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Active Building as an Energy System: Concept, Challenges, and Outlook

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ABSTRACT Over the last decades, environmental concerns and the global tendency to reduce the use of fossil fuels and replacing them with renewable energy sources (RESs) to face the increasing rate of greenhouse gas (GHG) emissions have increased. Buildings consume a significant amount of energy and therefore, they are responsible for a noticeable part of the total GHG emission. Thus, when we talk about decarbonization of the energy systems, buildings are an important sector of the energy system that needs to be considered. Using RESs, smart technologies, and information and communication technologies along with the improvement in energy efficiency, are a number of endeavors to increase the role of building on the way toward decarbonization. In the new environment, the buildings are not passive players of the energy systems and they are able to take an active role and participate in the energy-efficient operation. While they are able to manage their resources and serve the local energy requirements of the residents in the best possible manner, they can participate in the energy and balancing markets and support the network operators as a service provider. In this paper, we present a comprehensive review of active buildings' concept, challenges and outlook to pave the way for the researchers from academia and industry who want to start working in this area.

INDEX TERMS Active building, energy systems, decarbonization, demand response, flexibility, energy efficiency, resident comfort, Internet of Things, renewable integration, energy storage systems, systematic review.

I. INTRODUCTION

Over the last years, global awareness and the tendency to reduce the use of fossil fuels and replacing them with renewable energy to face the increasing rate of greenhouse gas (GHG) emissions has increased. The increasing penetration of renewable energy resources (RESs) into the energy systems imposes uncertainty on the operation of these systems that call for a paradigm shift in this area. Smart grids are known as one of the technological development solutions to help the operators of the energy systems to cope with such evolution in a systematic manner. The smart grids provide infrastructures for bi-directional energy and information flow, a high level of flexibility on the supply, and demand-side which is a necessity in the current uncertain renewable integrated energy systems. In such an atmosphere and due to the rapid decrease in the production cost of the small-scale energy sources like photovoltaic (PV) panels and battery energy storage technologies, the role of end-users of the energy, especially, the buildings and homes are radically changed. In the new environment, the buildings are not passive players of the energy systems and they are able to take an active role and participate in the energy-efficient operation. So, these so-called "Active Buildings" are able to manage their resources and serve the local energy requirements of the residents in the best possible manner, and in parallel, they can participate in the energy and balancing markets and support the network operators as a service provider [1].

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A. THE CONCEPTUAL OVERVIEW OF THE ACTIVE BUILDINGS

In this section, the active building concept will be introduced and the main features of a building that make it *active* are discussed. Also, using a systematic literature survey, the current works on this topic is precisely analysed and classified to highlights the main areas that are under evolution.

WHAT IS AN ACTIVE BUILDING?

The worldwide evolution toward the decarbonization calls for a holistic approach to energy [1]. Therefore, buildings as one of the largest sectors are in forefront of this evolution. For this reason, new building codes need to be developed to clear the pathway to a net-zero carbon system and highlights the design, construction and operation approaches to the upcoming generation of buildings.

The "Active Building" is a conceptual evolution that emerged by the development in the small-scale renewable energy sources and smart technologies. It evolved the passive role of the buildings to a self-sufficient and energy-efficient agent that enabled to have double-sided interactions with the neighbours in a district and to the upstream network.

This term is a reflection of their active involvement in the energy systems and decarbonization goals. In the energy system context, an active building is able to be defined as a system that has the potential of energy production, storage and trading/sharing (see, Figure 1).

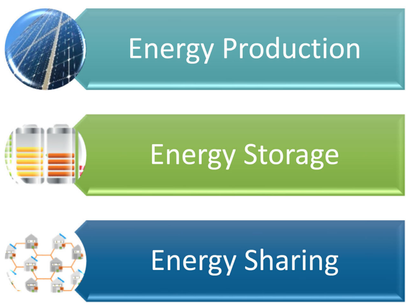

FIGURE 1. Main elements that make a building *active*.

In the definitions and conceptual explanations on the active building, the following elements have a pivotal role [2]

- *Building Fabric and Passive Design:* which refer to the coordination between the engineering and architecture design approach consisting of natural daylight, natural ventilation, and fabric efficiency. Buildings are designed for occupant comfort and energy efficiency.
- *Energy-Efficient Systems With performance Monitoring:* This denotes to the smart control and energy-efficient systems to optimize the consumptions of the different loads. Data collection through inbuilt monitoring to do performance validation, optimization, and update control strategies.
- *On-site (mostly renewable) Energy Generation:* various RESs should be installed according to the site conditions and building load profiles combining, where applicable both PV and solar thermal technologies.
- *Energy Storage Systems (ESSs):* that help to manage peak/valley demand, reduce the dependency on upstream grids and provide better control to support the infrastructure and enable flexible control to provide virtual power plant (VPP) integration.
- *Electric Iintegration:* active buildings are an important point for integrating the electric vehicle (EV) charging. In the presence of bi-directional charging, EV will be able to discharge its energy to the building (which is called vehicle-to-building or V2B), participate in the demand-side response (DSR) programs and collaborate with the wider building control systems.
- *Intelligently Manage Integration With Micrograds and national energy network:* where refers to the active role of active buildings in managing their interaction with wider energy networks with the aim of minimizing uncontrolled import or export of energy by effectively utilizing the onsite generation, potential DSRs and sorted energy.

B. THE ROLE OF BUILDINGS IN IMPROVING THE NETWORK OPERATION

In this part, the role of active buildings in optimizing the operation of the electricity networks is introduced. More details on the electricity distribution network optimization are provided in [3].

To show the interaction between the active buildings and the network operators, we use the proposed infographic of Figure. 2. As can be seen, this interaction is depicted as two sides of a balance and the balance will be stable at some optimal operation point of the network. To achieve that point, the distribution system operator would attempt some incentive mechanisms or send some warning signals that will be shared through the communication system with the active buildings for procuring the required amount of energy and ancillary services for the network. All of these interactions are based on a data platform that needs to be carefully designed from the cybersecurity perspective.

C. THE ROLE OF BUILDINGS IN DECARBONIZATION

Buildings are the consumers of about 40% of total energy consumed in the EU [4], and as a result, they are responsible for a significant part (about 36%) of the total GHG emission. So, when we talk about decarbonization of the energy systems, buildings are an important part of the energy sector that need to be addressed. Using RESs, smart technologies, and information and communication technologies along with the improvement in energy efficiency, are a number of endeavors to increase the role of building on the way toward decarbonization.

D. THE ROLE OF ACTIVE BUILDING IN TRANSITION TO LOW CARBON ENERGY SYSTEM

One of the most important GHGs is the carbon dioxide; the increased concentration of this gas in the atmosphere is mostly due to the overuse of fossil fuels. As discussed

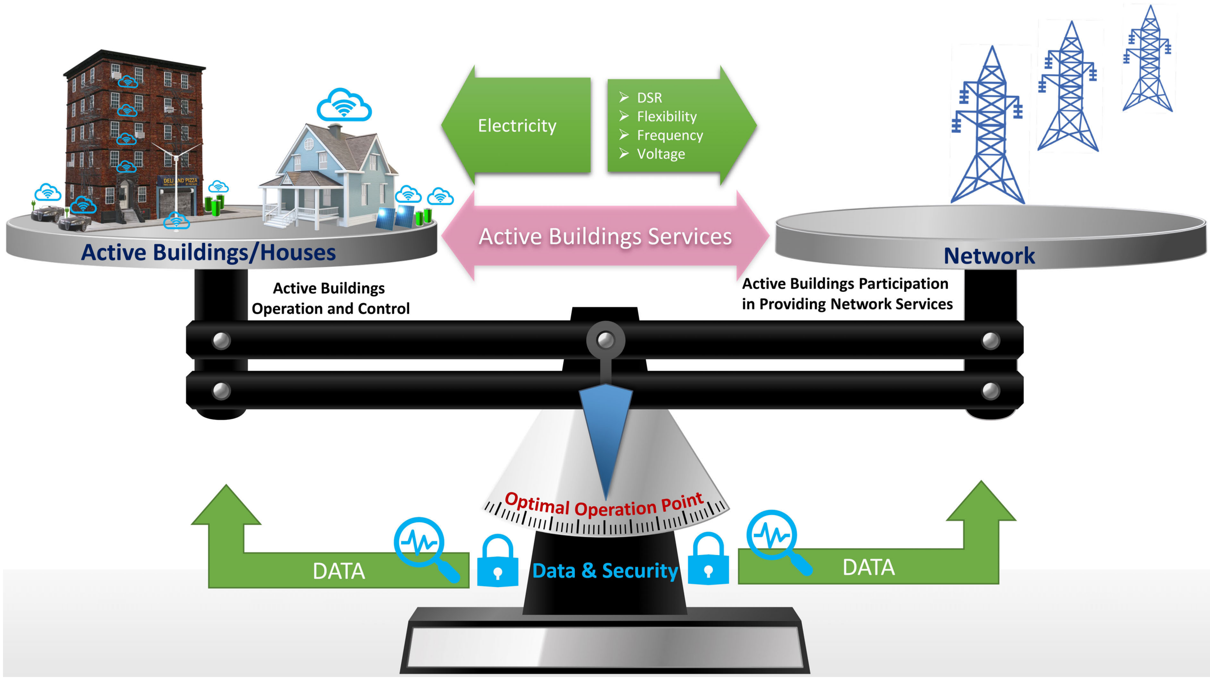

FIGURE 2. Integration of active buildings and their energy services into the electrical energy networks.

previously, buildings are responsible for a significant of CO_2 emission, a vast majority of which is due to the demand for power and heat for buildings [5]. Growth in demand for energy is primarily due to changes in energy consumption behaviours; therefore, there is a clear need to use RESs, to design a new structure for the energy system, and to address historical energy use, in order to reduce energy consumption and dependency on fossil fuel, and thereby build a sustainable energy system. Since, for many countries, the grid infrastructure is not ready to accept all of these changes, buildings are a desirable option for facilitating this transition [6].

The buildings sector is considered easier for energy consumption reduction than other sectors, and potentially more cost-effective. Hence, there are many opportunities for decarbonization in the building's environment, although this potential may vary based on the case and region [7]. On the other side, understanding why, how and when the energy is utilized in a building is really important to reduce energy consumption and associated GHG emissions.

In the active building, there is appropriate infrastructure and technologies to produce, store, control and monitor energy usage considering multiple criteria and various requirements which pave the way for meeting the decarbonization goals. Moreover, active buildings can mitigate the stress on the main grid through smart control.

II. A SYSTEMATIC REVIEW OF THE LITERATURE

A systematic review is presented in this part considering the works published in the area of active building energy systems. As it will be explained in subsection II-A, a comprehensive literature survey is done on the publications in this field and a number of high-impact works are short listed and precisely analysed.

A. SURVEYING METHODOLOGY

We started this literature survey by gathering scholarly articles and books from different areas. To this end, we considered a wide range of publications that have the keywords of "*active building*" <and> "*smart building*" <and> "*energy*" in their titles since we plan to bring a broader overview of the works presented in this field and categorize and analyze them in a systematic way. We used the Web of Science database where this exploration led to a total number of 273 documents over the last decade from 2010 to 2020.

B. A STATISTICAL OVERVIEW

These 273 documents are from a total of 63 countries, and are the product of collaborations of 414 institutions. The top 36 keywords with the highest frequency of occurrences in the published documents of this field are depicted in Fig. 3. As shown in Table 1, among them, the USA, China, Spain, Italy, and the UK have the most published documents with 68, 34, 26, 19, and 15 publications, respectively. The average number of citations to the total published works of these countries were 18, 16, 18, 8, and 17, respectively.

Additionally, based on the Table 2 *Nanyang Technological University, Singapore*, *University of Murcia, Spain*, *University of California, Berkeley, USA*, *Technical University of Denmark, Denmark*, and *University College London, the UK* with respectively published 12, 8, 7, 6, and 6 articles while by

FIGURE 3. Keywords that have the highest frequency of occurrences in the published documents of this field.

TABLE 1. The top 5 countries with the highest number of published articles in this field.

Name of the Country	Number of Documents	Average Citation
The USA	**68**	**18**
China	34	16
Spain	26	**18**
Italy	19	8
The UK	15	17

TABLE 2. The top 5 institutions with the highest number of publications in this field.

Name of the Institutes	Number of Documents	Average Citation
Nanyang Technological University	**12**	14
University of Murcia	8	23
University of California, Berkeley	7	21
Technical University of Denmark	6	8
University College London	6	**57**

TABLE 3. The top 5 Journals with the highest number of published documents in this field.

Name of the Journal	Number of Publications	Average Citations
Energy & Buildings	**25**	16
IEEE Access	17	6
Applied Energy	16	20
Energies	14	10
IEEE Transactions on Smart Grid	11	**35**

considering the average number of citations to the published works, the University College London shows the highest research impact in this field with a Citations-per-Publication of 57.

Also, the top 5 journals with the highest number of published documents in this area are introduced in Table 3 and the average citations of each of these journals as a measure of their research impact are reported. As it can be seen, *Energy & Buildings* has the highest number of published documents in this field and the *IEEE Transactions on Smart Grid* has the highest research impact among them with the average citation value of 35.

In Fig. 4, a quantitative representation of the works presented in this field over the last two decades is demonstrated

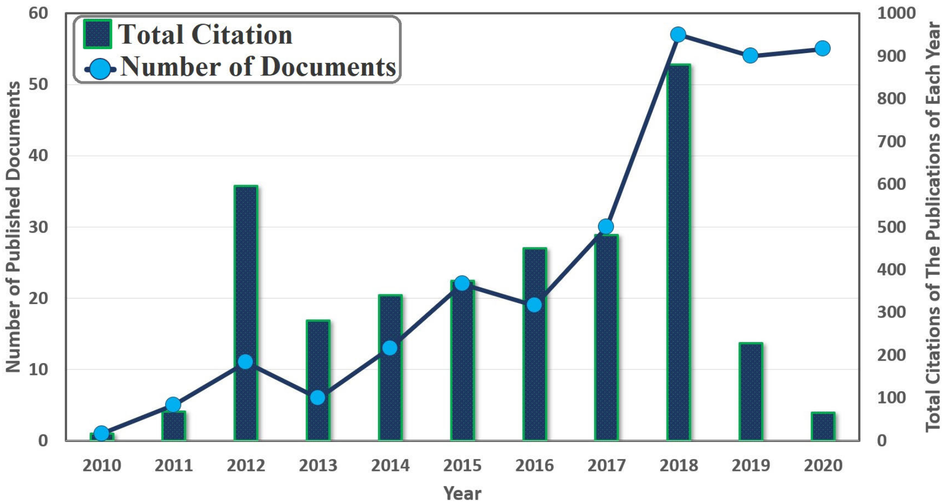

FIGURE 4. A quantitative comparison of the published articles in each year with the total number of citations they have received.

along with the number of citations to the published of each year.[1]

C. LITERATURE SURVEY

After the above quantitative analysis, all the journal publications are selected and analyzed in a qualitative assessment process. To this end, every publication was associated with a technical category and then analyzed to assess its relevance to the topic. A label is assigned to each paper to highlight the papers from the quality and relevance point of view. At this stage, a total of 52 documents remained. Among them, there are 20 scholarly articles with more than 50 citations that make the core references of the works presented in this table.

A comparison taxonomy of the technical contents of the selected works is presented in the followings paragraphs and tabulated (in yearly order) in Table 4.

In [9] an autonomous framework for demand-side management is proposed. This framework includes three basic layers for admission control, load balancing, and demand response management. The proposed structure facilitates the integration of various energy resources, upgrading and maintenance, the collaboration between different components. The authors in [24] explore the policy measures and their effectiveness for improving energy efficiency in the buildings compared with the intelligent building energy management.

A mixed-integer linear programming (MILP) model of the building energy management system (BEMS) has been presented in [36] to explore the cooperative assessment of the operation of BEMS considering EV potentials to trade energy bi-directionally, PV uncertainty, EV driving uncertainty, and the different priorities for selling the energy to the grid. In [10] a multiagent-based smart control structure with particle swarm optimization (PSO) has been provided to control and manage the integration of plug-in hybrid EVs in a smart building.

Authors in [16] present a BEMS based on the multiagent systems to manage electricity, cooling, and heating energy sectors. In [15] an MILP approach has been provided to minimize the energy consumption costs of a day-ahead of an intelligent building with several smart homes. This model includes both energy and operation costs.

In [46], an energy management scheme presented for buildings inside a microgrid in which EVs are considered as important components for improving the buildings' performance in terms of energy and economic. Also, in this reference, the building-to-vehicle and vehicle-to-building frameworks have been discussed. An MILP model has been proposed in [29] for scheduling the operation of distributed energy resources (DERs) and optimize both the energy consumption cost and the CO_2 emission in the smart homes. Moreover, the daily energy consumption of appliances has been scheduled by considering economic and environmental sustainability.

In [38], an mixed-integer non linear programming (MINLP) model has been presented that optimizes multiple buildings operation alongside microgrid considering comfort and energy management. This model minimizes the cost of energy purchase from the grid by guaranteeing constraints of the main grid.

A thermal energy storage system based on phase change material for energy management in smart buildings has been also presented. Furthermore, a two-stage method of dispatching thermal and electric combined has been designed in [41].

A two-stage optimization model is studied in [55] for multiple home energy management system and local distribution companies to increase operational efficiency of the grid and decrease peak load, power losses and energy cost.

To reduce the peak load, a dual tracking control-based energy management system has been presented in the smart

[1] The reported information for the year 2020 is not for the whole year. It is based on the information received on 9^{th} November 2020 from the *Web of Science* website: *https://www.webofknowledge.com/*

TABLE 4. A comparison taxonomy of the published works in the field of active building energy systems.

		Focus											Technologies														Model	
Reference	Publication Year	Control & Monitoring	Cyber-Physical System	Operation & BEMS	Data-Driven Analysis	Building Physics	Cyber Security	P2P, V2B, B2V	Residents' Comfort	Policy & Regulation	Thesis	Review/White Paper	Renewable Generation			Energy Storage System		Electric Vehicle	IoT & Sensor Networks	CHP	HVAC & TCL	Heat Pump	Demand-Side Response	Other Network services	Multi-vector Analysis	Network Interaction	Optimization	Data-Driven
													WT	PV	FC	BAT.	TH.											
[8]	2011	-	-	-	-	*	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	DS	-
[9]	2012	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-		*	*	-	-	-	MILP	-
[10]	2012	*	-	-	-	-	-	-	*	-	-	-	*	*	-	-	-	*	-	-	-	-	-	-	-	*	-	-
[11]	2012	*	-	-	-	-	-	-	*	-	-	*	-	-	-	-	-	-	*	-	-	*	-	-	-	-	-	-
[12]	2012	*	-	-	-	-	-	-	*	-	-	-	*	*	-	*	-	-	-	-	-	-	-	-	-	*	-	-
[13]	2012	-	-	*	-	-	-	-	*	-	-	-	-	*	-	*	*	-	-	*	*	*	-	-	*	*	MIP	-
[14]	2012	*	-	-	-	-	-	-	*	-	-	-	*	*	-	*	-	-	-	-	-	-	-	-	-	-	-	-
[15]	2013	-	-	*	-	-	-	*	*	-	-	-	*	-	-	*	*	*	-	*	-	-	-	*	-	*	MILP	-
[16]	2013	-	*	*	-	-	-	-	-	-	-	-	-	*	-	*	*	-	-	*	*	-	-	-	*	*	NLP	-
[17]	2013	-	-	-	-	-	-	-	*	-	-	-	*	*	-	*	-	-	-	-	-	-	-	-	-	*	NLP	-
[18]	2013	-	-	*	-	-	-	-	*	-	-	-	-	-	-	*	-	*	-	-	*	-	*	-	-	*	LP	-
[19]	2014	*	*	-	-	-	-	-	*	-	*	-	-	-	-	-	*	-	-	-	*	*	-	*	-	-	LP	-
[20]	2014	-	-	-	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[21]	2014	*	-	-	-	-	-	-	*	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[22]	2014	*	-	-	-	-	-	-	-	-	-	-	*	-	-	*	-	-	-	-	*	-	*	-	-	*	GT	-
[23]	2014	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	*	-	-	-	MILP	-
[24]	2015	-	-	*	-	-	-	-	-	*	-	-	-	*	-	-	-	-	-	-	*	-	-	*	-	-	NLP	-
[25]	2015	*	-	-	-	-	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	*	-	-
[26]	2016	-	-	-	-	*	-	-	-	-	-	-	-	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-
[27]	2016	*	-	-	-	-	-	-	-	-	-	*	-	-	-	*	*	-	-	-	-	-	*	-	-	*	-	-
[28]	2016	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	*	-	-
[29]	2016	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	*	*	-	*	-	-	-	-	*	-	MILP	-
[30]	2016	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	*	*	-	-	-	-
[31]	2016	-	-	-	-	-	-	-	-	-	*	-	*	*	-	-	-	*	-	*	-	*	*	*	-	-	-	-
[32]	2017	*	-	-	-	-	-	-	-	-	-	-	*	*	-	-	*	-	-	-	-	*	*	*	-	-	CP	-
[33]	2017	-	-	*	-	-	*	-	-	-	-	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-
[34]	2017	*	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*
[35]	2018	-	-	*	*	-	*	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	*
[36]	2018	-	-	*	-	-	-	*	-	-	-	-	-	*	-	*	-	*	-	-	-	-	*	-	-	*	MILP	-
[37]	2018	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	*	CP	-
[38]	2018	-	-	*	-	-	-	-	*	-	-	-	-	*	-	*	-	-	-	-	*	-	-	-	-	*	MINLP	-
[39]	2018	*	*	-	*	-	-	-	*	-	-	*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[40]	2018	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	*
[41]	2018	-	-	*	-	-	-	-	*	-	-	-	-	*	-	-	*	-	-	-	-	*	-	-	-	*	-	-
[42]	2018	*	-	-	*	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	*	*	-	-	*	LP	-
[43]	2019	-	-	-	-	-	-	*	-	-	-	*	*	*	*	*	*	*	-	*	*	*	-	*	*	*	-	-
[44]	2019	-	-	*	-	-	-	-	-	-	-	*	*	*	-	*	-	*	-	*	*	*	-	-	-	-	-	-
[45]	2019	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	NLP	-
[46]	2019	-	-	*	-	-	-	*	-	-	-	-	-	*	-	*	-	*	-	-	*	-	-	-	-	*	DS	-
[47]	2019	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	-	*	-	*	-	-	-	-	-	-	*
[48]	2019	-	-	*	-	-	-	-	*	-	-	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-
[49]	2019	-	-	-	*	*	-	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	*
[50]	2019	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	*	-	*	-	*	-	-	-	-	*
[51]	2019	*	-	-	-	-	-	-	*	-	-	-	-	*	-	*	*	*	-	-	*	*	*	-	*	-	QP	-
[52]	2019	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	*	CP	-
[53]	2019	-	-	*	-	-	-	-	*	-	-	-	-	-	-	-	-	-	-	-	*	-	-	-	-	-	-	-
[54]	2019	*	-	*	-	-	-	*	-	-	-	-	-	*	-	*	-	*	-	-	-	-	*	-	-	*	QP	-
[55]	2019	-	-	*	-	-	-	-	*	-	-	-	-	*	-	-	-	*	-	-	-	-	*	*	-	-	NLP	-
[56]	2019	*	-	-	-	-	-	-	*	-	*	-	*	*	-	-	*	-	-	*	-	*	*	*	-	*	-	*
[57]	2020	*	-	-	-	-	-	-	*	-	-	-	-	-	-	-	-	-	*	-	-	-	*	*	-	-	-	-
[58]	2020	-	-	*	-	-	-	-	*	-	-	-	-	*	-	*	-	-	-	-	-	*	*	*	-	*	MILP	-
[59]	2020	*	-	-	-	-	-	-	*	-	-	-	-	*	-	*	-	-	-	-	*	-	-	-	-	-	MILP	-

WT: Wind Turbine; PV: Photovoltaic; FC: Fuel-Cell; BAT.: Battery; TH.: Thermal; EV: Electrical Vehicle; CHP: Combined Heat & Power;
CP: Convex Programming; GT: Game Theory; DS: Dynamic Simulation; QP: Quadratic Programming; SOCP: Second-Order Cone Programming

grid that creates a microgrid including PV, battery energy storage, and EV [54].

A model for comfort and energy management have been presented in [12]. The smart optimization and multiagent system have been developed in applying control system to decrease energy consumption and increase occupant comfort in the smart buildings. A smart multiagent control system with a hierarchical smart optimizer has been designed. Also, a GUI-based platform has been provided for customers in order to control the building system according to their own priorities in [14].

In [57], experimental research has been done to remotely control the heating system of individual rooms in the buildings by considering the resident's comfort. The effect of actuation on increasing energy efficiency in buildings has been explained in [11]. An energy-efficient structure has been developed to drive the Heating, Ventilation and Air Conditioning (HVAC) systems, and control different plug-loads. Also, a policy based on the presence of the occupant in the building has been developed to control turn on/off of these systems.

The authors in [51] have proposed a model predictive control (MPC) framework to manage the heating and electric sources in harmony in smart buildings to meet the target of nearly zero-energy and participate in demand response programs automatically while maintaining human comfort. A distributed MPC approach for Volt/VAr control using a smart building in active distribution networks has been presented to control power quality in [52]. The authors in [32] have presented a robust distributed optimization model within an MPC framework for operational scheduling of flexible loads. Also, this model maximizes the flexibility of customers for providing some services to different actors.

Ostadijafari *et al.* [59] have developed a price-responsive operational model for HVAC systems of the buildings by considering the DERs and flexible loads. In order to minimize the cost of energy consumption by flexible loads, a nonlinear economic MPC has been presented by maintaining occupant comfort. In [53], authors have proposed a multiobjective optimal scheduling model to control the HVAC systems, especially in smart buildings where maintaining thermal comfort is essential. Two main objective functions are maximizing thermal comfort and minimizing the fluctuation of power.

Reference [19] presents a mathematical model for thermal behavior of buildings based on physics, MPC and robust MPC. Moreover, the cyberphysical facet of HVAC systems in view of design flow has been addressed. Also, in [56], thermal energy management and optimization of the buildings, control of energy generation, and using the results of these two studies with a holistic solution of energy management is proposed.

In [21] a comprehensive study on the smart control systems for managing comfort and energy in smart buildings is conducted. Also, this review paper provides information about comfort and energy and future trends. The main focus of this study includes the control system, human comfort, occupants' behavior, smart computational techniques, and simulation tools. In [50], the generated data by the Internet of Things (IoT) is analyzed to find a precise model of thermal comfort. Also, a deep neural network has been utilized for modeling the relation between thermal comfort and operation of controllable building.

A model to analyses the occupant behavior effect on thermal comfort and energy performance is proposed in [8]. Also, a probabilistic method to find occupants' behavior has been implemented. Dong *et al.*, in [37] present a new platform that provides the interaction between load controls of building and the main grid easily by considering occupancy behavior. This framework can forecast, simulate, and optimize energy consumption and buildings' indoor temperature, the set-point of the generator by keeping the acceptable frequency of the grid. Besides, this integrated platform leads to saving costs up to 60% in comparison with the decoupled platforms.

In [26], a new system which integrated the PV and thermo-electric systems is presented. Also, in order to explain the thermal patterns of these new systems the analytic thermal and electric model of PV cells, the model of air duck, and thermo-electric radiant panel model are presented.

Ma *et al.*, in [34], present a method to detect the activity of electrical appliances in smart buildings. This method uses a smart meter device In order to make detection and learning processing. Moreover, this study has proposed the appliance fingerprint concept and diversity of fingerprints and accordingly a multi-source assortment algorithm has been proposed.

The authors in [25] investigate regulation service reserves that are provided by DSRs. They have considered an operator of a smart building that adjusts total consumption as a result of market signals, triggered in reaction to an unexpected need for regulation services.

An appropriate review on the stimulant for demand response and a comprehensive summarized of architectures, control and communication protocols, and technology infrastructure in this field have been presented in [27]. In [22] a novel DSR framework based on the stochastic differential game is developed. This study focuses on controllable loads that are related to dynamic systems like HVAC and water heating.

Moradzadeh *et al.*, in [18] suggest a decentralized optimization model for the demand of the residential sector in order to minimize customer and utility cost with preserving occupant satisfaction. Also, because of a wide range of uncertainty in demand of residential sectors a two-stage pricing has been presented which stimulates customer to participate in demand response programs. In [23] a framework to distributed demand response management has been presented for coordinating demand response presented by residential sectors.

Four important technologies include IoT, big data, cloud computing, and monitoring technologies have been investigated based on the common operations in [35]. Furthermore, a novel system to collect and manage data of sensors has been explored. Also, some solutions have been proposed to increase energy efficiency in the smart building. The authors in [33] provide a comprehensive technical review on both opportunities and challenges confronted by the IoT in the intelligent buildings considering: the intelligent buildings requirement, the ability of the IoT in decreasing the energy cost and improving surveillance in buildings, novel improvement in power over Ethernet, and some crucial concern related to IoT development like standardization, architecture, and cybersecurity.

In [48] the state-of-the-art of IoT is explored. The concepts of IoT and the enabling technologies related to IoT in the smart buildings, some IoT applications at the building level, and opportunities and challenges of integration of IoT in the smart buildings have been presented. In [40] an IoT gateway has been designed and developed to integrate legacy protocols into a BEMS software based on cloud computing.

Zhang *et al.*, in [45], focus on the problem of optimal communication scheduling to obtain the architecture of optimal communication by considering the wireless communication technical characteristic and the smart meter physical location. The authors in [49] have proposed a framework for smart buildings that is composed of seven layers including IoT components for service provision. Furthermore, a smart light system based on this framework has been designed and implemented. In [47], an IoT-based learning framework of the plug-and-play thermal model in buildings is investigated and developed. It can automatically detect the building thermal model without user intervention.

The authors in [39] review recent research works on the predictive control system, data processing, and building automation. This review paper focuses on improving energy efficiency in buildings by information and communication technology. A comprehensive review of forecasting methods of electric demand has been conducted also various models used and future trends have been presented in [20]. Besides, the latest research on demand prediction has been analyzed in the presence of smart grids.

In [13] a stochastic optimization analysis is presented and resolved by the scenario tree method for the planning of the smart building. They have compared the performance of various kind of energy storage systems like battery and cold/heat storage systems along with the optimal capacities of ESSs. In [44] the authors have reviewed different works about convex optimization methods for managing and decreasing energy consumption through ESSs with and without RESs in buildings.

In [42] a new bi-level optimization framework is presented which includes models of buildings and smart distribution grid together with their constraints. In [17], an adaptive attitude bidding strategy-based negotiation is presented. In this model, a complete set of factors for the integrated smart buildings into the utility grid has been considered.

Lawrence *et al.*, in [28], present ten critical questions about integrating intelligent buildings to the smart grid and provide appropriate answers for them. These questions are about: definition, main technologies, the scale of smart grid interaction with smart buildings, the effect of this interaction on the building's vulnerability and the resiliency and stability, measures for interacting control systems of HVAC with the smart grid, public policy for stimulating to integrate the smart building into the smart grid, the role of society for encouraging to participate in demand response and smart grid, strategies for directing occupancy behavior to improve this interaction, and the critical development and research to meet this interaction and implementation of smart buildings and smart grid.

The authors in [43] have conducted a review on the interaction and integration of energy between the different types of buildings and electrical vehicles by considering various forms of energy, advanced conversion of energy, different energy storage system, and interactions of the hybrid grid.

In [30], [31] the relationship between buildings and energy sectors has been investigated based on a web survey and interviews in Sweden. Also, cooperation barriers of these two sectors have been identified and some suggestions to strengthen this cooperation has been presented. The buildings and energy sector perspective in the smart buildings, market and business models, and views of stakeholders have been presented.

In [58] a multiagent system-based framework for transactive energy management in the residential buildings has been presented to optimize energy cost and mitigate overloads in the grid. Also, an energy management system has been proposed to schedule DERs and loads in the buildings.

III. CONTROLLABLE NANO ENERGY SOURCES AT ACTIVE BUILDING

The climate change as an undoubtedly major challenge of the world of today, necessitated the global community start working together to reduce emissions and limit global warming. To meet the mentioned emission targets and concurrently meet the growing energy consumption in the different sectors (and especially in buildings with the share of about 40%), there is a worldwide demand for utilizing the distributed renewable energy sources.

Since the 1990s, the rate of uptake of RESs has increased by 2%, annually. These resources have been used in various sectors; however, as it has been shown in Table 5 about 41.7% of the total renewable energy are consumed in the residential, commercial and public sectors [60]. Implementation of building-size RESs, including micro-wind turbines and PV along with the penetration of ESSs and the EVs not only supply power to commercial and residential buildings but also provide the ability to sell surplus energy to the grid. Fig. 5 illustrates the energy resources that are implemented in an active building.

A. PHOTOVOLTAIC

PV is a solid-state component which directly converts solar energy to the electricity without requiring fuel, moving parts, and causing pollution. PV systems originally utilized in space technologies then gently have found their way in various

TABLE 5. Share of the different sectors from the renewable sourced energies in 2017 [60].

Sectors	Percentage (%)
Residential, Commercial & Public	41.7
Electricity Plants	35.1
Industry	10.5
Transport	4.4
Combined Heat & Power	3.0
Others	5.3

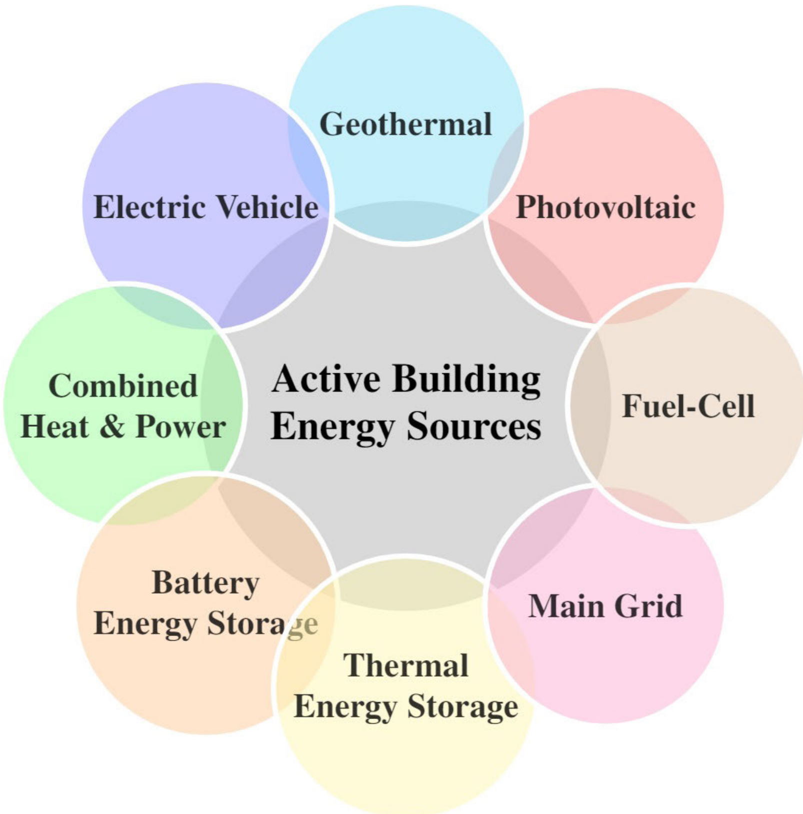

FIGURE 5. Potential energy sources in an active building.

applications especially in the demand-side energy production [61]. Indeed, PV is one of the most appropriate technologies which help to use solar energy efficiently and covert building to a prosumer structure in energy systems. PV modules or arrays have been installed on support structures conventionally. However, these technologies can be installed on buildings or integrated into them as building envelope such as roof, facade, or skylight which are called Building Integrated Photovoltaic (BIPV). BIPVs are also used in applications such as thermal insulation, weather protection, and noise protection [62].

According to Fig. 6, BIPVs can be divided into two categories. Roof-integrated systems also are divided into the skylight, standing seam products, shingles, and tiles which skylight is a semitransparent roof-integrated module, standing seam product is a long roof-integrated opaque module, the shingle is continuous roof-integrated opaque BIPV module, and tile is a roof-integrated BIPV module similar to roof tiles. Facade integrated systems are divided into glazings, spandrel panels, and curtainwall products. Glazing is a semi-transparent facade integrated module that daylight can come inside the building. Spandrel panel is facade integrated BIPV system that provides noise protection. Curtain wall product is facade integrated BIPV panels that equilibrate daylighting and shading occurrence [63].

B. WIND TURBINE

Another promising building-level renewable energy sources are small-scale wind turbines (WT). The building-integrated WT is referred to every type of wind turbines which can be integrated into the built environment by installing either off or on the buildings. There are different kinds of wind turbines for buildings including (*i*) building-integrated wind turbines; (*ii*) building-mounted wind turbines; (*iii*) building

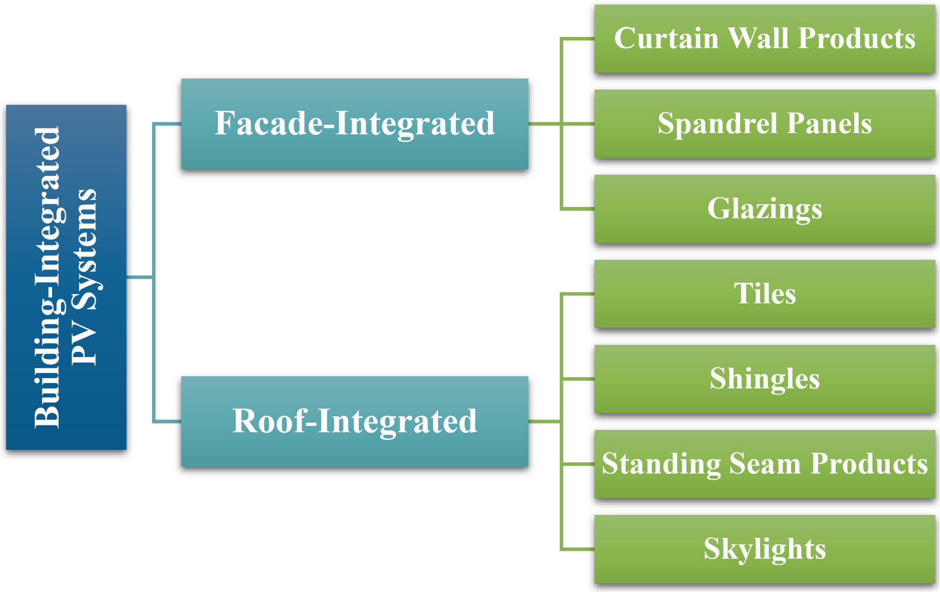

FIGURE 6. Taxonomy of the different types of building-integrated PV systems.

augmented wind turbines [64]. Additionally, common types of building-integrated wind turbines include a horizontal axial wind turbine, vertical axial darrieus, and vertical axial savonius [65].

C. ENERGY STORAGE SYSTEM

The integration of RESs imposes more uncertainty on the energy system as they are affected by diurnal and seasonal variations. Therefore, it is an undeniable need to use ESSs along with RESs in order to balance their effects and maximize the efficiency of energy systems. ESSs are able to provide flexibility for managing generation and demand at the building level and also might participate at the network level for increasing the integration of renewable energy and deferring investment for upgrading the infrastructures.

D. ELECTRIC VEHICLE

The transportation sector is responsible for about 22% of the GHGs globally and therefore extensive works have been done in order to evaluate EVs impact on this issue [66]. EVs are the other promising technologies on the demand-side and usually at the building and houses and act like a prosumer. Building-to-Vehicle (B2V) and Vehicle-to-Building (V2B) technologies include the bidirectional electricity flows between the buildings and EVs. In the clear language, B2V refers to the charging process of the EVs by the building, and V2B is named the discharging process of EVs into the building. The purpose of V2B is the utilization of EV as an occasional energy resource in buildings. The main goal of these concepts is to exploit the utilization of the potential of EVs for accelerating the movement toward the net-zero energy building [67].

E. FUEL-CELL

A fuel cell is a device that converts the energy of fuel from the chemical form into electrical by electrochemical reactions directly. Fuel cells use hydrogen as fuel and convert energy with a clean and efficient mechanism also, these technologies are compatible with RESs for achieving sustainable development [68]. The fuel cell is similar to a battery in a different aspect, but it can provide more electrical energy over a much longer period of time.

F. CHP

Micro combined heat and power (CHP) as a small-scale unit for generation of heat and electric power is becoming more popular in buildings. It is able to be applied as a direct replacement for gas-fired boilers as a micro-CHP unit is similar in shape and size to a conventional boiler of the buildings [69]. A micro-CHP generates electric power on-site and uses by-product thermal energy to meet water and space heating loads. Also, micro-CHP can supply space cooling loads by using thermal output to regenerate the desiccant in desiccant dehumidification systems and drive chiller [70]. CHP generate electrical and thermal energy, simultaneously, in a more efficient and environmentally friendly way.

IV. ACTIVE BUILDING ENERGY MANAGEMENT SYSTEM

The building energy management system (BEMS) consists of all the measures that are planned and implemented for controlling and monitoring energy consumption. Building assets such as HVAC and lighting would intensify the energy wasted if there is no appropriate control and management on them. A number of key features of a BEMS are presented in Fig. 7 [71].

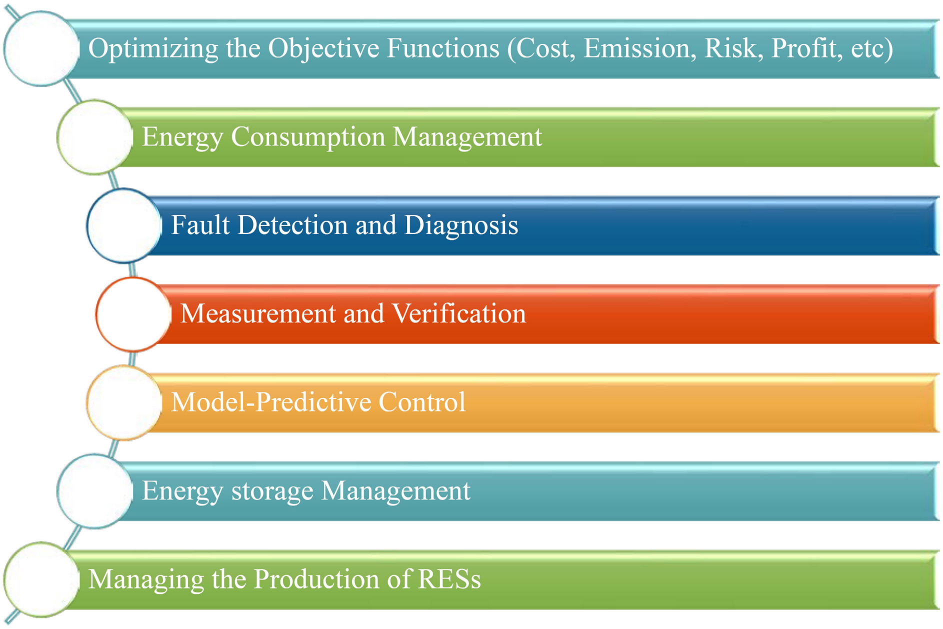

FIGURE 7. Some of the key features of a BEMS.

A. SMART BUILDING ENERGY MANAGEMENT SYSTEM

Integration of control system with BEMS provides an opportunity for adjusting abnormal energy consumption. Also, in the presence of the advanced information and communication technology and by using an automatic control system, a BEMS become more practical and popular. The advanced and smart BEMSs contain integrated centralized system which can communicate with other systems and subsystems such as solar thermal, EV, ESS, and HVAC and have a real-time data exchange. The smart BEMS is able to monitor and adjust the set-points of all subsystems. Building Information Modeling (BIM) is an essential part of smart BEMSs since it can store geometric and physical information of building and component's information which make a more reliable BEMS [72], [73].

B. IoT-ENABLED BUILDING ENERGY MANAGEMENT SYSTEM

The IoT is a network of physical objects that includes software, sensors, and electronic devices. The emerging of inexpensive and advanced sensors, user-friendly application as a software-as-a-service, and cloud-provided services led to deploy the IoT in buildings. To make a building IoT-enabled, all objects are equipped with IoT with sensing, networking, identifying, and processing capabilities to share data with each other and the users [33].

Therefore, IoT brings valuable capabilities such as dynamic context-aware decision-making potentials and intelligent autonomy which facilitate obtaining the smart building's goals. IoT influences on management and operation by providing high-level services which deliver adequate signals to devices and profitable information to users [48], [74].

V. CHALLENGES AND OPPORTUNITIES OF ACTIVE BUILDINGS

There are a number of opportunities and challenges in the development of the active buildings that are analyzed in this section.

A. THE ROLE OF ACTIVE BUILDINGS IN NET-ZERO CARBON STRATEGY

To meet the Paris Agreement, significant changes are required in the economy and society. All parts of the economy and social sectors will play a role, from the power sector to industry, agriculture, forestry, transportation, and buildings. Among them, buildings have a key role in implementing the net-zero carbon strategy as they are the consumer of about 40% of the total energy consumption and they are also the junction of multiple energy vectors that open the way for a holistic approach to the energy.

B. LOOKING ACTIVE BUILDING THROUGH THE LENS OF WHOLE ENERGY SYSTEMS

An active building is the one who interacts with the local and whole-energy system and in its simplest form, it is either energy neutral or acts to minimize local energy imbalances to reduce congestion, defer network investment while improving resilient and maintaining system security. By having a range of innovative technologies, active buildings are able to offer both energy and flexibility to local and national network operators which will enhance the energy efficiency [1]

C. MARKET-BASED OPERATION AND CONTROL OF THE ACTIVE BUILDINGS

Considering the relatively small size of the energy transactions at the building level, they would not be able to directly

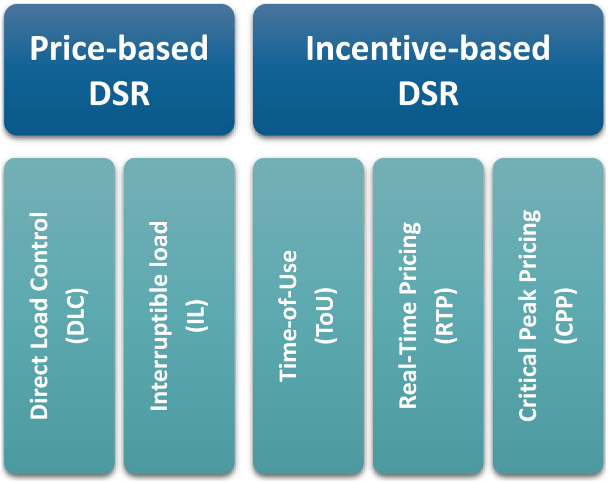

FIGURE 8. Potential demand-side response services in the electricity sector.

participate in the wholesale or even retail energy markets. In this regard, they can contribute as a part of a portfolio of an aggregator which may limit the potentials of active buildings.

However, due to the advent of transactive energy and peer-to-peer (P2P) electricity markets [75], [76], active buildings are conceptually allowed to directly trade their electrical energy with the other peers within the market. These so-called P2P markets rely on a bottom-up perspective by allowing small scale energy providers like active buildings and electric vehicles (EVs) to freely choose the way they buy/sell their required energy. An overview of the motivation, challenges and market designs of these new P2P markets is presented in [77].

D. ACTIVE BUILDING AS A NETWORK SERVICE PROVIDER

Participation of active buildings in electricity markets can mainly be divided into the demand-side response and ancillary services:

1) DEMAND-SIDE RESPONSE

According to the FERC definition, demand-side response is: "*changes in electric usage by demand-side resources from their normal consumption pattern in response to changes in the price of electricity over time or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized*". Integration of the DSR is an important feature of active buildings that according to the definition, it can be managed in the forms presented in Fig. 8. A comprehensive review of the DSR tools in electricity markets is presented in [78].

The objective of DSR policies is to smooth the daily load of a system by shifting the load (including the peak shaving and valley filling).

2) ANCILLARY SERVICES

In the power system, some services are required by the system operators to maintain the security of supply. These kinds of services include both mandatory services and services achieved via market-based mechanisms. Potential ancillary services that can be achieved from the active buildings are illustrated in Fig. 9 includes:

- Voltage and reactive power support;
- Constraint management;
- Grid losses reduction;
- Power quality services (i.e. improvement in voltage dips and flicker, as well as harmonics compensation);
- Frequency response services.

E. ACTIVE BUILDING INTEGRATION INTO THE ELECTRICITY DISTRIBUTION NETWORK

An active building, as a nano energy hub and the junction point of multiple energy vectors, is able to intelligently integrate the actions of all players in an efficient way. These actions involve the operation of DERs (e.g., PV, WT, and CHP), ESSs and EVs, and energy consumption. They are actively participating in procurement of the required energy and ancillary services of the grid, while also efficiently deliver sustainable, affordable and secure energy to the residents. In this regard, active buildings use innovative technologies for energy production and storage together with smart control and monitoring systems.

Considering the increasing penetration of the active buildings into the low-voltage distribution grids, it is of great importance to consider their potentials as active energy agents in enhancements of the distribution grid operation performance. The active buildings would affect the technical parameters of the grid including the voltage of buses they are directly connected, and the neighbour buses, flow of the lines in the grid, and power losses. Considering operation mode of active buildings and behaviour of the occupants, the impact that an active building would have on the grid will change.

An active building can also provide a range of active and reactive power using their available facilities. This can be used internally or to provide a service for the other neighbor active buildings or the main grid. Therefore, the optimal operation strategy for an active building is subject to the potentially conflicting objectives of the involved stakeholders, including active building residents, the distribution system operator, neighboring buildings, energy suppliers, aggregators and regulatory bodies. Hence, the optimal operation of an active building and the distribution grid are interrelated, and a techno-economic-environmental decision-making process is required to find the best possible operation strategy for a distribution grid. This strategy should consider the requirements and constraints of active buildings and the comfort of occupants while improving network performance.

Active buildings would also be able to be energy-positive and participate in the provision of flexibility services or any other active/reactive services for the distribution grids [3]. This is an interesting aspect of active buildings that make them a viable option to assist in coping with the intermittent nature of renewable resources [1].

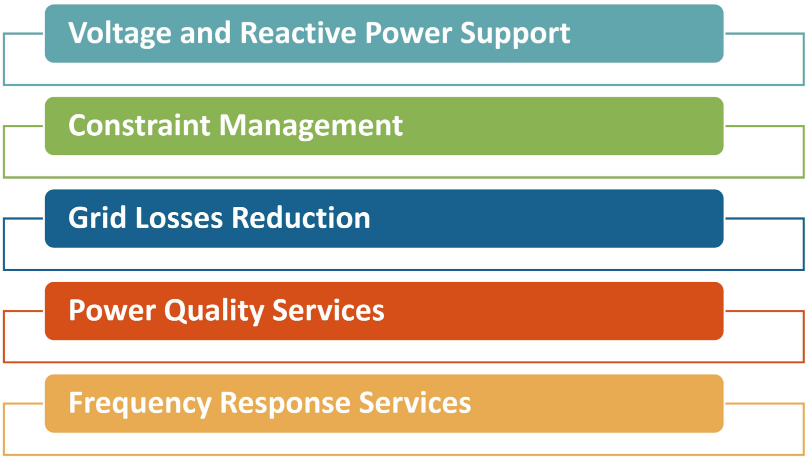

FIGURE 9. A number of ancillary services that can be provided by active buildings to the network.

F. CHALLENGES AND RESEARCH QUESTIONS

There are a number of challenges need to be faced and research questions need to be answered in order to leverage the benefits of active buildings in the energy systems and especially their impact on the decarbonisation efforts.

These challenges summarised in the following research questions:

- How the whole energy system may benefit from a substantial rollout of active buildings, to what degree and what problems may arise in the process?
- To what extent will the active building design be influenced by the energy system requirements?
- How can millions of active buildings be effectively integrated into the distribution grids operation and planning?
- What is the best possible operation strategy of the future distribution grids that improve the network performance while considering building's requirements and constraints and occupants' comfort?
- How these active buildings will be able to be positive-energy and participate in the provision of energy and ancillary services for the distribution grids?
- What might be appropriate market mechanisms or incentives (in short-, mid- and long-term) to enable active buildings participation in enhancing the distribution grids operation efficiency?
- Considering the evolution in the penetration of electronic/power electronic based devices that use Direct Current (DC), is Alternate Current (AC) still the best choice for design and operation of the power networks especially in the distribution grids?
- What are the features of the future building/grid energy management systems?

VI. CONCLUDING REMARKS AND OUTLOOK

In this paper, an overview of the concepts, challenges and outlook of the active buildings as an energy system presented. Using a systematic review of the literature, the works done in this field are investigated and potentials for new research works were highlighted. Also, different assets inside an active building are briefly introduced. Moreover, the challenges and opportunities of these agents in the future of energy systems are discussed.

This field is a vivid research area that needs to be explored in detail and the following directions are needed to be more investigated:

- The value of active buildings on the energy systems in short-, mid- and long-term needs to be assessed to help the policy-makers in designing a meaningful incentive mechanism;
- Considering the developments in cryptocurrencies and blockchain technologies, the role of peer-to-peer transactions at building level and also at district level would become highlighted and these evaluations need to be considered in the operation and planning of the distribution grids;
- Another direction is the design of methods and mechanisms for using the potentials of active buildings in the time of emergencies for preventing a widespread power outage or in contingencies to accelerate service restoration;
- The role of active buildings in improving the resilience of the energy systems is another motivating field of research that needs to be investigated;
- As occupant behaviour is the most important factor in the operation of the buildings, in-depth studies need to be done on this issue from the perspective of the social sciences.

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