Intelligent Buildings in Smart Grids

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During the last decade, the smart grid (SG) concept has started to become a reality, mainly thanks to the technical progress achieved in telecommunications, informatics and power electronics, among other domains, leading to an evolution of the traditional electrical grid into an intelligent one. Nowadays, the SG can be seen as a system of smart systems that include cyber and physical parts from different technologies that interact with each other. In this context, intelligent buildings (IBs) constitute a paradigm in which such smart systems are able to guarantee the comfort of residents while ensuring an appropriate tradeoff of energy production and consumption by means of an energy management system (EMS).

Keywords: intelligent building ; cyber-security ; smart grid ; system of systems ; cyber-physical system ; energy management ; communication technologies

1. Introduction

The theoretical concept of the smart grid (SG), proposed several years ago [1][2], has become a reality during the last decade [3], and nowadays is evolving towards new paradigms like the Internet of Energy (IoE) [4][5]. Many research works are currently being conducted in different knowledge areas to implement smart grids, highlighting their multidisciplinary nature. The benefits of SGs are well known, and they have been described in many papers; these include an increase of the overall resilience and efficiency of the electrical grid [6], introduction of renewable power sources, application of demand response and load control mechanisms, and improvement of the energy quality [7], to cite some classic examples. The need for a more flexible, reliable and protected network became evident during the year 2020, and this is still true in 2021, as a result of the impact in energy use caused by the pandemic situation [8]. On the other hand, the recent rise of cyber-physical systems (CPSs) has conferred a novel regard of the SG [9], whose structure and key elements constitute a remarkable paradigm of CPS [10]. Furthermore, SG can be seen as a cyber-physical system of systems (CPSoS), due to the diversity and complexity of its components, whose interoperability must be ensured [11]. The varied interactions among the elements inside the SG must be managed through interdisciplinary and integrated systems engineering approaches [12].

From this perspective, intelligent buildings (IBs) can be viewed as one of the key systems which compose the whole CPSoS that is the smart grid [13]. There are several essential characteristics of an IB that can be cited [14]: integration of a monitoring system to notice its own environment, communication with occupants and with the grid, energy management capability by means of an energy management system (EMS), and self-learning ability to enhance its performance. Some of these abilities are shared with the SG, namely energy management and optimization or operation enhancement, just to name a few. This vision of IB as a subsystem of the SG can additionally be supported, since there are different technologies inherent to the SG that can be also integrated into IBs, enabling the mutual interaction between them [15]:

- Electrical microgrids (MGs) at building level or for groupings of several buildings, allowing flexibility and distributed energy generation [16];
- Virtual power plants, as a part of the SG, which employ smart metering and communication technologies [17].

Special attention must be paid to bidirectional communications, which take advantage of the cyber (software) and physical (hardware) features of the Internet of Things (IoT) [18][19]. In this context, smart meters (SMs), together with wired and wireless communication technologies are the most usual widely adopted solutions [20][21]. In addition, IBs are able to participate in the power grid energy balance, becoming grid-responsive buildings, and taking advantage of the communication network of the SG to ensure an optimal coordination [22]. This interaction of IBs with SGs as a part of them can be extended, reaching a group of buildings and even the overall city, which will become smart, too [23][24]. Since the early stages of smart grid development, it has been clear that reliability would be also a crucial requirement to be guaranteed [25]. Indeed, the application of worldwide communication technologies related to the IoT is one of the main reasons for the security problems that concern the SG. Many different incidents have been reported in the power system in the last several years, with the Stuxnet attack marking a turning point because of its virulence and the severe failures that it caused in different countries [26]. Since then, it has been clear that cyber-security must be guaranteed in intelligent power grids as a tool for increasing their resilience face to cyber-attacks [27], including all the different subsystems of the SG, such as MGs and IBs [28][29].

Taking all these elements into consideration, this paper conducts a survey, from a multidisciplinary point of view, of some of the main security and privacy issues related to IBs as part of the SG, including an overview of building energy management systems (BEMS) and the main communication networks employed to connect IBs to the overall SG. To carry out this survey, the main guideline was to adopt a global and systemic attitude in order to ensure exhaustivity and coherency when studying the different types and levels of security issues. As a consequence, we needed to first study the whole ecosystem in which physical and cyber elements of an IB and an SG can be represented as systems, by exploring the systems engineering domain. Thereafter, we were able to study the identified elements and their interactions by prospecting more detailed topics from different knowledge domains: telecommunications, informatics, electronics, and energy management. The methodology followed in order to carry out this survey then started with a literature review on the previously cited domains. The main criteria applied to this literature review were database, year of publication, and type of publication, prioritizing survey papers published in journals with Impact Factor. The main keywords to select the bibliography were cyber-physical systems, intelligent buildings, building energy management systems, communications, smart metering systems, and cyber-security, always mixed with the term smart grid. Regarding each one of the different sections of the paper, the final validation of the selected references was conducted using a top-down approach, starting from the most general concepts to the most accurate ones: SG and IBs viewed as two systems of systems (SoS) interacting together; presentation of the inherent characteristics of an IB to finally focus on the technical aspects of energy management and communication technologies; and lastly, the cyber-security concerns of communications employed in IBs that contribute to the energy management are detailed according to the OSI model, to better delimitate the proposed solutions.

2. From the Smart Grid to Intelligent Buildings

2.1. The Smart Grid, a System of Systems

As previously mentioned, an SG is an example of a system of systems. The work presented in [30] considers the modern energy SG as an SoS that requires interdisciplinary knowledge to be shared, considering the seven SG domains identified by [31]: bulk generation, transmission, distribution, markets (selling), operations, service provider, and customer. For [32], an SG is composed of independent systems that share goals and act jointly. According to [33], “a system of systems is an assemblage of components which individually may be regarded as systems and which possesses two additional properties: operational independence of the components and managerial independence of the components”. This introduces a very interesting perspective of the SG as an SoS, composed of a set of technological subsystems, a control and set of management subsystems, and a set of communication subsystems [34]. Moreover, this definition is enhanced by [35], which defines an SG as a cyber-physical system, including a description of the “cyber infrastructure” (communications, control, measurement, i.e., control/management and communication set) and the “physical infrastructure” (i.e., the power network infrastructure [10]: power plant, transmission system, and distribution system, i.e., technological set + end users/customer premises), as shown in Figure 1.

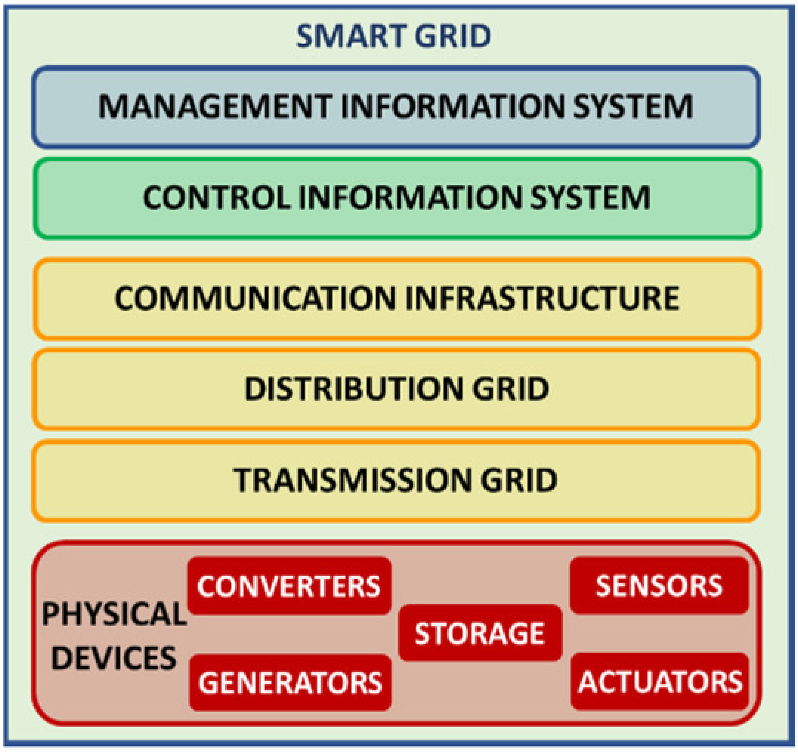

Figure 1. Global perspective of the SG as an SoS, with the physical and cyber infrastructures.

From this perspective, the impact of different kinds of attacks on the SG can be evaluated from both cyber and physical points of view, making it possible to select the most appropriate security solution to reduce the impact in each of the two parts [36]. Several authors have applied the CPS concept to production systems (cyber-physical production system—CPPS [37]) to improve their performance and their efficiency by introducing new types of sensors [38], collecting data, and supporting decision making through big data technologies, which can be associated with the implementation of Industry 4.0 technologies [39]. In addition, cyber-physical human systems (CPHS) are able to consider human actors as resources participating in the “production” of the technological subsystems of a CPS, but also as users or decision makers in the cyber subsystems of the CPS [40][41]. Furthermore, an SG can be seen as a specific CPS, called a cyber-physical power system, composed of a physical system (power network infrastructure) and cyber systems, proposing the integration of the real and virtual worlds, dynamic communication, information processing such as big data streams, and autonomous capabilities [42].

The SG can be seen as a cyber-physical system of systems (CPSoS), which also belongs to another, higher-level, multidisciplinary SoS, the smart city, contributing to its development and deployment thanks to the opportunities made possible by SGs for delivering sustainable energy [43]. In this frame, the SG constitutes an SoS that includes different elements:

- Traditional electrical system, composed of power plants, transmission grid and distribution grid;
- Customer-side system, including several elements located at the end of the distribution network, like electrical microgrids (MGs), intelligent buildings (IBs) and smart homes (SHs), and electrical vehicles (EVs);
- Communication system, which gives the SG its intelligent nature, mainly composed of communication networks and data storage and processing centers.

2.2. The Intelligent Building, a System of Systems

The first time the concept of the intelligent building appeared was in the United States during the 1980s [44]. From this starting point, IBs have evolved as another example of CPS, which is a system of the overall SG, while, at the same time, the IB constitutes an SoS in itself, composed of different types of subsystems, namely technological, economical, and human. Nowadays, IBs are in a position to be considered cyber-physical ecosystems interacting with their environment, both external (SG and other IBs) and internal (aimed towards the upgrade of their occupants’ comfort) [45]. Some of the main features of IBs that can be cited include automation, multifunctionality, adaptability, interactivity, and energy efficiency, and IBs include several technologies such as control systems, renewable energy, energy storage systems, sensors and actuators, and SM [46].

We consider an SG to be both an SoS and a CPS. A CPS is a set of systems that integrates cyber components and physical components [47]. Cyber components have communication capabilities and collaborate to control and coordinate physical processes. An IB is composed of physical components that produce, store and consume energy, and cyber components that control, communicate and coordinate the physical components. We therefore consider an IB as a CPS. Incidentally, due to this conception of the CPS, an IB is also an SoS, composed of cyber and physical systems as well as, of course, physical power networks.

Other authors have proposed the concept of the “cyber power internetwork” to define the current structure of intelligent power networks [48]. Here again, on one hand, the power network is composed of a physical part, namely the power system, while, on the other hand, the cyber part includes information and communications technologies (ICT) with different components: acquisition, processing, implementation, and communication. The interdependencies between the different elements of the cyber-power system also influence the reliability and the security of the system as a whole. Figure 2 depicts the proposed vision of SGs as a CPSoS, integrating an IB as a CPS.

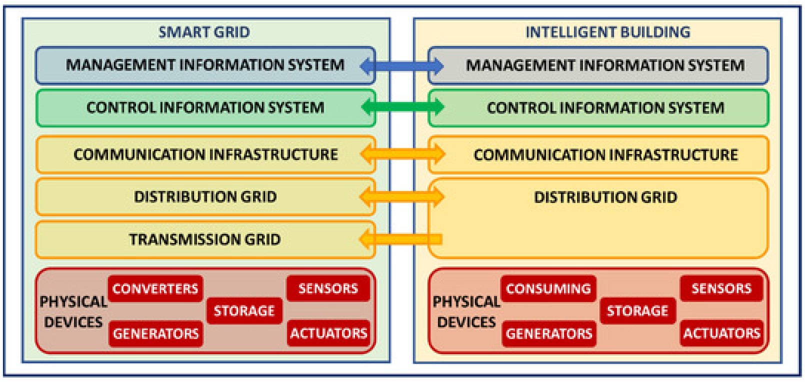

Figure 2. Global perspective of the integration of IBs and SG as SoS.

3. Main Features of Intelligent Buildings as Part of Smart Grids

The proposed perspective, which overlaps two complex systems in the form of IBs and SGs, although presented and justified from a theoretical approach, must also be supported from a technical point of view. At the beginning of this paper, some technologies inherent to SGs that can be applied to IBs are raised. However, conversely, there are several capabilities of IBs that require interaction with SGs in order to operate in a proper manner [49]:

- Smart metering, a part of the whole advanced metering infrastructure (AMI) of the SG;
- Management and control methods to guarantee the energy efficiency in the building and the power balance in the electrical grid.

This perspective of IBs as active systems of the SG, including the existing electrical and communication interactions, is schematized in Figure 3 [45][49].

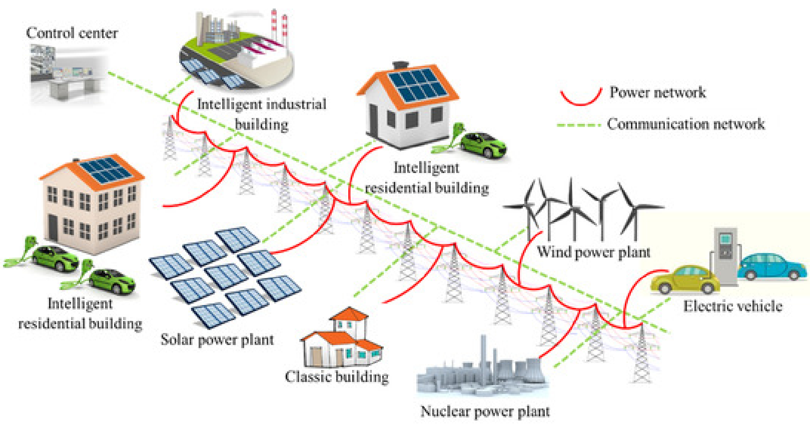

Figure 3. Intelligent buildings as systems within the whole smart grid.

Bidirectional communications, wired and wireless, allowing data transfer inside a building, but also between individual buildings and the power grid, are needed. This feature, together with energy management capabilities, constitute two inherent particularities that define the nature of IBs compared to conventional buildings, while at the same time reflecting the integration of IBs in the SG [50]. Thus, in the following subsections, the focus will be placed on energy management systems as the core of IBs, along with the most relevant communication technologies.

3.1. Energy Management in Intelligent Buildings

Recent studies have highlighted that buildings are responsible for around 40% of total energy use [51], and the lockdowns imposed to address the COVID-19 pandemic during 2020 also had a non-negligible impact, increasing the residential energy demand by between 11% and 32% [52]. Consequently, IBs are regarded as being the main actors in the context of aiming for more responsible use of energy, while at the same time ensuring a tradeoff between energy efficiency and indoor environmental quality in order to guarantee the comfort of building occupants [53]. The application of appropriate energy management in buildings is interesting both from an ecological and a pecuniary perspective, thanks to the energy savings that it provides, which can reach a yearly augmentation varying between 11.39% and 16.22%, according to the study conducted in [54]. Considering the relevance of these results, the essential aspects of energy management systems are presented next.

3.1.1. Building Energy Management System Architecture

At present, modern buildings, as they are SoS, include a great variety of heterogeneous systems and devices, ranging from classical appliances like lighting, hot water or heating ventilation and air conditioning (HVAC) to more recent ones such as renewable energy generation, electrical vehicles and intelligent storage systems. Therefore, in order to achieve a coordinated and tuned operation of all these elements inside a building in an interactive and automatic way, integrated complex algorithms called building energy management systems (BEMS) need to be applied [55]. BEMS are heavily based on building automation systems (BAS), the CPS nature of which is accentuated, since they are composed of HW and SW parts, as explained in [56]. The conceptual architecture of a BEMS is presented in Figure 4 from a twofold point of view: control layers, and cyber and physical parts, including the interaction with the SG.

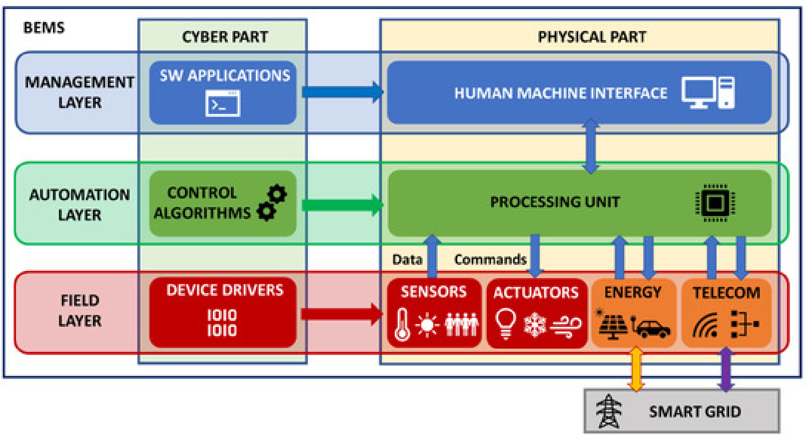

Figure 4. BEMS conceptual architecture.

Several types of sensing technologies are employed to gather the data needed for the optimal energy management of the building [57], alongside the functionality of interaction both with the SG and with other BEMS by means of wired and wireless communication technologies. When the BEMS includes bidirectional transmission of data and power between the IB and the SG, it can be considered to be an integrant part of the IoE. An exhaustive review is performed in [58], analyzing the opportunities provided by the key technologies of the IoE for the maximization of the energy efficiency in buildings. As will be presented later, this twofold exchange is based on the IoT and a number of different control mechanisms, and it is mandatory for ensuring the power balance of buildings when integrating local distributed generation. Accordingly, the concepts of the zero energy building (ZEB) and the net-zero energy building (NZEB) have emerged over the last few years [59]. A ZEB adds renewable energy generation to the “green building” principle, resulting in a building capable of balancing its own energy generation and consumption. Two kinds of ZEB can be defined, depending on their connection to the grid [60]: autonomous/standalone ZEB, which is not connected to the grid, and NZEB, which is in turn connected to the electrical grid. Thus, the NZEB is able to balance the energy interacting with the SG in a bidirectional transfer of power. A review of recent advancements in the NZEB field was performed in [61]. A future approach is represented by positive energy buildings (PEB), which will produce more energy than they require for their operation, making it possible for them to supply other buildings connected in the surrounding area [62].

In the same way, many efforts have been carried out in recent years concerning the development of home energy management systems (HEMS) [63], which can be considered a particular case of BEMS. The final purpose of HEMS is the same—the reduction of energy consumption—but the requirements for achieving this objective are slightly different from BEMS. Certainly, ensuring the development of low-cost IoT-based solutions compatible with existing gadgets that are affordable for the general public is one of the main goals of HEMS, in contrast to BEMS, which focuses on industrial or office buildings, where the most important goal is to assure a high level of reliability. The basic architecture of an energy management system of a NZEB is shown in Figure 5.

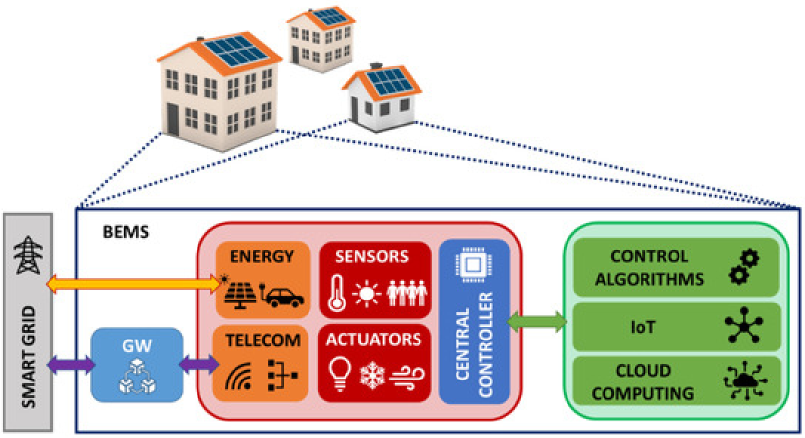

Figure 5. General architecture of a BEMS of a NZEB.

As can be seen, on one hand, the global system consists of a physical part, including sensing and measuring devices, smart appliances and actuators, local renewable energy generation, energy storage devices, communication facilities, a gateway (GW) to allow the interconnection with other IBs and the SG, and a central processing unit [64]. On the other hand, there is also a cyber part, comprising the different computing solutions, which are based on the IoT, edge computing (EC), and cloud computing [65]. Last but not the least, the energy management system must adequately cope with occupant behavior in order to be really accepted by building users [66][67].

A crucial requirement for the correct operation of the whole power grid is to ensure the balance between energy demand and supply. Traditionally, this task was only carried out by power plants, that is, on the generation side. The emergence of new actors in the SG such as distributed energy resources, electrical vehicles, and energy storage systems, often as part of a greater whole such as an IB, is changing this typical top-down operation, since generation is now placed at the distribution and demand level, close to the final consumers. In this context, the emergence of BEMS and HEMS and their associated intelligence, combined with their ability to communicate with the grid, has boosted the materialization of demand-side management (DSM) programs [68], which constitute a typical example of bidirectional interaction between IBs and the SG. DSM tries to achieve energy efficiency in households and buildings by means of consumption shifting, the goal of which is to push the energy use towards valley periods. This approach is more popular in residential buildings, since users are able to choose the manner in which they use their energy, and when to use it [69].

Among the different already-existing DSM solutions, demand response (DR) is considered one of the most suitable options for providing electricity flexibility to IBs interacting with the grid, because of the possibility of load shifting, including renewable energies, at an affordable price, as was described in the comprehensive survey conducted in [70]. The main DR strategies can be classified into two categories [71]: price-based, which is centered on changes in the grid price, and incentive-based, which encourages customers to shift their consumption to outside peak hours by providing discounts in the billed amount, or even allowing the grid operator to turn off/on several customer loads to match energy consumption and generation. The nature of the load (uncontrollable, curtailable, uninterruptible, interruptible, regulating and energy storage) is also considered by the BEMS to decide how to proceed, from simple scheduling to complete load disconnection [72]. Moreover, the DR program can also be combined with smart energy storage devices to use the stored energy during peak hours instead of using energy from the grid, leading to a price reduction of up to 18% [73].

Load-side energy management strategies can be also applied for groups of buildings at the distribution grid level. In this case, the main risk is the lack of coordination between the set of buildings and the SG when applying this management strategy, leading to a reduction in efficiency and, worse, to a stress situation for the distribution system. To ameliorate these sorts of problems, [74] proposed an operation framework for load aggregation and disaggregation involving three types of intelligent entities: the system operator at the transmission level, the distribution system operator, and, finally, the BEMS for load scheduling. Another approach was implemented in [75] to manage the energy of a cluster of buildings, including photovoltaic generation. This solution was based on load scheduling (hybrid heat and power), and two types of

DR were applied: increase of power consumption and reduction of heat generation, and vice versa, depending on the PV generation level.

3.1.2. Making the Energy Management Systems More Intelligent

- General management methods

Data gathered using sensing devices are processed by the central platform, which can employ different control schemes in order to find the right decision. These control schemes, which can be defined as general purpose management strategies, can be classified as either conventional or intelligent [76]. Conventional controllers, a category that includes basic types such as on/off switching, PID controllers and predictive and adaptive methods, are mainly oriented towards guaranteeing energy savings, without taking into account the comfort of the occupants of the building. To override this limitation, intelligent control schemes have been developed. As presented in [76], these control schemes mostly include model-based predictive control (MPC) and artificial intelligence (AI)-based techniques like multiagent systems (MAS) and fuzzy logic. However, the role of the MPC in energy management is often that of a DSM [77][78]. To efficiently integrate distributed generation, AI techniques must take into account both the consumer and producer sides of energy management, which has recently resulted in more promising solutions for the design of BEMS.

A BEMS was proposed in [79] for the management of heating ventilation and air conditioning in a commercial building using fuzzy logic algorithms (FLA). In [80], the authors proposed a fuzzy logic controller (FLC) for the energy management of a university building. The BEMS was developed using Matlab/Simulink software (MathWorks, Inc., Natick, MA, USA) and aimed to make a selection or a combination from among three energy sources: the main grid, local solar PV, and a local battery. It was also able to control the charging of the battery while keeping in view the demand of loads, in addition to providing energy to the main grid in the case of excess power. Also using Matlab/Simulink, a FLC for a residential building was designed in [81]. A recent work using FLA proposed a solution for processing the environmental data to advise building users with the aim of achieving minimum energy consumption [82].

Considering the distributed nature of an MAS, this technique is prevalent in the management of complex systems in general, and in the energy management of SGs in particular [83][84]. The work conducted in [85] studied several MAS dedicated to power engineering applications, as did that presented in [86], whereas [87] proposed two solutions for the supervision and analysis of a large quantity of data from a multisource electric network. An MAS for controlling production units, storage equipment and charges, based on Matlab/Simulink, was developed in [88]. Other works have defined an MAS as a set of several agents interacting with each other or with their environment [89]. The interest in the MAS is due to its agent properties and abilities. An agent is defined as a software or hardware entity, autonomous, i.e., able to interact with its environment and to make decisions with respect to its own strategies using artificial intelligence techniques such as machine learning (ML) and deep learning (DL) [90]. Depending on the level of autonomy and intelligence of an agent, different types are possible. For example, [91] studied a MAS for managing the energy consumption of a microgrid and classified agents as follows:

- Reactive agents, with a stimulus–response behavior based on sending and receiving messages;
- Cognitive agents, with a high level of intelligence and autonomy. These agents can memorize their history and develop a learning ability by adopting ML behavior. An example of an MAS with a “learning” phase for better managing a large and complex microgrid was proposed in [92];
- Hybrid agents, offering combined behavior: reactive with respect to some properties and cognitive with respect to other properties. The main properties to consider here are autonomy, cooperation, and adaptation.

To conclude, MAS dedicated to the management of IBs strengthen BEMSs and help human people manage their warmth by supporting energy consumption optimization. Table 1 provides an overview of the energy management methods cited in this paragraph, including their most important features or weakness.

Table 1. Active energy management methods for buildings.

Energy Management Method Classification	Energy Management Method	Kind of Building	Observation
Conventional Methods	On/Off switching	Nonresidential	Based on classic rules algorithms
	PID controllers		Can be software implemented or use an external device
Intelligent Methods	Predictive and adaptive methods		
	Model predictive control	Nonresidential	Often used for DSM
	Fuzzy logic	Nonresidential & residential	Supports cloud or edge computing
	Multi Agent System	Nonresidential & residential	Distributed nature Supports cloud or edge computing Supports learning ability

- Contribution of computing tools in intelligent energy management

Several intelligent energy management methods, in particular AI techniques, are benefiting from the development of other AI techniques such as ML and DL, as well as other new technologies such as big data, IoT, and cloud computing.

In this way, the FLC proposed in [93] aimed to design a BEMS using cloud computing. The FLC was integrated into a cloud service, providing the BEMS with the following features: automation, and intelligent monitoring services, through both the web and through smartphones. Cloud computing accelerates and facilitates the deployment of BEMS, since it allows data processing in the cloud. A more recent concept than cloud computing, edge computing (EC), which consists of data processing performed close to the IoT sensor or device instead in the cloud, has begun to be promoted as a suitable option for SG management. EC provides several benefits for the SG [94] that are also useful for energy management in buildings: reduction of processing latency for time-sensitive applications (load control, DR) and support for the application of cognitive solutions (data fusion, reinforcement learning), while at the same time fostering interoperability among the different elements and systems of the SG and the interactions between the SG and these systems (users, buildings, energy sources).

Deep learning techniques are a solution that is becoming more and more popular in recent years for BEMS. One interesting application is the forecasting of the energy consumption in buildings in order to implement adapted mechanisms to optimize the energy management [95]. The BEMS based on MAS have also combined some DL techniques, for making agents more adaptative and intelligent. A sailboat microgrid managed by MAS, where an agent has used a recurrent neural network (RNN) to forecast the available daily solar energy which can be converted by the photovoltaic panel installed in the boat, has been developed in [96]. Always related to the energy consumption forecasting, a solution based on convolutional neural networks (CNN) along with a long short-term memory autoencoder is implemented in [97], resulting in smaller prediction errors than other concurrent solutions for periods of 1 h and 1 day. In fact, the artificial neural networks (ANN) are among the tools used by DL to perform the artificial learning, and the two relevant types of ANNs used in DL are CNNs and RNNs.

- The Internet of Things and related computing solutions

The recent emergence of the IoT has made this paradigm one of the key components of modern BEMS and HEMS [98]. Indeed, the benefits offered by the application of the IoT in BEMS are large: a set of low-power distributed intelligent sensors for monitoring different parameters of the building (temperature, lighting, humidity, air quality), processing capability allowing the application of the aforesaid control methods, different sorts of bidirectional communication technologies, and a wide range of actuators for optimizing energy consumption following the control system instructions. A recent study concerning the use of the IoT to improve building energy management was conducted in [99], highlighting the suitability of IoT technologies for five main applications: energy consumption control, predictive control for temperature regulation, sensing of residents' comfort, integration of controllable devices, and smart home applications. In [100], an energy management system for homes, based on the IoT, was proposed. This solution incorporates an Electronic Device Sleep Scheduling Algorithm to handle the energy consumption of sensors, which is a major concern in these systems. Similarly, the IoT for a BEMS was recently applied in a commercial building, the main aim of which was to implement a DSM strategy [101]. The proposed solution included smart compact energy meters to monitor the power quality (sag, swell, transients) and the energy use, as well as communicating with the building users. For its part, the system proposed in [102] goes further, and takes advantage of the IoT and the existing BEMS of an academic building to monitor environmental conditions and their influence on the learning experience.

3.2. Communication Networks and Intelligent Buildings

To provide the previously mentioned services, including DSM and customer participation, the implementation of a bidirectional communication infrastructure constitutes a key feature of the SG. This infrastructure is essential for offering the ability to exchange data between the different entities of this SoS, including generation, distribution, substations and end user entities [103]. Therefore, IBs, to be a part of the overall AMI, need to possess this two-way communication capability in order to provide reliable and real-time information for optimal power delivery, avoiding disturbances and outages as much as possible from the generating units to the end users.

3.2.1. Communication Technologies for Interconnecting IBs to the SG

Regarding the need for a two-way communication infrastructure, the scientific literature reveals that a large number of communication technologies are already available for interconnecting IBs to the overall SG. In [104][105], these technologies are categorized in consideration of their main communication medium: wired or wireless. From an IB point of view, this communication infrastructure needs to support two main information flows [106][107]. The first flow is dedicated, inside the IB, to gathering data from sensors and electrical appliances that are stored in data concentrators, like SM, and used to provide information to end users and to control, using actuators, their appliances. The second information flow is used to exchange data between the back-haul of the SG and the IB through SM or GW. Thus, in the context of IBs, communication network technologies, as illustrated in Figure 6, can be classified into Inward-IB and Outward-IB communication networks.

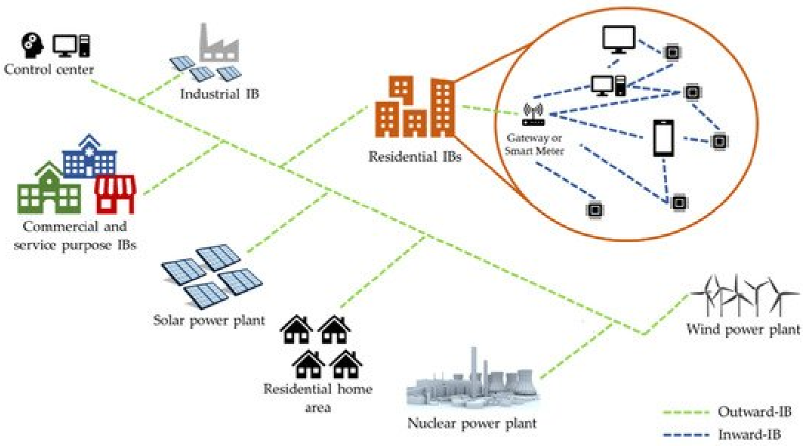

Figure 6. Inward-IB and Outward-IB communication infrastructure for the SG.

The proposed classification can be correlated with another classical one, proposed in [16][108], where SG communication technologies are categorized into home area network (HAN), neighborhood area network (NAN), and wide area network (WAN). Considering this classification, HAN and NAN could cover Inward-IB communication networks, since a building can also be considered to be an association of several neighbors, as in residential buildings, for example. To cover this perspective, the building area network (BAN) level was also defined in [109]. Furthermore, NAN and WAN technologies could be used for Outward-IB communication networks, because an IB can be interconnected with other neighboring IBs or with the utility's back-haul system of the SG. Table 2 compiles the main technologies that can be used for IB communications purposes, including their proposed classification and the main classifications employed in the literature.

Table 2. Main communication technologies for Inward-IB and Outward-IB networks.

Communication Technologies	Inward-IB Network	Outward-IB Network	Media	HAN	NAN	WAN
PLC	✓	✓	**Wired**	✓	✓	✓
Optical fibers		✓	**Wired**			✓
Digital Subscriber Lines		✓	**Wired**		✓	✓
Wi-Fi	✓		**Wireless**	✓		
Bluetooth	✓		**Wireless**	✓		

Communication Technologies	Inward-IB Network	Outward-IB Network	Media	HAN	NAN	WAN
EnOcean	✓		**Wireless**	✓		
ZigBee	✓		**Wireless**	✓	✓	
Z-Wave	✓		**Wireless**	✓	✓	
LPWAN		✓	**Wireless**		✓	✓
DASH7		✓	**Wireless**		✓	✓
Cellular technologies		✓	**Wireless**		✓	✓
WiMax		✓	**Wireless**		✓	✓
Cognitive radio		✓	**Wireless**			✓
Satellite communication		✓	**Wireless**			✓

3.2.2. Communication Infrastructure Requirements for IBs as a Part of the SG

As mentioned previously, a two-way communication infrastructure is essential for enhancing the efficiency of the electrical grid with respect to power generation and distribution to customers. As for the whole SG, this communication infrastructure, deployed at the IB level, needs to be secure, available and scalable. In parallel, its reliability, as well as the interoperability between different devices used to collect data or control appliances, must be also ensured [106].

Firstly, to guarantee the availability of SG services, an IB should provide a communication infrastructure that allows data exchange within itself and among the entities of the overall electrical grid. Furthermore, the adopted communication infrastructure must consider that an IB could be dedicated to different purposes: industrial, residential, or commercial, or to services, such as hospitals [56]. As a result, this infrastructure will differ from one building to another. For example, in some of them, the SM can act directly as a GW within the overall SG [110], whereas in residential buildings, several smart meters, one per customer, will be interconnected with a concentrator, which plays the role of GW with the Outward-IB world and enables, at the same time, different BEMS services. In addition, to transfer information into and out of the IB, its communication infrastructure needs to guarantee the interconnection of heterogeneous devices and communication technologies [107]. As one example, sensors and actuators from different manufacturers could be interconnected, using a mesh network based on ZigBee technology, with a BEMS, which also offers end users a way of controlling their smart appliances through more common network technologies such as Wi-Fi or Bluetooth [111].

Secondly, latency and bandwidth also constitute a major issue for providing a reliable and scalable communication infrastructure at the IB level. Latency and bandwidth requirements, particularly, depend on the nature of SG services [105][112]. In AMI, low-latency performance for real-time monitoring (12–20 ms) is needed in order to better regulate and adapt the energy demand. On the other hand, higher latency is generally allowed for remotely connecting or disconnecting the IB, as an electrical load, from the overall SG. With respect to bandwidth requirements, transferring low-payload data from sensors to smart meters typically requires low bandwidth, whereas the exchange of information between the SG back-haul and IBs through gateways needs a larger bandwidth.

Furthermore, the coexistence of several heterogeneous devices or networks that must be interconnected causes a major issue in terms of interoperability. Nowadays, as suggested above, GW or SM already plays, at the IB level, an important role in connecting devices that use two or more different communication protocols. Nevertheless, interoperability remains a key issue in SG development, and requires efforts towards the standardization of activities [106][113]. In this way, as stated in [65][114], open protocols used for building automation, such as BACnet, KNX or LonWorks, appear to be a major solution, allowing several products provided by different manufacturers to be compatible with one another. Moreover, the need to converge towards a scalable and interoperable communication infrastructure makes TCP/IP-based networks an interesting solution [112]. Exploiting emerging IoT technologies built on IP architecture offers many advantages over other solutions, such as the ability to support data flow over multiple link layers or to connect many devices [115][116]. Thus, using IoT protocols such as 6LoWPAN or RPL [117][118], sensors, actuators and SM connected through an Inward-IB communication network based on ZigBee or Z-Wave technologies could be more easily interfaced with Outward-IB networks, which generally also use IP-based solutions.

Finally, as shown previously, a set of distributed and interconnected devices is necessary at the IB level to provide a reliable BEMS while serving, at the same time, the global functions of the SG. This characteristic makes security and privacy a complex issue in IBs, as entities of the SG SoS [105][119]. Therefore, ensuring secure data storage and transportation from IBs to SG while also protecting information provided by the IB stakeholders is a fundamental requirement for guaranteeing the stability and reliability of power delivery. In this context, the use of heterogeneous devices and network technologies to communicate inward and outward in IBs is a major source of vulnerabilities that could severely disturb the operation of BEMS and SG services [120]. Indeed, sensors and actuators deployed in a distributed manner inside IBs to collect data and control electrical appliances are, in general, resource-constrained and low-powered devices that communicate at low data rates and through mesh networks like ZigBee. Thus, these devices are more vulnerable to attacks. This explains why GW or SM that embed robust security layers are mainly used as communication bridges between IBs and external SG entities [118]. In addition, IBs seem to be easier to attack since they are more accessible than, for example, SG control centers or power plants. By exploiting the weaknesses in their communication infrastructure, such as low-security-level devices or vulnerabilities related to end users, unauthorized users could compromise, through the IB, the performance of the whole electrical grid by manipulating control applications, changing control parameters or interfering with exchanged data [121].

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