT smart sensors and devices through a diverse range of communication tools

3. IoT is applied to supervise the SG across the application interfaces

RESEARCH CHALLENGES AND SOLUTIONS

The major issues that traditional electric grids and the conventional method for electricity distribution have

Table 5. Research challenges and solutions in the smart grid field

Challenge	Application	Solution	Advantages	Reference
Dynamic demand pricing and consumer energy consumption scheduling	Reinforcement learning (RL) based multiagent learning algorithm in microgrids	The consumer and service provider both learn the strategy without having any prior knowledge of the microgrid's dynamics	improved pricing options for the service provider and efficient energy consumption planning	[107]
Consumer energy consumption scheduling	Deep learning (DL), RL, convolutional neural networks (CNN), Q-learning and Recurrent neural network (RNN) in consumption scheduling at small commercial and residential buildings	Calculating each appliance's energy usage to address the consumer energy consumption scheduling	Scheduling of consumer energy consumption	[108]
Cyber attacks	RNN and blockchain (hash and short signatures) for energy exchange	During trading, fault-tolerant energy transactions identify intrusions	Energy trading that is secure, fault-tolerant, protects privacy, and has high throughput	[109]
Equipment health monitoring	Wind turbine condition monitoring with DL	Unsupervised learning algorithms are more prevalent than supervised learning algorithm	Effective maintenance	[108]
Electric vehicle (EV) charging in SG	DNN for charging of EVs	Makes real-time charging decisions based on historical data on connections	Reduced EV charging cost	[109]
Load forecast in SGs	ANN, CNN, stochastic models for building energy prediction	Energy consumption prediction taking into account many dynamically changing parameters	Accurate energy load prediction	[110]

faced have seen significant improvement as a result of the integration of SG technology. For handling of high-dimensional data and ensuring efficiency in the data transactions throughout the energy supply chain, SG technology uses ML techniques, and more specifically, the subset of DL approaches. Additionally, through skillful control of consumer power consumption and by enabling energy-sharing facilities, SG technology places a strong emphasis on consumer satisfaction, thus transforming the consumer into a prosumer (producer and consumer). The SG still has some unresolved demand response (DR) management problems and upcoming difficulties that must be resolved for improvement of future electricity requirements. This section discusses the various research challenges, the current problems, and future directions for SG technology. Some of the most prevalent challenges and the corresponding technical solutions are summarized in Table 5.

The SG 2.0 grid architecture is composed of four layers, as illustrated in Figure 13, which also shows the fundamental elements of each layer. Specifically, the SG2.0 architecture comprises (i) a physical component layer; (ii) a communication and control layer; (iii) an application layer; and (iv) a data analysis layer.

The physical component layer embraces the sensory devices that enable data collection for real-time monitoring and decision-making, including IoT devices [e.g., smart meters, smart loads, smart sensors, phasor measurement units (PMUs), remote terminal units (RTUs), current transformers (CTs), and voltage transformers (VTs)].

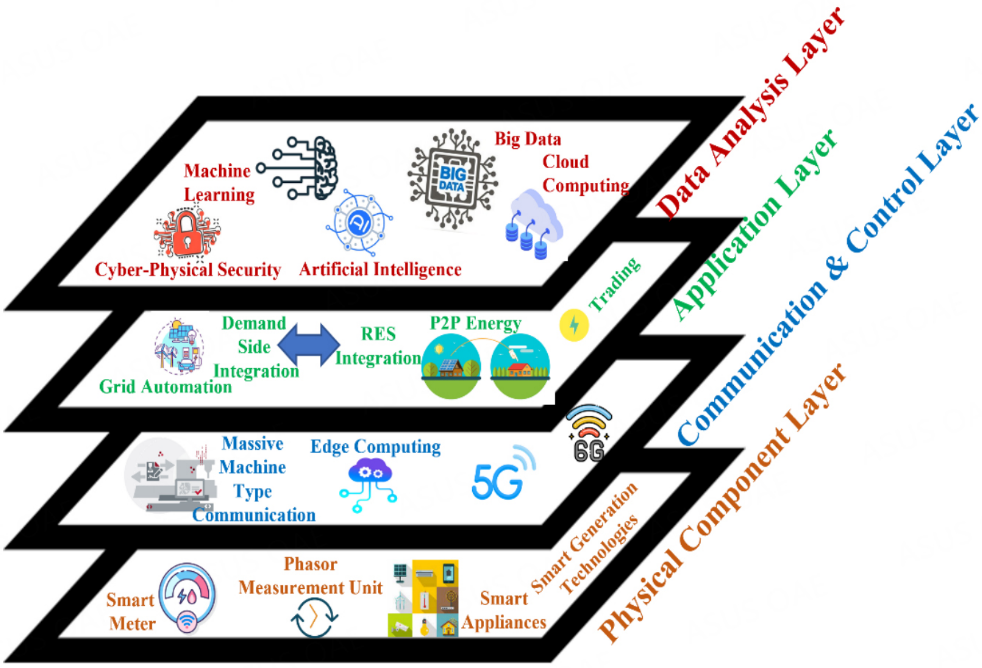

Figure 13. Layers of Smart Grid 2.0 or Energy 5.0.

Shared data and information can be used to perform real-time monitoring and control of Smart Grid 2.0 thanks to the communication infrastructure and Internet-based protocols[110]. With a low level of assistance from a third-party service provider, the communication and control layer enables fast, dependable, and in-the-moment communication between devices (machine-to-machine, or M2M).

The application layer of the future Smart Grid 2.0 comprises the services related to electric vehicles (EVs) for trading with charging stations through P2P energy transactions, microgeneration and large-scale power plants that incorporate renewable energy generation, battery storage, and automated, efficient, and dependable transmission/distribution networks[111].

The data analysis layer aids in performing cloud-centric data management, trend analysis, and grid control at an underlying level[112]. The Smart Grid 2.0 infrastructure includes data management, secure data routing, privacy preservation, and dependable storage.

The AMI manages the data that are derived from all the above layers because it collects synchronized smart meter measurements from both consumer and prosumer locations and is connected to the communication network.

LIMITATIONS IN SMART GRIDS TOWARDS ENERGY 5.0

An SG can be realized as a set of technologies that improve both existing (and new) electricity distribution networks by the provision of intelligence, which in turn promotes better usage of the electrical energy and higher distribution efficiency. The application of detection, measurement, and control devices with suitable communication channels to all parties involved in the electricity production, transmission, distribution, and consumption processes makes the intelligent network possible, and allows users, operators, and the automated devices to receive information with regard to the status of the network and to respond dynamically to changes in the condition/status of the grid. Although several benefits with regard to the implementation of SGs are listed below, certain limitations are also emerging[113,114].

Smart Grid benefits

- Increased reliability
- Operational efficiency and optimization of investment
- Network operation and planning
- Variations in the cost of energy
- SGs offer the potential to reduce electricity consumption by 30%
- Increased user responsiveness with personalized consumption
- Intelligent infrastructure technology for global energy distribution that could reduce greenhouse gas emissions from the energy sector

Limitations

- Increased cost caused by the replacement of analog meters with more sophisticated smart meters
- Lack of regulatory standards for SG technology
- Lack of official technology documentation

CONCLUDING REMARKS AND OUTLOOK

In this manuscript, a literature review of the current state of the art in the field of electrical energy generation and distribution has been presented and discussed. As part of this discussion, important concepts such as Energy 4.0, Energy 5.0, and SGs have been described. Among the key findings of the literature investigation, it was evident that the modern societal, academic, and industrial worlds are converging toward the design, development, and implementation of sustainable solutions to reduce environmental pollution and their environmental footprint. More specifically, several government organizations have presented and continue to work on such initiatives, with the focus on long-term and incremental implementation of technologies and techniques that were mainly introduced and developed within the framework of Industry 4.0.

The contribution of the manuscript also extended to detailed discussion of the technical frameworks required for integration of SGs into modern society and industry. These frameworks are based on previous implementations for smart and intelligent energy distribution management systems that were mainly used in the manufacturing domain. These implementations have created information islands that can enable the development of a broader SG by providing additional data. However, given that the frameworks above can be elaborated further, the creation of a wider SG that goes beyond the industrial sector is feasible.

Following consideration of the recent technological advances discussed in the preceding paragraphs along with the opportunities arising in the field, future work will be focused on further expansion of the existing frameworks to allow them to work in collaboration and form an industrial SG. Then, connection of the industrial SG with the academic SG proposed by the authors in a recent research work (not available online to date) will follow, with the aim of expansion of the SG and the functionalities provided to the energy producers.

Furthermore, more experimental tests will be required to combine the energy demands of clients on different tiers, to distribute the electrical energy more efficiently, and wherever possible to minimize the load to the grid and support the use of electrical energy derived from alternative power sources. One of the most important problems faced in the current grids is the lack of a suitable infrastructure to transform them into SGs. In this context, further elaboration of the existing frameworks will be required.

DECLARATIONS

Authors' contributions

Conceptualization, supervision: Mourtzis D

Conceptualization, writing-reviewing and editing, methodology, software: Angelopoulos J

Conceptualization, writing-reviewing and editing, software: Panopoulos N

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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