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Power to heat: Opportunity of flexibility services provided by building energy systems

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ABSTRACT

Buildings play a crucial role in global electricity consumption, but their function is evolving. Rather than merely consuming energy, buildings have the potential to become energy producers through participating in flexibility services, which involve demand response and distributed energy supplies. However, the new technological and societal challenges that arise from temporal and spatial changes on both supply and demand sides make building services increasingly complex. This paper presents an opportunity for flexibility services offered by building energy systems via power-to-heat technology and discusses four key aspects: quantitative indicators based on thermal inertia, model predictive control for building flexibility, flexible system optimization for smart buildings, and applications of flexible services. Thermal inertia is a crucial factor that transcends technical constraints and serves as a bridge between the demand and supply sides. Demand-side response and data-driven cogeneration under model predictive control are essential for managing building flexibility. In addition, flexible system optimization is achieved through the combination of demand-side trading and disturbed system optimization. Applications of flexible services represent a combination of demand-side trading and disturbed system optimization in the fields of engineering and sociology. Finally, the paper explores the challenges, as well as the potential and models of building flexibility services technologies, including features that can facilitate automated operational decision-making on both the demand and supply sides.

Introduction

The traditional rigid framework of the global energy system is transitioning towards a more flexible model, characterized by decentralized and mobile providers that primarily rely on renewable sources of energy [1,2]. Due to the widespread development of the renewable energy and thermal inertia of architectures, the buildings play a critical and complex role in the current transitional period and will contribute to the ongoing energy transition [3,4]. Researchers and policymakers have focused on the buildings as a critical component of the pathways for the net zero greenhouse gas emissions [5,6]. Flexibility services of building is a fundamental concept that has gained significant attention. It refers to the ability of a building or built environment to adapt and accommodate changing needs, functions, and technologies over time. The concept of flexibility recognizes that buildings are not static entities but rather dynamic systems that should be able to respond to evolving user requirements and societal demands. The flexibility provided by buildings can not only save the conventional consumption of electricity generation but also the constructions of energy storage [7,8]. Therefore, the flexible services provided by the building energy system have been identified as one of the main tracks for the extensive market penetration of the distributed energy and the most promising applications. In the field of energy applications, building flexibility is particularly evident in the dynamic balance and thermoelectric response of the demand side and supply side.

Building is the main part of the energy consumption, where the heating system contributes the most to the total building consumption [9,10]. Building energy flexibility refers to the ability of a building or a building energy system to adjust and adapt its energy consumption and generation patterns in response to changing conditions and requirements. This flexibility allows buildings to respond to variations in energy supply, demand, and pricing. It involves technologies, strategies,

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and control systems that enable buildings to modulate their energy usage, shift loads to off-peak periods, utilize on-site energy generation, and even contribute surplus energy back to the grid. The concept of building energy flexibility encompasses various aspects, including but not limited to demand response, energy storage, load shifting, renewable energy integration, and advanced control strategies. It aims to optimize energy use, enhance the resilience and reliability of the energy system, and contribute to the overall sustainability and efficiency of the built environment. The flexibility of building energy consumption is reflected in the thermoelectric conversion process of the buildings. Accounting for the influence of the thermal inertia for the building envelopes and structures, buildings can operates smartly by a set of designs and managements [11,12]. The thermal inertia enables demand-side management at the peaking time and achieves the benefits from the load shifting, favoring the reduction in the grid stress [13,14]. Besides, the potential room for the renewable energy growth means that the novel prediction technology can be merged with optimization methods for better performance [15,16]. Although buildings offer flexible services, they continue to face challenges from both the supply and demand sides. On the demand side, managing and responding to electricity demand presents difficulties, but providing options such as flexible modes and time periods for electricity consumption can help address these challenges [17,18]. In supply-side, the variability of renewable energy and climate difference bring more unpredictability for the process of power to heat [19,20]. Therefore, a flexible managing strategy can balance the demand side and the user side to realize the collaborative response of the two. Many examples have corroborated this, like a zero-emission building in KhshU [21], flexible BIPV facility in Turkey [22], many cases proved the huge potential of building flexible services [23].

The flexibility services provided by building energy system is a concept that could meet the future needs on both demand and supply-side. The rapid expansion of the distributed energy resources is transforming not only the way that electricity is generated, but also how it is traded, delivered, and consumed [24], which bring new possibilities of building flexibility. Flexibility studies in different types of buildings, such as residential, commercial, educational, healthcare, and public infrastructure also show various features [25]. A body of previous investigations have been made on the flexible energy system services to conquer this dilemma, especially for the flexible services provided by heat pump [26]. Lamnatou et al. [27] summarized the changes in smart technologies of the photovoltaics and storage systems in residential buildings; however, the impact of demand-side data for building services was also ignored. The possibility of further analysis of the control strategies for improving the energy flexibility provided by heat pump systems in buildings was verified in the review of Péan et al. [28]. Mlecnik et al. [29] discussed the progress of key policies and factors in building energy systems, reporting plenty of data but not conducting a deep analysis of demand-side changes. However, they did not consider the quantifying factor for building flexibility.

Most reviews confirm the flexibility and resilience of building energy systems but fail to fully consider increasing impact of optimization and prediction methods [30], which are driving forces for future energy system transformations applications. Pallonetto et al. [31] provided a detailed summary of the assessments and control optimizations of demand response programs in residential buildings, confirming their superiority. However, the quantifying factor policy of the building flexibility was still not taken into account. They have considered the small-scale renewable energy system in buildings. The large-scale renewable energy system that has not been considered in their work is expected to promote the energy system more effectively. In their study, Li et al. [32] conducted a review of flexible photovoltaic systems for buildings, focusing on their design, energy performance, and cost. However, the review did not include a summary of the demand side. Similarly, Salehinejad [33] presented a blueprint for future building design, but did not account for the impact of various demand response methods [34]. Luo et al. [35] acknowledged that there is still room for improvement in data-driven cogeneration of building energy systems, particularly with regards to integrating data-driven optimization and demand-side flexibility. Current capabilities, limits and open issues of buildings have been commented and reviewed by Ascione et al. [36]. However, it should be noted that the flexibility of the demand side, which includes occupant behavior [37], as well as the supply side, has not been uniformly considered.

On the one hand, model predictive control (MPC) for building flexibility refers to the application of MPC techniques to optimize and control the energy consumption and generation within a building or a building energy system. MPC utilizes mathematical models of the building's energy dynamics and considers constraints, such as comfort levels and energy efficiency targets, to make real-time control decisions [38]. It enables adaptive and proactive management of energy resources, allowing buildings to respond dynamically to changes in energy supply, demand, and pricing. MPC focuses on optimizing the operation of the building's energy systems to achieve desired objectives while considering constraints. On the other hand, flexible system optimizations for smart buildings refer to a broader approach that encompasses various strategies and technologies to enhance the flexibility and adaptability of buildings as a whole [39]. It involves the integration of advanced sensors, data analytics, automation, and control systems to optimize the overall building performance, including energy efficiency, occupant comfort, and operational flexibility. Flexible system optimizations for smart buildings aim to create intelligent and responsive building environments that can dynamically adjust to changing conditions and user requirements. This approach often goes beyond energy systems alone and considers other aspects of building operations and management, such as space utilization, occupant behavior, and maintenance. While MPC for building flexibility is a specific control strategy within the broader scope of flexible system optimizations for smart buildings, they are complementary approaches that work together to achieve building energy flexibility [40]. MPC provides the control mechanism to optimize energy systems, while flexible system optimizations provide the framework and technologies to enable dynamic and adaptive building operations [41].

Difficulties and challenges arise when it comes to effectively utilizing building flexibility [42]. In order to overcome these challenges, this paper aims to comprehensively review and summarize technological advancements related to building flexibility, including both the supply and demand sides. Special attention is given to discussing building flexibility services that consider thermal inertia beyond traditional building constraints. Initially, this paper provides a brief summary of the current state of power-to-heat technology in building systems. Additionally, it delves into the key performance indicators for building flexibility, from both the supply and demand perspectives. Afterwards, model predictive control involve data-driven cogeneration and demand side response on electricity market are reviewed. The flexible system optimizations for smart buildings are discussed including 6E analysis (Energy, Electricity, Entropy, Exergy, Economy, and Environment analysis), smart appliances, and P2P trading. The flexibility services provided by buildings energy system should have the following three characteristics: quantized indicators based on the thermal inertia, model predictive control for buildings flexibility, and flexible system optimizations for smart buildings. The applications of building flexible services are also introduced and reviewed in the view of supply and demand side. The challenges and perspectives of developing flexibility services are discussed in this article, along with proposed research directions and solutions to address the aforementioned dilemma. Fig. 1 illustrates the basic structure diagram of the flexibility services offered by buildings.

Thermal inertia of power-to-heat in buildings

Energy systems are currently experiencing a significant shift from being fixed and simplistic to being distributed, complex, and adaptable.

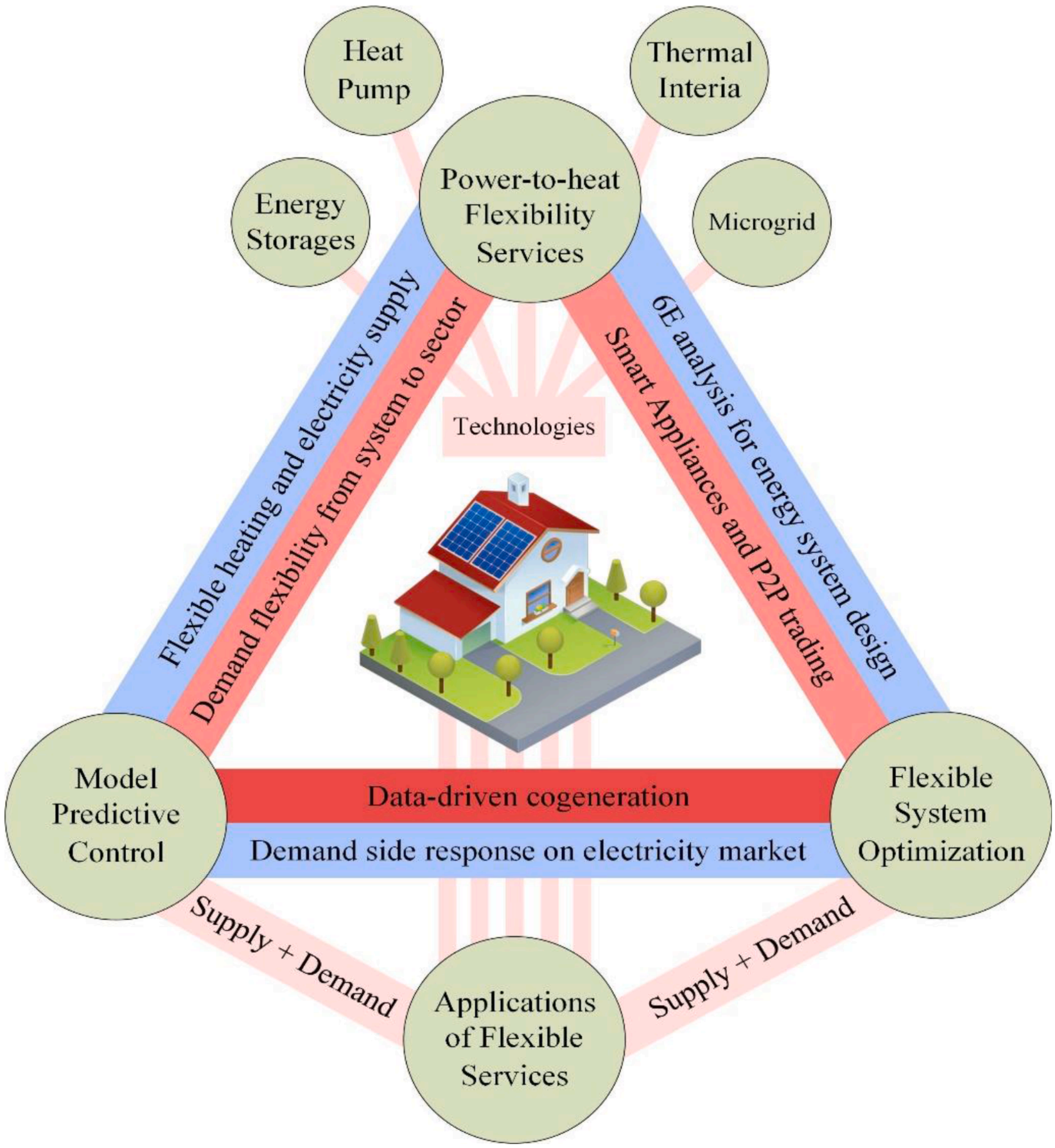

Fig. 1. Structure diagram of flexibility services provided by building energy systems.

As a consequence of this transformation, buildings have emerged as playing a vital role in addressing climate change and promoting energy efficiency and demand flexibility because of thermal inertia. Technological advancements, fueled by renewables and electric-powered heating systems within buildings, offer cost-effective means of mitigating the devastating effects of climate change and fossil fuels. As extreme weather conditions increasingly cause greater damage to power-to-heat systems, it has become imperative to establish a flexible and reliable supply of heat and power, via building adaptability, in order to rapidly respond to immediate challenges. Additionally, buildings are inevitably connected to carbon emissions, as illustrated in Fig. 2 which depicts the multilevel relationship between energy demand within a building and its corresponding energy system operation. Building energy demand in the United States is responsible for consuming 75% of all electricity utilized and producing 35% of carbon emissions. Similarly, in China, carbon emissions resulting from building heating needs are escalating at a startling speed [43]. It is crucial to quantify building resources, such as energy efficiency and demand flexibility, so as to reduce carbon emissions and adhere to the Paris Agreement. The key performance indicators (KPIs) for building demand flexibility enable the provision of flexible services for the decarbonization pathway, which is particularly relevant in contemporary times.

The IEA (International Energy Agency) project provides valuable insights into building energy flexibility by examining the various aspects and implications of flexible energy systems in buildings [44]. Their research covers topics such as demand response, load shifting, thermal storage, and the integration of renewable energy sources [45]. The project emphasizes the importance of building energy flexibility in achieving energy efficiency, grid stability, and renewable energy integration goals. Additionally, the Annex67 project, also known as the "Energy Flexible Buildings" project, offers a comprehensive and in-depth exploration of building energy flexibility [20]. It focuses on developing and implementing advanced control strategies and technologies to enable flexible energy management in buildings. The project investigates various factors, including thermal storage, demand response, grid interaction, and optimization algorithms, to maximize the potential of building energy flexibility. The proliferation of electrification has underscored the crucial role of buildings in the sphere of energy supply and demand, manifesting as a two-way interactive trend. The research in traditional building and power sectors has remained siloed, failing to leverage the advantages of co-optimization. Against this backdrop, this chapter elucidates the hallmarks of contemporary building flexibility

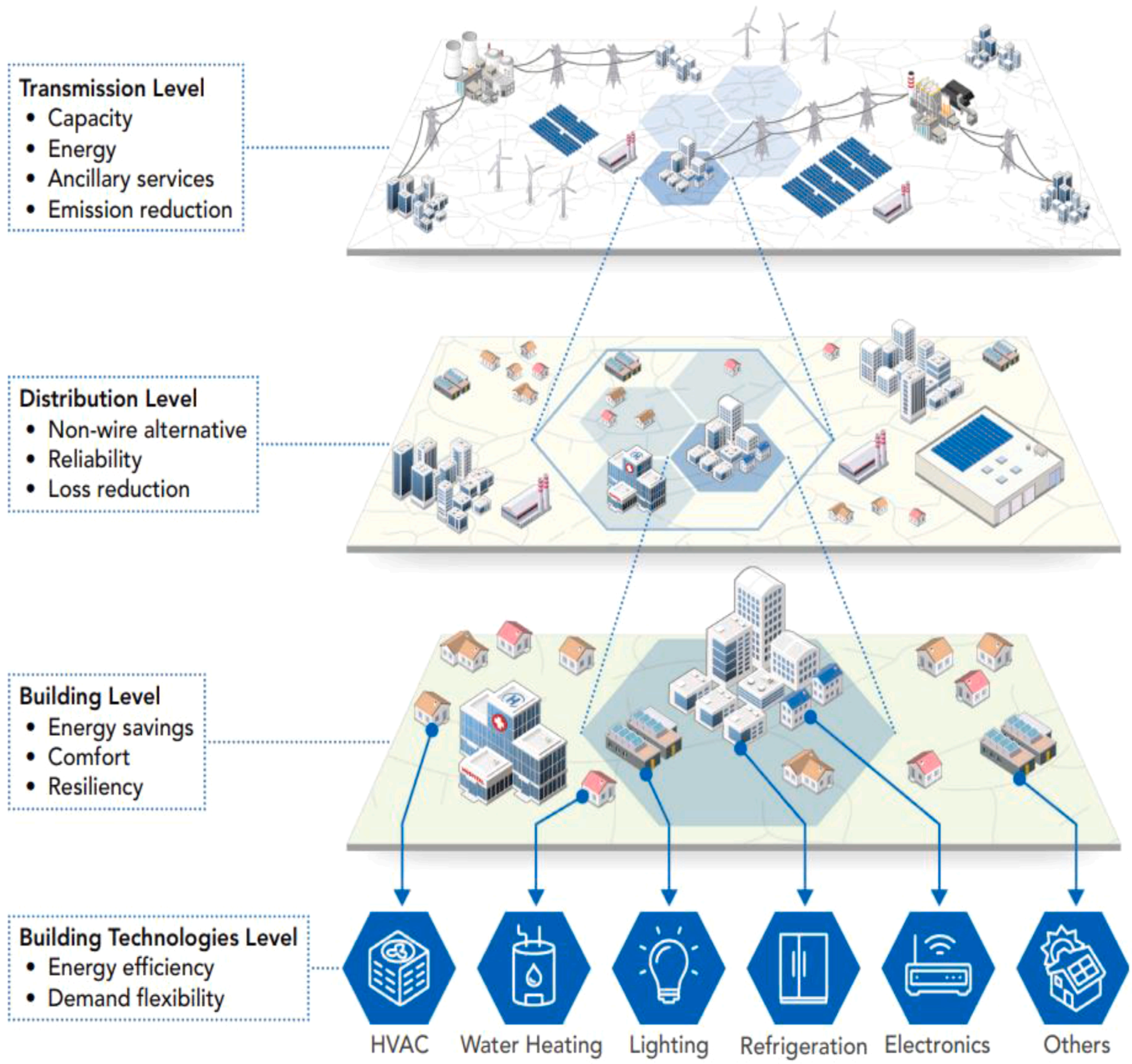

Fig. 2. Multilevel benefits from building energy efficiency and demand flexibility [48].

services in relation to both the supply and demand sides. Furthermore, the key performance indicators (KPIs) that dictate building flexibility are summarized and delineated. Studies on the measurement and practical application of building flexibility in relation to thermal inertia have provided valuable insights for building flexibility services. Many case studies have employed various methods, such as temperature monitoring and thermal simulations, to assess thermal inertia. Leveraging thermal inertia through flexible building design strategies leads to reduced energy demand, improved thermal comfort, and more stable indoor conditions [46]. However, challenges related to climate variations, materials, and occupant behavior should be considered. Future research directions include exploring the optimal balance between thermal inertia and responsiveness, investigating innovative materials and technologies, and conducting long-term monitoring studies for real-world energy savings assessment. More detailed analysis has been shown following parts [47].

Supply side: flexible heating and electricity supply

The thermal inertia of buildings has been the focus of particular attention within the context of heat and electricity supply [49]. The thermal adjustment of a building is not as adaptable as that of electrical equipment, rendering it less flexible. Demand deviation based on thermal inertia offers a means for achieving effective and flexible building services, wherein the building can be heated earlier or later to increase its operational efficiency [50]. Through intelligent control systems and energy storage technologies, electrothermal coupling can realize the dynamic allocation and optimal use of building energy to adapt to different needs and time changes [51].

The grid flexibility represents the key source of power stability, especially given the gradual emergence of temporal randomness and spatial distance associated with renewable energy production [9]. Typically, flexible services are realized through the supply side of energy provision, often via carbon-intensive energy generators [52]. However, recent years have seen a shift towards the characterization of building flexibility based on electric and thermal power, in which renewable energy sources play an increasingly crucial role, albeit giving rise to heat storage-related challenges [53]. Nuytten et al. [54] investigated the flexibility of buildings using a combined heat and power system that incorporated thermal energy storage. The researchers discovered that centralized storage facilities offered more flexibility than separate units, with the primary source of flexibility being the ability to delay electrical power consumption. This concept of forced and delayed energy storage flexibility has been embraced in many subsequent studies, such as those conducted by Zhou et al. [55], Hulst et al. [56], and Dréau et al. [57], particularly where the power curve of buildings is indeterminate. Incorporating the power curve into the building flexibility framework primarily involves gaging the time-dependent differences between maximum power and reference power. However, this definition may become increasingly complex in high-renewable energy settings [58].

In addition to temporal supply-side flexibility considerations, numerous studies have illustrated the spatial impacts of electricity production, such as power transmission distance, which can significantly influence the cost of producing electricity. This variability in electricity production, attributable to spatial impact, has a critical bearing on user choice and demand-side response [59,60]. Coninck et al. [53] examined conventional utility rates in direct connection with the cost of electricity supply, confirming that electricity demand for heating, ventilation, and air conditioning (HVAC) systems is heavily influenced by the pricing of power grid electricity. Dréau et al. [57] evaluated and demonstrated that building flexibility should encompass factors such as comfort, capacity, efficiency, and shiftability, as well. Nevertheless, attaining heat comfort may be more complex, as it is influenced by the energy supply equipment. Building-integrated photovoltaics and solar thermal systems have been shown to impact building heat demand and supply [61]. Despite the challenges posed by various temporal and spatial conditions on the supply side, the benefits of integrating local electricity and heat sources into buildings have been established [62]. Fig. 3 illustrates the various aspects and dimensions of energy flexibility characterization.

Demand side: demand flexibility from system to sector

Demand-side flexibility is achieved by adjusting building demand in conjunction with on-site generation. This interplay enables end-users to adapt to changing needs and adjust options based on the available facilities, facilitating greater flexibility. Fig. 4 illustrates the sources of flexibility in commercial and residential buildings. Utilizing the thermal inertia of a building to preheat or precool a space is an effective technique for shifting the electrical demands of HVAC equipment. Heat stored in building walls and other envelopes helps maintain thermal comfort for a certain period [63,64]. Previous research has recognized more than 40 unique types of end-users, mainly classified into two categories: commercial buildings and residential buildings. While most studies consider one or two types of end-users, some consider a range of types [65]. The scale of demand-side flexibility varies depending on the type of building, which can be classified into four levels: system, building, district, and sector.

At the system level, building heating and cooling systems are the primary focus of flexible evaluation, control strategy, and management

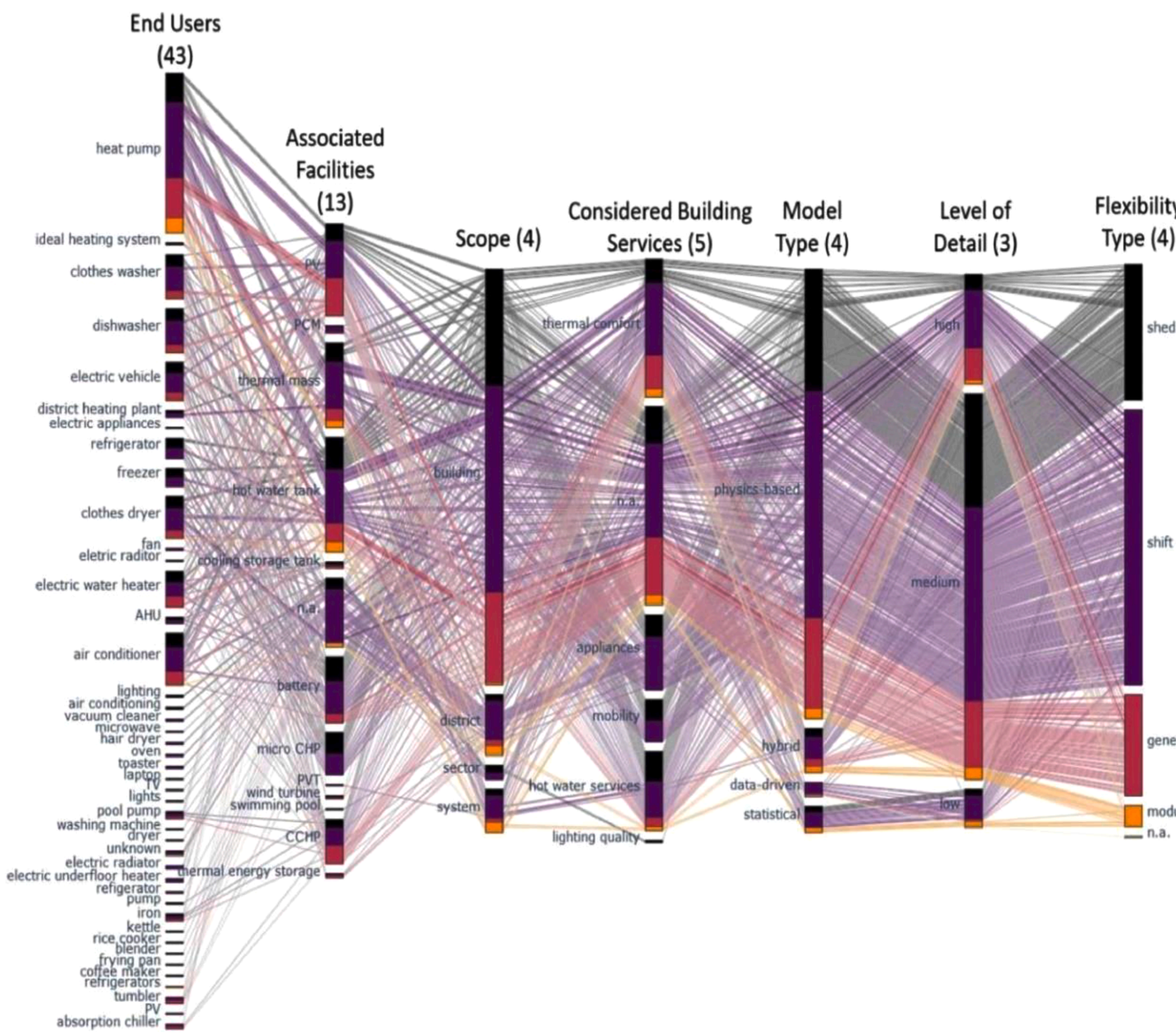

Fig. 3. Energy flexibility characterization aspects and dimensions [13].

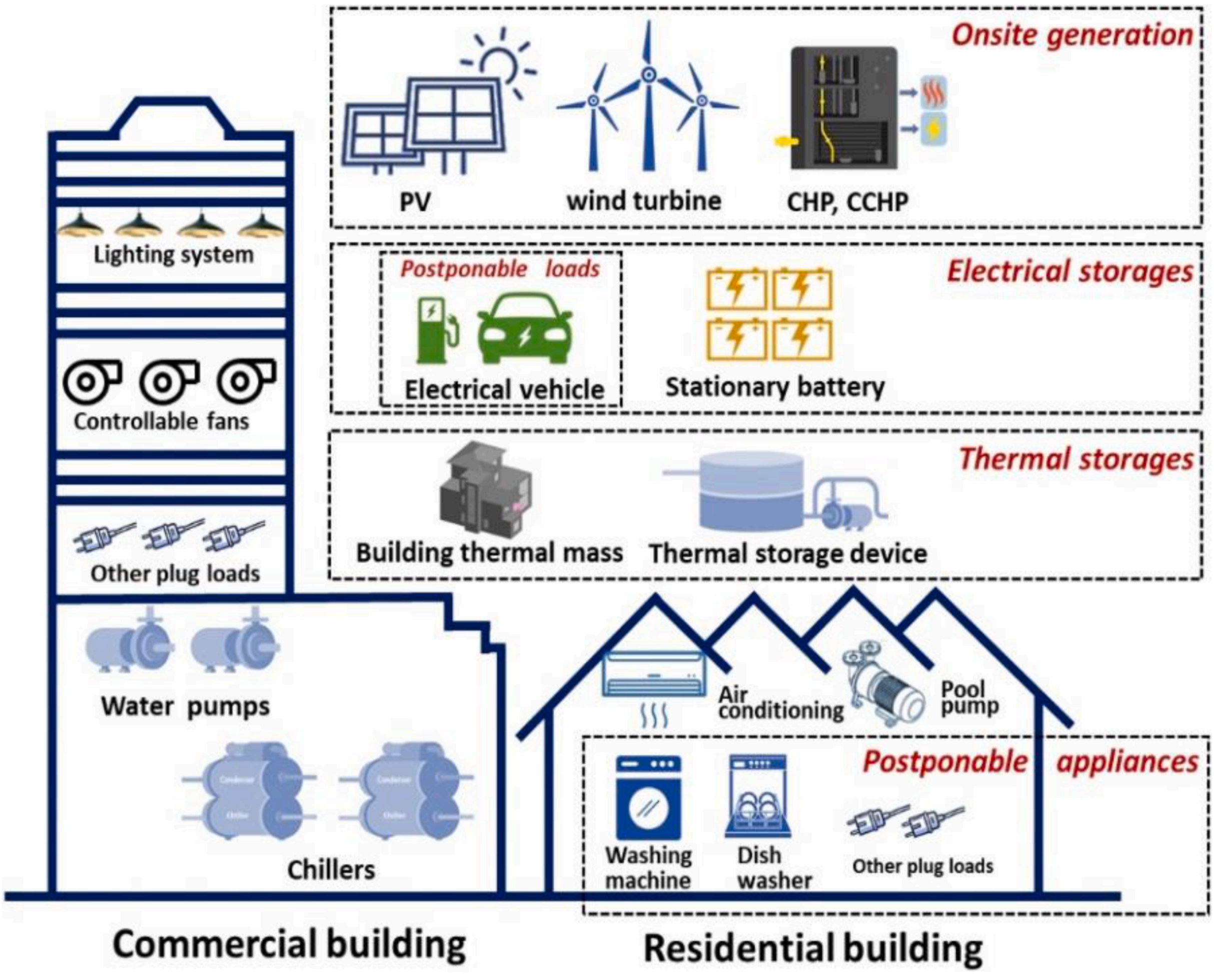

Fig. 4. Flexibility sources in commercial and residential buildings (demand side device except the generation device in the top right corner) [66].

methodology. The objective of building flexibility at the system level is to maximize the potential of demand flexibility and generate benefits through an appropriate strategy. In system-level evaluation, heuristic and optimization methods are implemented to enhance energy flexibility [67]. Heuristic methods typically consist of a set of operative conditions in system equipment. A specific flexibility metric is employed for simulation and operation. For instance, Hirmiz et al. [68] aimed to improve building flexibility by reducing electricity consumption during peak heat pump system hours. On the other hand, leveraging optimization for demand-side management is typically associated with tax rates and electricity prices. To achieve optimum operation, benefit or penalty functions are adopted to maximize benefits or minimize penalties [69]. Demand flexibility at the building level can be classified into two categories: design and operation. In the design phase, the main objective is to identify the most efficient combination of systems and architectural features. Many parametric modeling studies use heuristic methods, testing various parameter combinations exhaustively. Alternatively, some studies use parametric optimization techniques to identify the best design parameters and reduce energy costs for the entire building during the design phase. For heuristic studies, Arteconi et al. [70] identified the best combination at the design stage based on factors such as geographic location and design specifications. In contrast, Reynders et al. [11] used optimization methods to determine that an optimal control method was better suited and able to achieve the lowest cost. The operational phase of an application can involve the potential evaluation, comparison of control strategies, and assessment of energy management strategies. These applications can be classified into two categories: heuristic and optimal. For example, Ramos et al. [71] compared costs under different pricing strategies using various heuristic methods, resulting in increased economic benefits and decreased reliance on the grid. In contrast, Tang et al. [72] aimed to minimize power generation and thermal comfort costs through optimal operation.

At the district level, a collection of adjacent communities or buildings falls under coordination [73]. The principal application at this level focuses on demand-side response through operational strategies. Lu et al. [74] investigated the use of thermal mass and thermostats to modify the energy flexibility of residential buildings within a district, demonstrating their superior performance under dynamic pricing regimes. Fischer et al. [75] evaluated the energy flexibility potential of district residential heat pump pools by simulating baseline operation and smart grid-readiness, while also investigating central heating control for district building systems. Sector-level studies have explored the potential demand-side benefits of regional or national energy flexibility, which can guide energy policy and the design of building standards. There have been numerous studies in this category, such as the prevalence of building flexibility measures within the Dutch population, as assessed by Li et al. [76] through a large-scale survey. Another example is the findings of Vellei et al. [77], who quantified the flexibility potential of thermoelectric systems in French households, as well as suggested that existing infrastructure and more appealing tariffs could unlock building demand-side potential. Table 1 presents several typical building flexible demand-side strategies.

Key performance indicators of buildings flexibility

Accurate quantification of building flexibility necessitates the

Table 1
Several typical building flexible demand-side strategies.

Name	Basic Definition	Key Characteristics
Efficiency Improvement	Power demand is always reduced.	Long-term and continuous reduction.
Load Reduction	Reduce power demand during peak times or emergencies.	Power demand must be reduced within minutes, usually up to an hour, during peak or emergency situations.
Load Shifting	Change building energy usage time or use renewable generation to reduce peak-hours power demand.	Power demand must be cut down within minutes after notification, usually over two hours.
Dynamic Modulate	Receive grid operator signals and automatically adjust building power demand.	Building demand must be adjusted in second or sub-second intervals.
Generation Feedback	Reverse power generation for building or dispatch to the grid during peak-hours.	Power demand must be reduced within minutes after notification, usually for two to four hours.

consideration of three essential performance indicators that involve both the supply and demand sides: energy efficiency, time control, and cost reduction. In terms of energy efficiency, improvements to energy utilization efficiency are primarily achieved by adjusting the mixed utilization of renewable energy and energy storage equipment on the supply side. Munankarmi et al. [78] designed a home energy management system for use in residential buildings at the community scale, which effectively increases energy efficiency and demand flexibility. Tang et al. [79] introduced a dispatch strategy to unlock building energy flexibilities with multiple renewable energy resources, enabling power modulation to follow grid control signals in real-time. For time control, the indicator aims to shift peak hours after the dynamic response of building energy consumption. Policy measures such as penalties or incentives are frequently considered in this regard [80]. The benefits of building flexibility and energy efficiency for grid systems can both be accomplished through load shedding and peak time control [48]. Klein et al. [81] evaluated various flexibility and storage options, which confirmed the potential for time-shifting by unlocking building potential. Touzani et al. [82] implemented flexible load changes via deep reinforcement learning of distributed energy resources.

It is essential to note that the fundamental goal of building flexibility is to meet all energy demands while reducing costs for both the supply and demand sides [83]. Achieving the Nash equilibrium solution under multiple objective optimization conditions is the primary approach to reconcile this objective [84]. In previous traditional research, traditional indicators such as operating energy costs and energy consumption levels have been extensively studied. Most of the indicators from these studies can be readily applied, such as load coverage factor (self-generation), supply coverage factor (self-consumption), grid feed-in percentage, available storage capacity, and power utilization storage efficiency [85, 86]. Currently, research aims to explore the best control strategies to lower costs under different economic optimization requirements. Clauß et al. [87] utilized rule-based control to activate the energy flexibility of Norwegian residential buildings, whereas Alegría et al. [88] confirmed the use of heating demand as an energy performance indicator for cost decline. Table 2 summarizes the key performance indicators concomitant with building flexibility.

Model predictive control for buildings flexibility

The foundation for delivering adaptable services within the building rests on the thermal inertia and model predictive control. As renewable energy exhibits considerable instability, it becomes imperative for the energy management system of the building to accurately anticipate the direction of progress. To address this requirement, the forthcoming key technology would be the energy controllers constructed using the Model Predictive Control (MPC) framework. The MPC technology has the capability to regulate the distribution of energy supply and demand in coherence with the accessibility of renewable energy. With regards to

Table 2
Summary of key performance indicators of building flexibility.

Indicators	Program	Definition	Trigger	Manual	Voluntary	Participants
Time control	Time-of-Use	Utilities use time-based electricity prices to engage customers, with different prices for on-peak and off-peak periods.	Price	√	√	Residential, commercial, industrial
	Critical Peak Pricing	Utilities significantly increase the electricity price during specific time periods, such as the hottest hours of a summer weekday.	Price	√	√	Residential, commercial, industrial
	Real-time Pricing	adjust electricity prices at short time (e.g., hourly) to encourage customers to change their power usage.	Price	√	√	Residential, commercial, industrial
	Variable Peak Pricing	A combination of time-of-use (TOU) and real-time pricing (RTP), pricing is predefined, except for the peak periods.	Price	√	√	Residential, commercial, industrial
	Rolling Blackout	Electricity delivery is halted in different distribution region during preventing power outage in extreme conditions.	Event	×	×	All buildings
	Peaking Shift	The load peak time is shifted through the simultaneous actions of the demand side and supply side.	Incentive	×	√	All buildings
Costs decline	Peak Time Rebates	Provide customers with refunds during pre-specified peak time periods based on the reduction in demand compared to expectation.	Incentive	√	√	All buildings
	Direct Load Control	Directly control the operation of some equipment during peak time and offer payment incentives.	Incentive	×	√	Residential
	Capacity Market Program	Participants are compensated for being available on call and agreeing to reduce their energy usage to specific levels during special events.	Incentive	√	√	Commercial, industrial
	Interruptible/ Curtailable Service	Participants are paid for any reduction when necessary, but penalized if they fail to reduce.	Incentive	√	√	Commercial, industrial
	Ancillary Service Market Program	Independent system operators (ISOs) permit bidding load curtailments in electricity markets.	Incentive	√	√	Commercial, industrial
	Demand Bidding/Buy Back (DB)	ISOs offer load reductions at a price they like for curtailment.	Incentive	√	√	Commercial, industrial
	Emergency Demand Response	Utilities offer incentives to customers who voluntarily reduce their energy consumption during special events.	Incentive	√	√	Commercial, industrial
Energy efficiency	Grid supply	Buildings' thermal and electrical demand is currently met exclusively through the grid.	Event	×	√	All buildings
	Renewable Energy Supply	Buildings can alternatively meet their energy needs solely through distributed renewable energy sources.	Event	√	×	All buildings
	Hybrid energy supply	Utilize a hybrid supply of distributed renewable energy and grid power to fulfill the buildings' heat and power requirements.	Event	√	√	All buildings

electrical heating systems within the building, MPC has the potential to significantly enhance the flexibility of demand, curtail capital expenses, and enable flexible services for customers. While deep reinforcement learning (DRL) has gained attention in recent years for its ability to handle complex control problems, MPC continues to be recognized as a key control technique in various domains, including building flexibility. One of the key advantages of MPC is its ability to handle real-time optimization and control problems with constraints. MPC uses a mathematical model of the system and considers constraints on variables such as energy consumption, comfort levels, and equipment limits. By formulating an optimization problem and solving it at each time step, MPC can make control decisions that satisfy the constraints and achieve the desired performance. This makes it well-suited for applications in buildings, where maintaining comfort and meeting energy efficiency targets are crucial. Additionally, MPC allows for explicit incorporation of system dynamics and models, which can be advantageous in scenarios where accurate models are available. By utilizing the model, MPC can anticipate system behavior and make informed control decisions. In contrast, DRL typically relies on learning through interactions with the environment, which can be more data-intensive and may not explicitly capture the system dynamics [89]. Furthermore, MPC offers interpretability and transparency in control decisions. The optimization problem formulation in MPC allows for clear understanding of the objectives, constraints, and trade-offs involved in the control process. This interpretability is important in domains where human operators need to understand and trust the decisions made by the control system [90]. While DRL has its own strengths, such as its ability to handle high-dimensional and complex control tasks, MPC's advantages in handling real-time optimization, incorporating system models, and providing interpretability make it a valuable control technique in the context of building flexibility. But more often the two include each other.

Supply side: data-driven cogeneration

Forecasting serves as a crucial tool on the supply side, where its foremost objective is to efficiently anticipate the volatility of renewable energy. In cogeneration systems like PVT, the stability of the electric and heat supply is directly influenced by meteorological data and environmental factors [35]. Data-driven cogeneration systems present a cost-effective substitute to expanding the conventionally expensive energy storage facilities. This system outlines an energy management approach for buildings that incorporates data sensing, data analysis, and data-driven prediction. Data-driven cogeneration systems are often more intricate than customary controllers because they must perform online predictions, scrutinize multiple parameters relevant to the energy system, and deliver results within a restricted time frame [34]. Fig. 5 illustrates a scheme for the building energy system, featuring involvement in the electricity markets with multiple cogeneration resources.

Besides, electrothermal coupling technology has gained significant attention in recent years for its potential in enhancing indoor environmental control. By integrating electrical and thermal systems, it enables flexible heat transfer and control means, which can dynamically adjust and adapt to indoor environmental parameters, leading to a more comfortable and healthier indoor environment. Electrothermal coupling technology allows for precise and responsive temperature regulation by utilizing intelligent control systems. It enables efficient and localized heating or cooling, ensuring optimal thermal comfort for occupants [91]. This technology also facilitates zone-based temperature control, allowing different areas within a building to be maintained at individualized temperature levels, thereby optimizing energy efficiency. By dynamically adjusting the humidity levels based on occupancy and environmental conditions, this technology helps prevent the growth of mold and bacteria, thereby enhancing indoor air quality and occupant health. It also allows for personalized ventilation control, enabling occupants to adjust airflow rates according to their preferences and needs. The adoption of electrothermal coupling technology for indoor

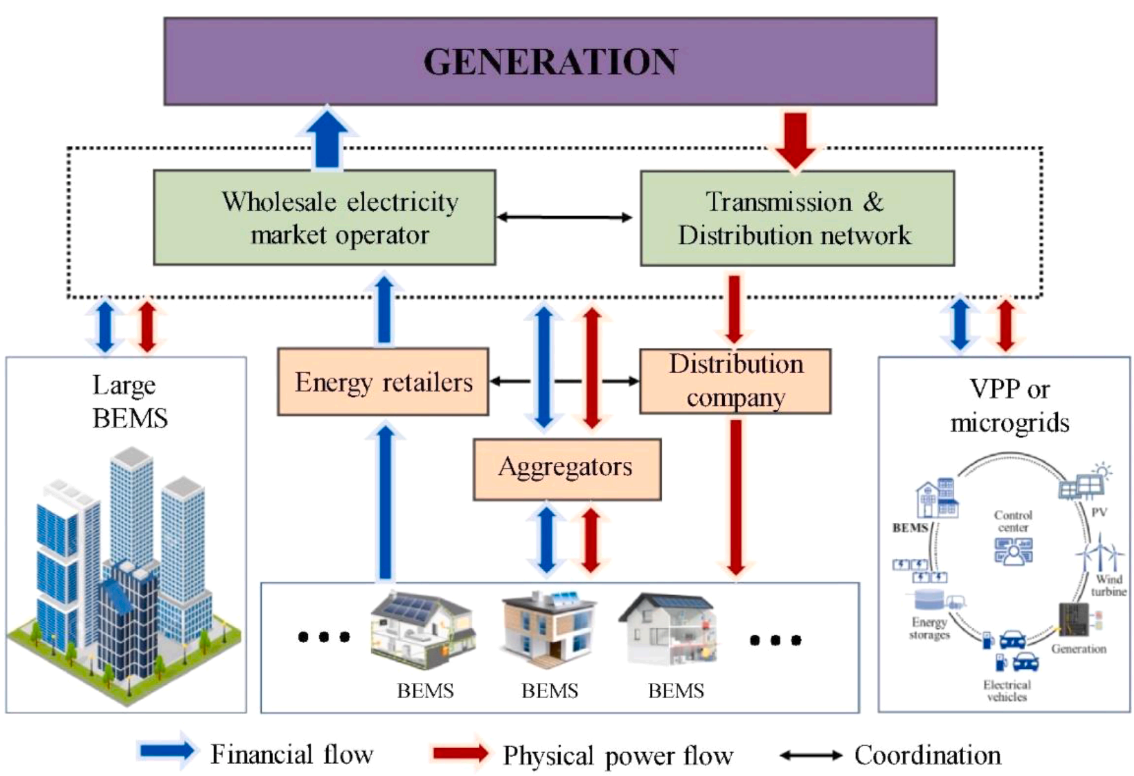

Fig. 5. Building energy system in electricity markets with multiple cogeneration resources (Building Energy Management Systems (BEMS); virtual power plant (VPP)) [79].

environmental control offers numerous benefits, including improved comfort, energy efficiency, and indoor air quality [92]. Electrothermal coupling technology enables intelligent monitoring of building equipment. By integrating sensors and advanced monitoring systems, real-time data on equipment performance, energy consumption, and environmental conditions can be collected and analyzed. This data-driven approach allows for proactive fault detection and diagnosis, identifying potential issues before they escalate into major problems. Fault diagnosis algorithms can analyze patterns and deviations, providing valuable insights to facility managers and enabling timely maintenance and repairs. This not only improves the overall operational efficiency of the building but also reduces downtime and maintenance costs. With remote access and control, building operators can monitor and adjust equipment settings and operational parameters from a centralized location. This offers convenience and flexibility in managing building systems, particularly in large or complex structures. Remote control functionalities also enable rapid response to changing conditions or occupant demands, ensuring optimal performance and comfort without the need for physical intervention. By leveraging electrothermal coupling technology for building operation and management, significant advancements can be achieved in terms of operation efficiency and maintenance convenience. The combination of flexible equipment operation, intelligent monitoring, and remote-control capabilities enables proactive and data-driven decision-making, leading to optimized energy consumption, enhanced occupant comfort, and streamlined maintenance processes.

The forecasted performance of data-driven cogeneration systems is largely dependent upon the modeling approach adopted for representing the energy system for the buildings. MPC in the context of building flexibility relies on prediction models to forecast future system behavior and make control decisions [93]. The prediction models used in MPC can be categorized into three main types: white-box models, gray-box models, and data-driven black-box models.

- White-box models are based on the state-space representation of the building system. These models use physical principles and mathematical equations to describe the dynamics of the system. They require knowledge of system parameters and are often derived from first principles or detailed physics-based modeling. White-box models provide a clear understanding of the underlying system dynamics but may require accurate parameter estimation and can be computationally intensive.
- Gray-box models combine physical equations with empirical data. They are typically based on simplified representations of the building system, such as the thermal resistance-capacitance (RC) network model. Gray-box models incorporate both the physical aspects of the system and empirical observations to capture system behavior. They strike a balance between accuracy and computational complexity, making them suitable for real-time control applications.
- Data-driven black-box models rely solely on observed data without explicitly modeling the system dynamics. These models leverage machine learning and statistical techniques to learn patterns and relationships from historical data. Data-driven models, such as neural networks or regression models, can handle complex nonlinearities and uncertainties. They are often used when detailed knowledge of the system is unavailable or when the system dynamics are highly nonlinear and difficult to model accurately.

Most traditional controllers employed for building energy supply, based on physical parameters, can be classified as white-box predictive models. White-box models typically rely on historical experience, utilizing physical parameters as input to make informed decisions [94]. The adjustment process in white-box models is often rigid and cannot account for unexpected contingencies or emergencies. gray-box or black-box models, which are considered more appropriate, are currently employed in the majority of energy supply-side forecasts. gray-box models are a hybrid of physical parameter prediction and artificial intelligence and necessitate less computation but eliminate the inscrutability of black-box models while providing relevant supply-side guidance. Li et al. [95] performed a comparative evaluation of gray-box MPC strategies using actual meteorological data, and the results demonstrate the resilience of this model, suggesting a hybrid control method for optimal building flexibility.

Black-box models exhibit notable capabilities in handling various nonlinear behaviors exhibited by renewable energy; nevertheless, it is usually imperative to provide adequate datasets for training purposes to attain a requisite level of sensitivity and accuracy capable of fulfilling the dynamic demands of building energy systems. In recent years, artificial neural networks (ANNs) or other machine learning methodologies have predominantly featured as the preferred approach for predicting energy supply using black-box models. In their study, Avram et al. [96], compiled successful implementation of ANN, resulting in better predictions. The researchers affirmed that the ANN black-box model effectively improved system performance. Nonetheless, the implementation of data-driven cogeneration systems entails the use of various sensors and monitoring devices, which pose a significant limitation in the proliferation of the black-box model [97]. To date, few effective demonstrations have been accomplished with data-driven cogeneration systems within buildings, mainly due to the financial benefits of implementation insignificance compared to the total cost [98]. The primary challenges of constructing robust and resilient data-driven cogeneration systems capable of adapting to dissimilar buildings entail the randomness of disturbances such as weather, changing loads, the performance and cost of modeling methodologies, and the contradictory nature of controlled objectives [99,100]. Through their experiments, Hu et al. [101] explore the use of zone-level ANN network and rule-based control for predicting thermal load, which could represent a viable black-model option for application in building supply-side systems. Fig. 6 illustrates a summary of the diverse data tools frequently utilized in data-driven cogeneration. The black box model is a prediction model that focuses on capturing the relationship between input and output variables without explicitly modeling the underlying physical processes. This model is often used when the underlying mechanisms are complex or not well understood. Graph networks are a powerful tool for modeling complex relationships in renewable energy systems of buildings, especially when considering spatial and temporal dependencies. These models leverage the graph structure to capture the interactions between different nodes, such as solar panels, wind turbines, and energy storage systems.

Electrothermal coupling technology offers unique advantages in terms of spatial layout flexibility within buildings. By integrating electrical and thermal systems, it enables adaptable and efficient solutions for building internal wiring, equipment installation, and room function conversion, catering to different usage needs and changes in space layout. This means that equipment can be installed in locations that best suit the spatial layout requirements, making it easier to reconfigure spaces or accommodate future changes in room functions. By harnessing the capabilities of this technology, architects, engineers, and building owners can create more adaptable and user-centric spaces that can easily accommodate future changes and optimize resource utilization.

Demand side: demand side response on electricity market

On the demand side, buildings are associated with demand response (DR…). The users' heating and cooling behaviors are primarily shaped by thermal comfort, while the availability of renewable energy sources determines their energy consumption patterns [102]. Moreover, the thermal mass of buildings permits them to act as thermal energy storage devices, presenting a unique opportunity for enhancing building flexibility. Generally, the thermal mass transfer of a building is facilitated using HVAC systems [103]. These HVAC systems frequently incorporate a Building Automation System (BAS) or a Building Energy Management

		Tool Categories				Data Coverage										Data Relations				Flexibility and Extensibility				Stage of Application						Adoption	
ID	Tool Name	Terminology	Ontology	Schema	Data Platform	Energy Use Data	Onsite Power Generation Data	Indoor Environmental Data	Outdoor Environmental Data	Equipment Operational Data	System Control Setting/Logic	Occupant Data	Design Basis Data	Building and System Asset Data	Utility Rates and Grid Signal	Hierarchy	Typology	Association	Others	Allow various levels of details	Allow missing data/ Capability of adding new data	Extensible	Use standard terminology	Building Design	Operation	Audit	Code Compliance	Rating	Commissioning	Development status (U - under development P - pilot application A - widely adopted)	Applicable building type (C - commercial R - residential)
1	ADI	x		x	x	x		x	x	x	x				x	x			x	Yes	Yes	Yes	Yes		x					A	C/R
2	Annex 66 Ontology		x			x		x	x	x	x	x				x				Yes	Yes	Yes	Yes	x	x	x	x	x	x	P	C/R
3	ASHRAE 201			x		x		x	x	x	x				x		x			Yes	Yes	Yes	Yes	x	x	x	x	x	x	A	C/R
4	ASHRAE 205		x	x						x	x						x			Yes	Yes	Yes	Yes		x	x		x	x	A	C/R
5	Asset Score				x								x	x		x	x	x		Yes	No	Yes	No	x		x		x		A	C/R
6	Audit Template				x	x							x	x	x	x	x	x		Yes	No	Yes	Yes	x		x		x		A	C/R
7	BEDES	x				x				x			x	x					x	Yes	Yes	Yes	Yes	x	x	x		x		A	C/R
8	BPD		x		x	x				x			x	x				x	x	Yes	Yes	Yes	Yes		x	x		x		A	C/R
9	Brick	x	x	x		x		x	x	x	x					x		x		Yes	Yes	Yes	Yes		x				x	P	C/R
10	BuildingSync			x		x				x		x	x	x	x	x				Yes	Yes	Yes	Yes	x	x	x		x		A	C
11	CA SDD	x	x	x						x	x		x	x		x		x		No	Yes	No	Yes	x			x			A	C
12	Energy ADE			x		x				x		x	x	x		x	x	x		No	Yes	Yes	No	x	x					A	C/R
13	ENERGY STAR Portfolio Manager				x	x								x		x		x		No	Yes	Yes	No		x			x		P	C/R
14	gbXML			x		x		x		x			x	x		x	x			Yes	Yes	Yes	Yes	x		x				A	C/R
15	GreenButton			x		x	x													No	No	No	Yes		x					P	C/R
16	HPXML			x		x				x				x	x	x				Yes	No	No	Yes		x	x		x		A	R
17	IFC			x		x		x		x		x	x	x		x		x		Yes	Yes	Yes	Yes	x	x				x	A	C/R
18	ISO 12655-2013		x			x	x									x				No	Yes	No	Yes		x	x		x		A	C/R
19	ISO 15489-2016	x												x	x				x	No	Yes	Yes	No			x				A	C/R
20	ISO 52000-1:2017	x				x								x					x	No	Yes	Yes	No			x				A	C/R
21	oneIoTa				x	x		x	x	x	x				x	x				Yes	Yes	Yes	No		x					P	C/R
22	Project Haystack	x	x	x		x		x	x	x	x							x		Yes	Yes	Yes	Yes		x				x	P	C/R
23	SAREF		x			x				x	x				x					Yes	Yes	No	Yes		x					U	C/R
24	SEED	x			x	x				x			x	x			x			Yes	Yes	Yes	No	x	x	x		x		A	C/R

Fig. 6. Summary of various data tools used in data-driven cogeneration [35].

System (BEMS) to automate DR... protocols. With advancements in peer-to-peer technology, demand-side information transactions have considerably accelerated. As a result, building heating systems can quickly respond to supply-side signals. Nonetheless, attaining effective forecast and regulation of load remains the most significant challenge for the demand side [104].

Buildings frequently contain multiple loads, creating possibilities for active thermal storage, active electrical storage (batteries), and indirect electrical storage (electric vehicles (EVs)) to optimize energy flexibility [105]. In electricity market demand-side response, building demand response can be categorized into three main groups: (i) price-based response, involving dynamic pricing to modify building load profiles; (ii) direct load control (DLC), accommodating user power usage adjustment during emergencies and peak periods, and (iii) transaction-based (market-based control), entailing the exchange of price/incentive information in the electricity market [106,107,108]. Effective demand-side forecasting is critical in all three scenarios. Based on different prediction methodologies, demand-side forecasting can be allocated to white-box, black-box, and gray-box models.

White-box models still rely on physical principles and have high-fidelity. Typically, white-box models are constructed using simulation software, such as EnergyPlus, IESVE, and TRNSYS [109]. These simulations necessitate meticulous inputs of the complete physical parameters (e.g., geometry, material properties, thermal properties, etc.) of the buildings. Cao et al. [110], designed demand-response programs for commercial buildings, which could likewise be classified as employing a white model due to the evidence-based equations. Although white-box models can enable the effective physical modeling of buildings, load-side prediction calculations are typically slower and impose more significant limitations and costs [111]. Consequently, white-box models are unsuitable for online load prediction and control of buildings [112].

Some successful white-box applications have combined buildings with thermal storage and batteries within simulation software [113]. These integrated system models are more straightforward to construct and possess greater robustness. Nevertheless, they fail to demonstrate the potential for generalization within a complex multi-energy system in the future [114].

Black-box models typically lack any relationship to building properties and consist primarily of empirical models and data-driven models. This approach typically demands training on datasets encompassing all possible operating ranges, including HVAC parameters, building daily power consumption, indoor and outdoor temperatures, and data covering all seasons to train the prediction model [31]. The primary challenge for developing a data-driven model for demand-side building energy management is acquiring an appropriate training dataset. After obtaining the requisite dataset, effective data labeling and feature evaluation become critical factors in generating an accurate and effective load forecasting model. Coccia et al. [115] devised an Artificial Neural Network-Base Model Predictive Control (ANN-based MPC) to unlock building energy flexibility. Their results indicated that the ANN-based MPC could reduce electrical energy consumption by -71% compared to the white model box. Ruusu et al. [85] defined a black-box model for multiple-source energy flexibility within a residential building. The new model could improve net economic outcomes by 38–168% or by 21–75% of the cost of imported electricity, confirming the superiority of the black-box model. Data-driven demand response (DR...) black-box models encompass several regression models [116,117], and the classification of Artificial Intelligence (AI) approaches for demand prediction is illustrated in Fig. 7. Due to technical updates, some content in Fig. 7 may have changed and is no longer applicable. Gray-box models represent one of the most promising models for future applications, combining physical and experience-based models [118]. These models

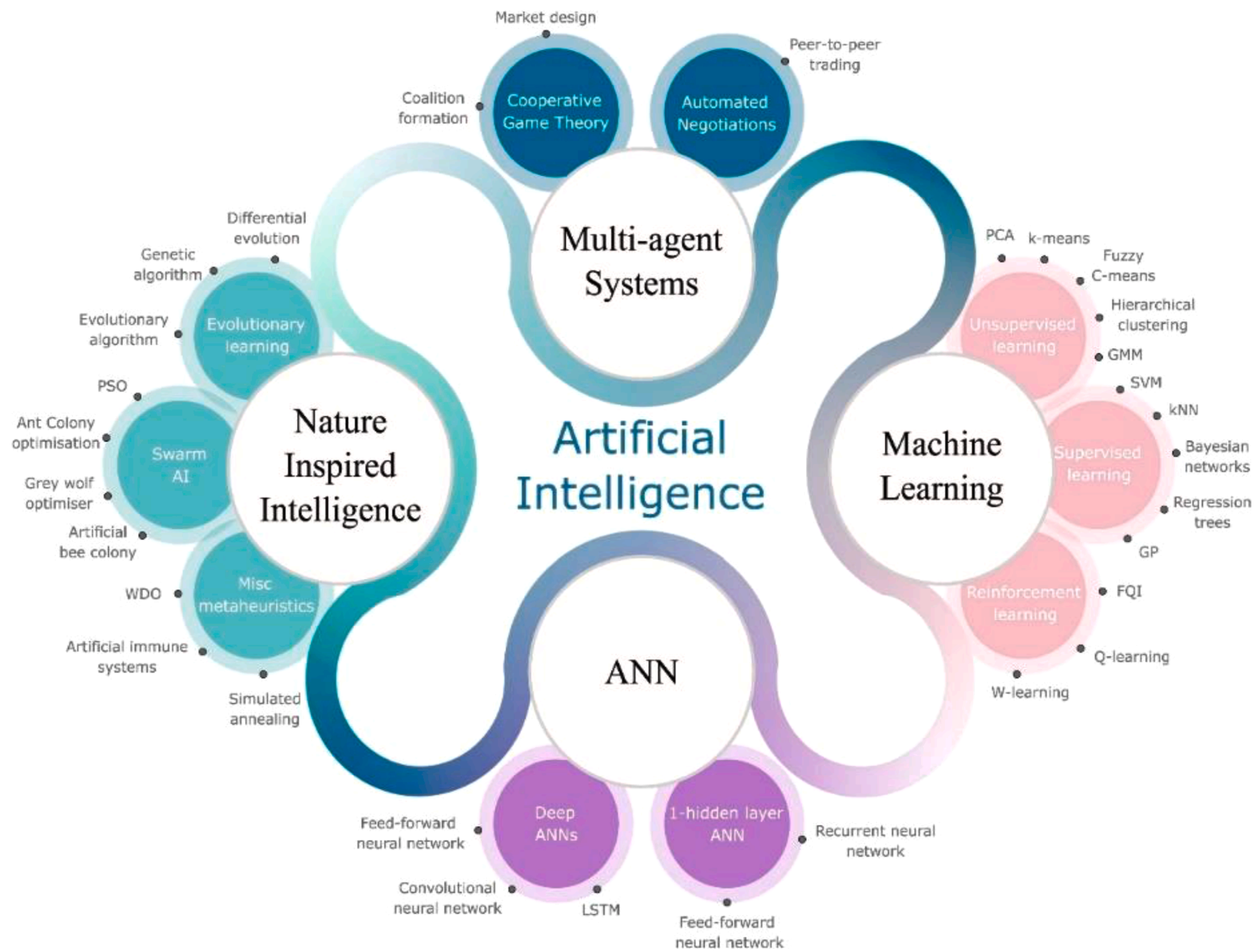

Fig. 7. Classification of AI approaches for demand prediction [123].

are well-suited for less complex buildings using a set of input, output, and state variables comprising first-order differential equations [119]. The resistance-capacitance (RC) model is a typical example of a gray-box model that employs experimental data to determine parameters and predict subsequent processes. The advantage of the gray-box model is that it permits a physical interpretation of model parameters and provides an understanding of the underlying rules governing building performance. This will aid in the formulation of relevant policies and economic planning [120]. Wang et al. [121] introduced a tunable gray-box model for building energy management. Compared to the baseline controller (the white box model), the gray-box model can achieve up to 46.6% energy cost reduction with fewer comfort violations. Cunha et al. [122] further affirmed the potential of gray-box models in explaining the heat enhancement of the phase change materials.

Flexible system optimizations for smart buildings

Reasonable predictions concerning supply-side fluctuations in buildings and demand response can assist decision-makers in making informed choices [32,124]. However, to improve building flexibility, it is essential to achieve the most efficient use of energy, maximize economic benefits, and minimize environmental impacts through system optimization and smart buildings after accurate predictions have been made [125]. From the perspective of building energy conservation, energy utilization efficiency and conventional 6E analysis indicators such as system COP, LCOE, LCOH and other parameters are often included in the analysis. These various methods and metrics for assessing building flexibility are important for increase building flexibility services. This optimization process entails both the supply and demand sides of the equation. Additionally, heating systems usually incorporate heat storage tanks, batteries, biogas pools, and electric vehicles to ensure stability. Furthermore, optimized materials such as phase change materials and nanofluids are employed to enhance the building devices' adaptability.

4.1 Supply side: 6E analysis for distributed energy system design

The optimization of the supply side frequently involves multi-objective analyses, which is typically achieved through 6E analysis. The 6E analysis comprises Energy, Electricity, Exergy, Entropy, Economy, and Environment analyses. These analytical tools can effectively aid decision-makers in managing the energy supply system [126]. Table 3 provides an overview of the primary analysis components, sources, and implications of the conventional energy system modeling framework.

Energy analysis concentrates on building heating systems, mainly focused on thermal energy utilization, such as ground source heat pumps, solar collectors, heat storage tanks, and other HVAC equipment [127]. The primary research indicators include, but are not limited to, the coefficient of performance, energy conversion efficiency, heat energy utilization rate, waste heat recovery rate, and other parameters. These parameters typically enable researchers to concentrate on the stability and performance of components during the research process

Table 3
Components, sources, and implications of normal energy system modeling framework for 6E analysis.

Component	Classification	Source	Description	Implications
Inputs	Building energy use (demand)	2019 EIA AEO [142]	Exhaustive building energy consumption	Load shapes and total electricity consumption
	Power generation (supply)	2019 EIA AEO [142]	Load defined by physical system including wind and solar generation	Grid scheduling and grid services are influenced by the low marginal cost of renewable generation.
	End-use load	Energy tools (simulation software)	Representative end-use load shapes	The potential from efficiency and flexibility measures may be underestimated or overestimated depending on the type of building.
	Building demand	Energy efficiency	Various efficiency corresponds to optimization or market trading	Electricity usage for building heating technologies
		Demand flexibility	Hourly electricity demand should be maximized by targeting intended reductions or increases.	Load shift/shed away from peak hours and avoid renewable energy curtailments,
		Energy efficiency and demand flexibility	Demand side scenarios should be combined with supply side scenarios.	Smart buildings and data-driven cogeneration
Model characteristics	Energy demand	Residential and commercial buildings	Commercial prototype models and various types of residential and commercial buildings with hourly load shapes should be included.	All possible variations in load shapes
	Technology optimization	Paraments improvement in building system	The building demand scenarios should consider the complete adoption of measures.	Upper bound of energy savings and load shed and shift
	Geographic extent	Building location and environment	Approximate independent operator and possible environmental impact	Focus on different level of buildings (system, buildings, campus, or nation level)
	temporal extent	Millisecond to hourly	Coordinate supply and demand sides of buildings	Combination of short-term and long-term forecasts
	Weather data	Building locations	A representative climate zone in the geographic boundary	Extreme events and future climate-change effects should also taken into consideration
Outputs	Assessment metrics	Renewable energy supply and consumption	6E analysis	Multi-objective optimization of supply side and demand side under different evaluation indicators
	Demand flexibility	Energy efficiency, time control, and costs decline.	Include higher penetrations of renewable energy and benefits of demand flexibility	Total system improvement in all seasons (summer, winter, intermediate) and all regions; No injustice and poverty tendencies;

and achieve more efficient energy utilization. Zhang et al. utilized effective energy analysis to optimize the electricity/heat production of a PV/T system [128,129].

Electrical analysis typically targets appliances and thermal energy conversion equipment within buildings, such as electric blankets and HVAC equipment. Commercial building equipment is known to consume significant amounts of electricity and is particularly susceptible to shock loads on microgrids or local grids [130]. Electrical analysis typically concentrates on parameters such as power supply stability, harmonic distortion rate, reactive power, zero-sequence protection current, and others to achieve stability and system reliability during the conversion process of electrical energy to thermal energy. Chen et al. demonstrated the efficacy of this method by conducting an electrical performance analysis of a space heating system utilizing photovoltaic/thermal collectors [131].

Exergy analysis is typically used in conjunction with energy analysis since a pure energy analysis cannot adequately evaluate the effectiveness of energy conversion or distribution systems and processes. While energy analysis is primarily focused on quantitative assessments of thermal energy conversion and utilization, exergy analysis is more adept at qualitative assessments [132]. For buildings utilizing heat pumps or district heating, exergy analysis facilitates the identification of primary contributors to exergy damage and their adjustment throughout the process, resulting in improved thermodynamic efficiency across the overall heating system [133]. Energy analysis provides an evaluation of a substance ability to perform work, while exergy analysis determines the maximum work that can be performed by a given substance in a building heating system.

Entropy analysis typically occurs in conjunction with exergy analysis and energy analysis. Entropy analysis is more responsive to the state of the heating system, while exergy analysis can also reflect the building environment [134]. The destroyed exergy is proportional to the produced entropy. Exergy is always partially or wholly destroyed per the second law of thermodynamics. Destroyed exergy or produced entropy is the leading cause of building heating systems falling short of theoretical thermodynamic efficiency. The combination of entropy analysis with other analyses allows decision-makers to accurately assess each component and improve the energy conversion efficiency of individual devices. Rico et al. achieved energy and entropy analysis of a residential building to open up possibilities for designing energy-efficient buildings [135].

Economic analysis is commonly combined with energy analysis to conduct techno-economic analyses of heating systems [136]. Techno-economic analysis allows for an effective assessment of the combination of capital costs, operations and maintenance, performance, and fuel costs, among other factors, vis-à-vis costs, benefits, risks, uncertainties, and time frames in a building heating system. Metrics like the levelized cost of electricity, internal investment rate, and levelized cost of heat are often utilized as indicators to aid operators in enhancing optimization and reducing costs [137]. Economic analysis can also assist stakeholders in understanding the potential value of their investments, as confirmed by Abokersh et al. [138]. The figure presented in this paper portrays the functions and costs of various flexibility sources in building systems. Fig. 8 illustrates the 5 levels of 6E analysis in building flexibility analysis.

Environmental analysis is a typical practice for building heating systems, as it aids in identifying and organizing the possible positive or negative impacts such systems can have on the environment [136]. Conventional environmental analysis typically measures CO_2 emissions, but nitrogen oxides have also gained considerable attention in recent years. The future of carbon trading markets and the carbon footprint analysis of renewable energies present increased prospects for environmental analysis of building heating systems [139]. These characteristics of environmental analysis effectively address research gaps in engineering and landscape science, environmental science, sociology, and several other disciplines. Galimshina et al. [140] proposed an optimal, robust, and cost-effective solution for building renovation that is environmentally sound. Their findings indicated that the heating system is the most critical element of renovation. Fig. 9 presents the carbon emission model for the residential building.

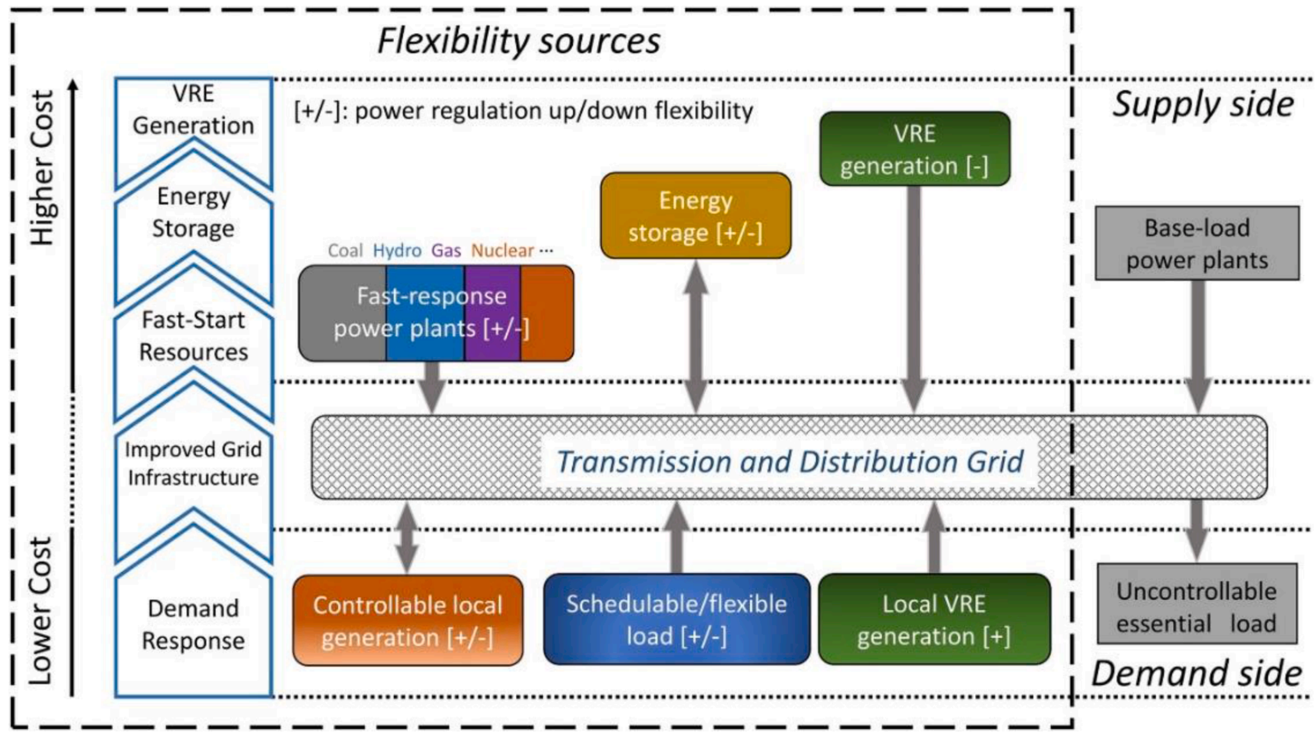

Fig. 8. Functions and costs of various flexibility sources in building system for 6E analysis [66].

Demand side: smart appliances and P2P trading

The growing trend of decentralized renewable energy production at low voltage levels within buildings has prompted modifications in electricity demand chain infrastructure, leading to the emergence of smart appliance concepts. These appliances can serve as upgradeable electricity networks, usually situated in the low voltage distribution segment. They enable intelligent control and facilitate multi-directional communication among sources, loads, and components to promote cooperative and cost-effective energy utilization. [113]. By integrating and connecting smart appliances as part of a well-designed demand-side management program, the building demand-side can effectively adapt to the current power supply chain infrastructure [143], enhancing the flexibility, agility, and responsiveness of the heating system to frequent changes.

When adopting building-centric operations as a demand-side flexibility resource, the impact on building performance mainly focuses on thermal comfort, indoor air quality, and comfort system response.

Previous research has primarily focused on potential evaluations, neglecting building performance issues. Such studies tend to oversimplify building performance problems and prioritize power performance characteristics in their evaluations. However, a numerical study by Morales-Valdés [144] revealed that implementing comfort relaxation strategies could lead to increased levels of percentage people dissatisfied (PDD) with indoor comfort. Zhang et al. [145] also suggested that direct load control strategies often result in adverse thermal comfort impacts on occupants. However, most electric thermal controllers thus far can only guarantee and supervise the heating system to work efficiently within a specified indoor temperature range. To meet DSM requirements, it is essential to ensure both the aforementioned thermal comfort and the best-selected control strategy. The smart appliances controller adjusts during operation according to the correct control objectives, building design and characteristics, local weather conditions, local energy production and consumption capabilities, and energy market environment as incentives or penalties for demand-side management.

Several factors make it challenging to objectively compare the demand-side response for heating and cooling systems in buildings under different conditions. Therefore, identifying relevant reference key performance indicators (KPIs) to characterize building demand-side responsiveness has become critical [146,147]. One unresolved issue is how to effectively manage numerous energy demands across different buildings, each with varying ownership and characteristics. Peer-to-peer (P2P) trading has emerged as a potential solution to this challenge [148]. The structure of smart contracting with P2P trading and fundamental steps for execution have been presented in Fig. 10. P2P energy trading facilitates the sharing of resources among consumers within a local distribution network, promoting decentralized electricity trading. This model, unlike centralized energy trading, encourages multi-party transactions that incorporate user preferences. The emergence of blockchain technology [149] and the increasing use of rooftop PV systems has provided a new opportunity for P2P energy trading. A significant disparity in knowledge exists between market mechanisms and energy exchanges [150], leading to various challenges in auctions, such as ensuring economic efficiency. As we transition towards a green future with a greater emphasis on renewable energy, dewellers are transforming from traditional energy consumers to proactive energy prosumers [151,152]. Through P2P trading, this transition would enable citizens to participate as active prosumers in a low-carbon future [153].

Applications of flexible services provided by buildings

Buildings equipped with a combination of BIPV systems and energy systems offer diverse flexible services. The multiple renewable energy sources, energy storage methods, and types of energy demanded by users [11] contribute to the many types of applications of flexible services provided by buildings on the supply and demand side. The development of model predictive control methods and flexible system optimizations has further complicated and increased the tenacity of future application couplings involving flexible services and energy systems [72].

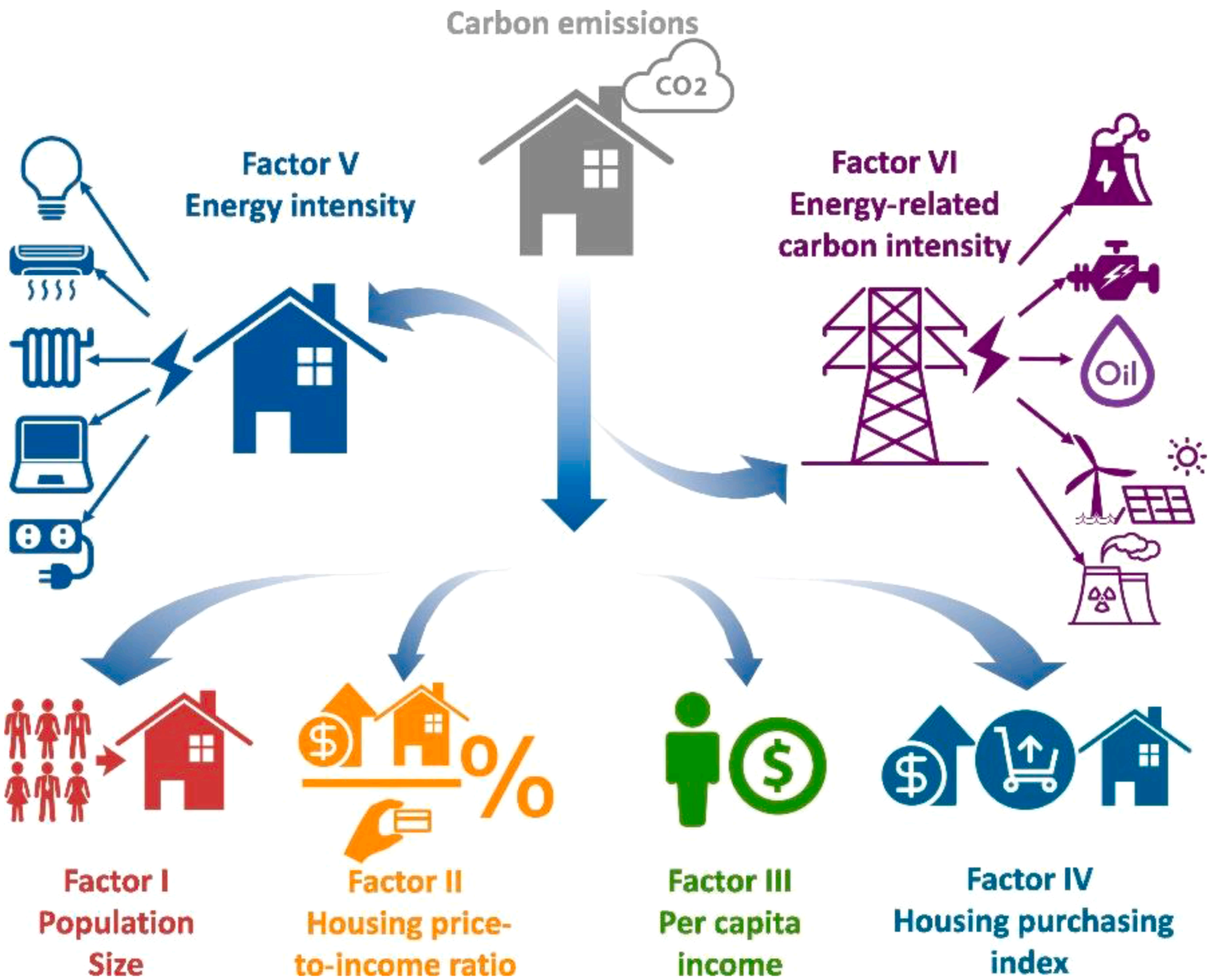

Fig. 9. Carbon emission model of the residential building [141].

Supply side: demonstration projects

In demonstration projects of buildings supply side, the coordinated scheduling of various sources of electricity and heat on the supply side is critical to successful application. Application methods differ across regions due to variations in climate and resources [27]. Practical applications often rely on equipment such as building-integrated photovoltaics, small wind turbines, battery packs, and ground-source heat pumps. Wang et al. [155] developed a distributed control scheme for loads within a community-building microgrid and successfully tested the effectiveness of this control method on the community. Miglioli et al. [156] reviewed the superiority of photovoltaic-thermal solar-assisted heat pump systems in buildings. Fathollahzadeh et al. [157] investigated the application of existing district chiller plants for minimizing electric demand. Through the model predictive control method, flexible resources are utilized to achieve these flexibility services.

In practical construction applications, economic cost is usually given priority in the design of schemes. As a result, the optimizations of many components [158] and improvements in material [127] cannot be standardized in construction. Real-world applications are more complicated due to factors such as weather and battery degradation [159]. Gomes et al. [160] developed a microgrid management system based on a multi-agent approach for an office building pilot project. The application of a hybrid AC/DC microgrid with a predictive control strategy for smart building services and energy management has also been confirmed in the studies of Wang [161] and Aoun [162] (Fig. 11). However, technical optimizations such as thin-film flexible architectural photovoltaics [163], supercapacitors [164], and phase-transition materials [165] may not be widely used in engineering projects due to high preparation costs.

Demand side: flexible services cases

Although demand-side response applications are typically related to electricity price regulation, occasional negative electricity prices resulting from the unpredictability of the climate can occur [166]. Various flexible service cases have been carried out in this field, and in most scenarios, building electric heating systems still play a critical role in these services [167,168]. Fig. 12 demonstrates the contribution of building heating systems and potential heat mitigation strategies. Yu et al. [169] have demonstrated the feasibility of power demand response based on smart home applications in China, which can reduce peak load by up to 49.3% and investment by up to 1.2 trillion RMB. The experiments of Imani et al. [170] confirmed the robustness of demand response in microgrid operation under uncertainties. The electricity market and P2P trading have a significant impact on demand response application in data-driven cogeneration systems [171]. Chreim et al. [172] demonstrated successful load scheduling applications based on demand response in smart grids. The recent promotion of the 5 G network-based internet of things is expected to provide more possibilities for the application of demand response in smart grids [173].

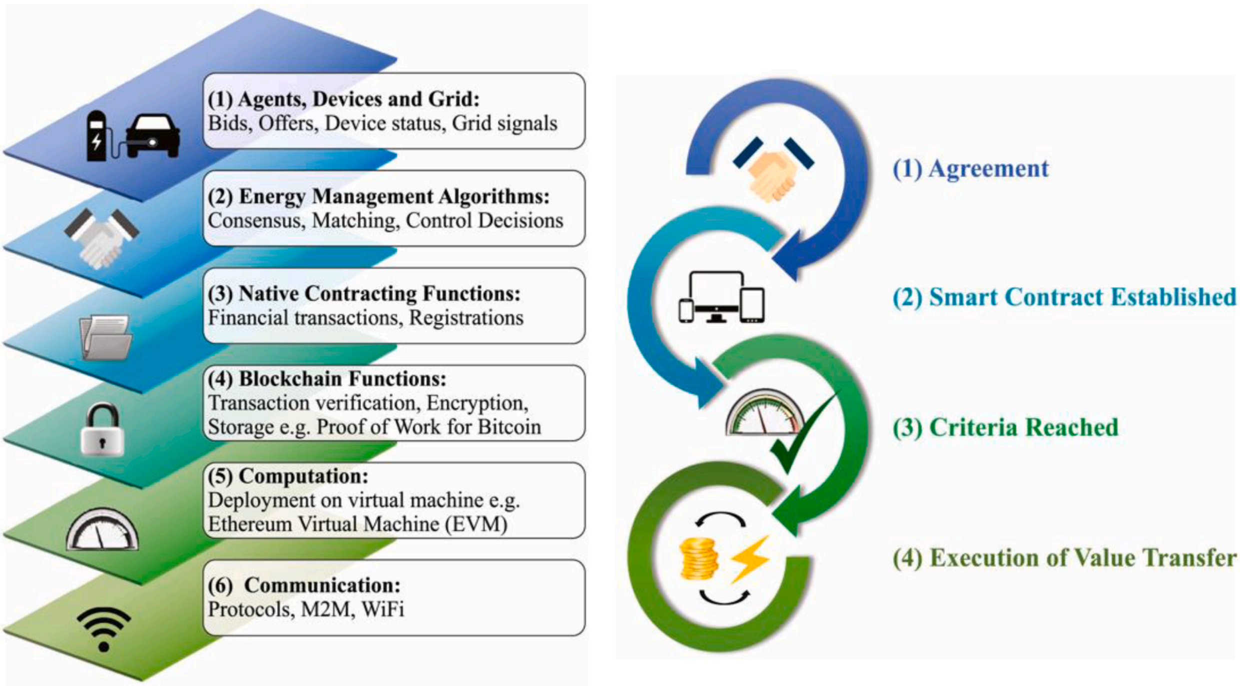

Fig. 10. Structure of smart contracting with P2P trading and fundamental steps for execution [154].

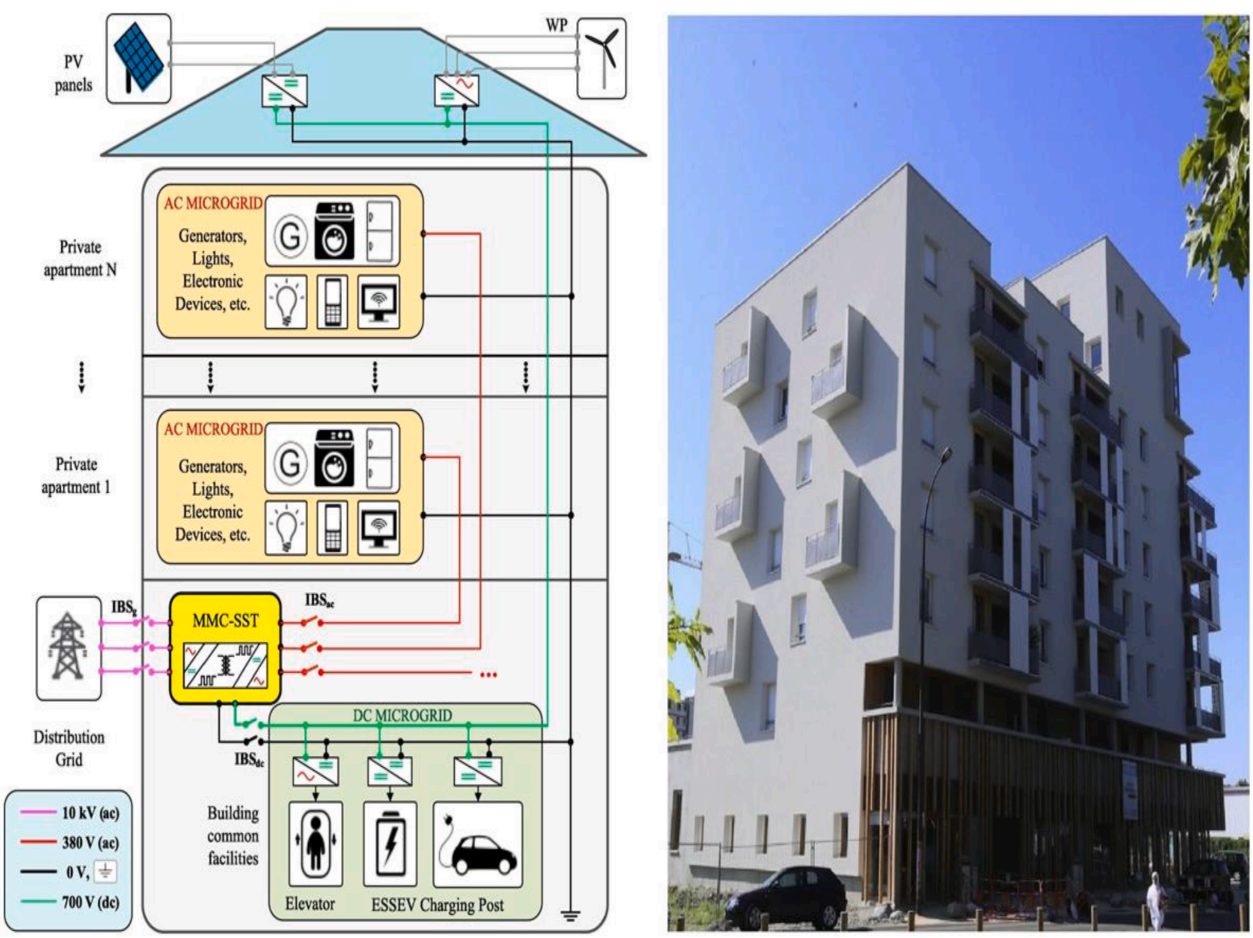

Fig. 11. The new hybrid ac/dc microgrid architecture for smart building [161] and one application of building with advanced control strategies [162].

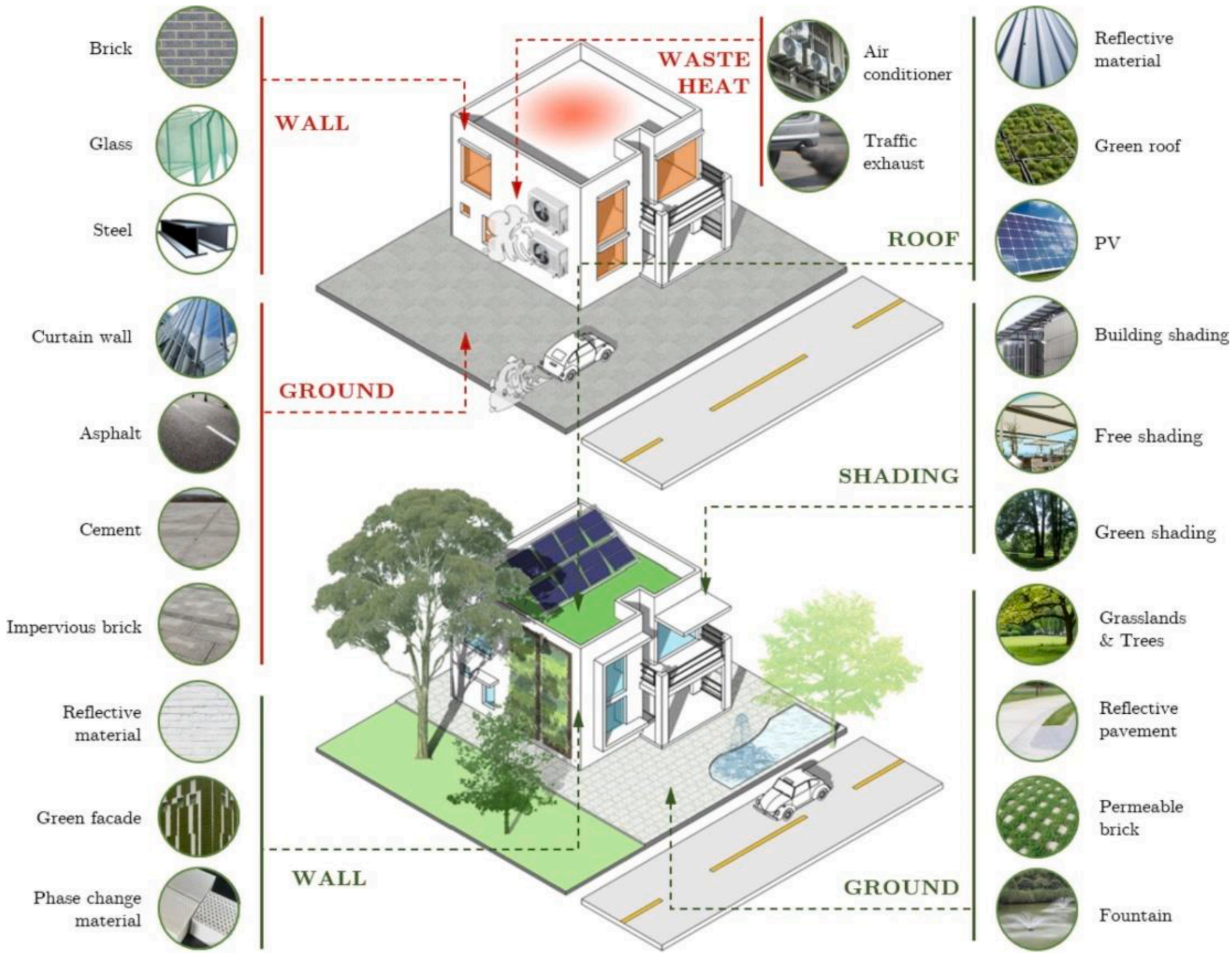

Fig. 12. Contribution of buildings heat system and potential heat mitigation strategies [174].

Challenges and perspectives of building flexibility services

Buildings are expected to play a significant role in the energy transition, but they currently face several major challenges. These include:

(1) Insufficient data collection under high levels of renewable energy penetration, especially for buildings considering thermal inertia.
(2) Limitations in analyzing gotten data and building user demand. Balancing energy efficiency and occupant comfort in building flexibility regulation, especially for model predictive control.
(3) Mismatches between heat load and power source and heating prediction at different time, which will affect flexible system optimizations for smart buildings.
(4) Geographical obstructions of microgrids, insufficient guiding policies, and communication barriers for energy system optimization and applications. To address these challenges and achieve flexible systems, the following research directions are crucial:
  - Developing efficient data sensing mechanisms and business models for distributed energy equipment connected to building microgrids. Creating dynamic models for building heating and grid-connected systems that consider the coupling effects of distribution networks. Formulating building-integrated business models that consider the interests of multiple consumers.
  - Creating a multi-time-scale carbon-energy-efficiency management and control framework to facilitate electric energy replacement in zero-carbon buildings under high-penetration renewable energy. Conducting evaluations of a building's ability to connect to the distribution network with demand-side response in mind. Comprehensive consideration of access capability, personal safety, and system efficiency is crucial in different application scenarios.
  - Implementing power/heat supply and load control technologies with smart buildings. This includes optimizing BIPV, energy storage, and controllable load to regulate power of source-load coordination in buildings. Optimal strategy for indoor and outdoor multi- power/heat supply and consumption system networks is also necessary. Additionally, data-driven source-load dynamic prediction and building energy efficient operation technologies are necessary.
  - Implementing efficient and effective operation and maintenance of building energy systems. This includes smart energy flexible management and services that enable peer-to-peer (P2P) electricity transactions in the market. Implementing online fault diagnosis methods and technologies based on artificial intelligence for distributed energy systems.

The concept of building flexibility entails the effective coordination of thermal inertia, model predictive control, flexible system optimization, and smart buildings. This approach enables various perspectives of building flexibility services, as illustrated in Fig. 13.

Conclusion

Buildings play a pivotal role in the ongoing energy transformation,

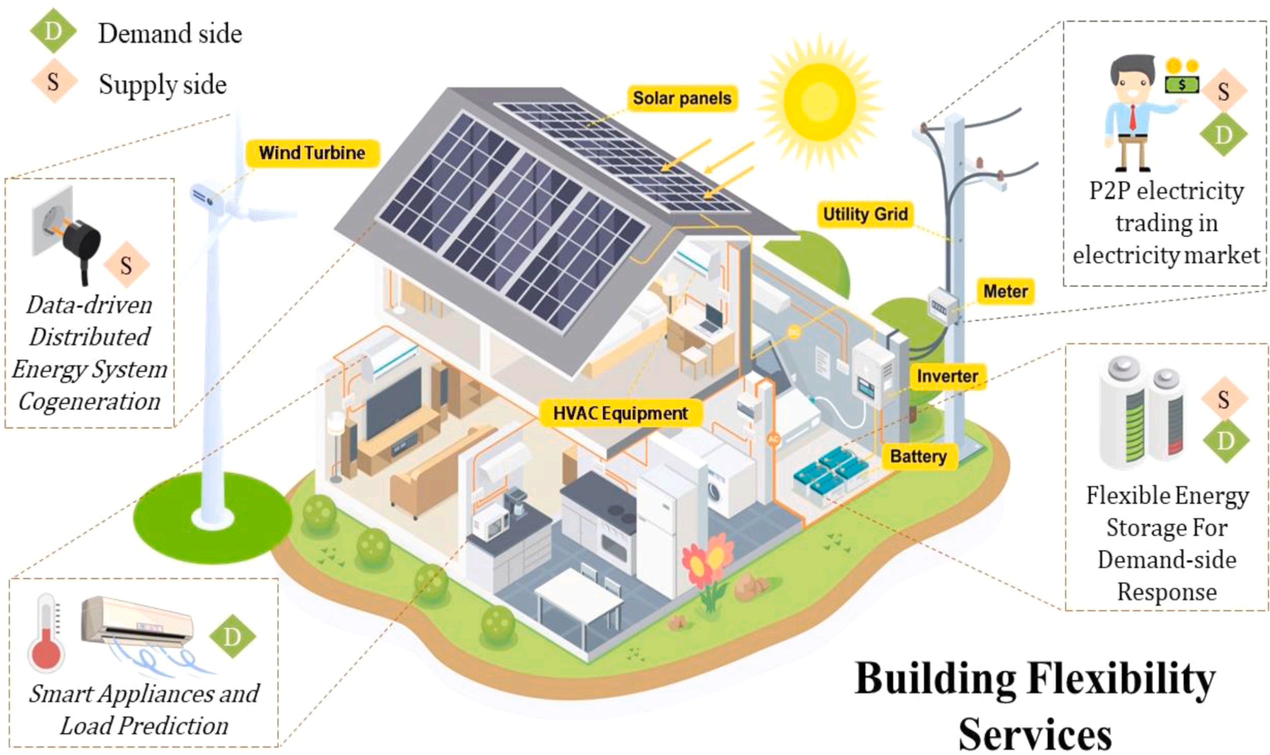

Fig. 13. Perspectives of building flexibility services.

making building flexibility a crucial aspect to explore. In this paper, we provide a comprehensive summary of recent research on building flexibility, focusing on the power-to-heat perspective. We address the challenges associated with current building energy systems and categorize relevant methods into three key aspects: thermal inertia of power-to-heat in buildings, model predictive control for building flexibility, and flexible system optimizations for smart buildings. Based on our findings, we propose recommendations for future research and practice to advance the field of building flexibility. Additionally, we propose a roadmap for realizing building flexibility systems. The main findings of this study can be listed as follows:

(1) The conventional employment of data sensing and limited analysis is a significant obstacle in optimizing flexible systems and predicting the performance of building-integrated distributed energy systems. To overcome this challenge, it is crucial to acquire comprehensive and high-quality data, particularly for the purpose of developing improved data-driven distributed microgrids.
(2) After conducting a comprehensive review of flexible services based on thermal inertia, specifically power-to-heat processing, we have identified and quantified key performance indicators of building flexibility. These indicators are categorized into three distinct aspects: energy efficiency, time control, and cost reduction. Additionally, the thermal inertia of buildings serves as a crucial foundation for implementing all flexible services.
(3) To further optimize building systems, effective analysis and precise data-driven prediction are essential. Despite the unexplored potential of demand-side data, the adoption of the 6E analysis framework may serve as a systematic approach to improving supply and demand coordination. Furthermore, among the most promising technologies for building thermal potential are smart appliances.
(4) Achieving greater flexibility in building energy systems will require the integration of various technologies, such as peer-to-peer trading and artificial intelligence. By leveraging the collective impact of these technologies, new possibilities for evolving the field of building flexible services will be realized. Consequently, the application of more efficient materials and improved components is essential to further improving the integration of flexible services in building systems.

CRediT authorship contribution statement

Zhengguang Liu: Methodology, Formal analysis, Writing – original draft. **Yuntian Chen:** Data curation, Writing – review & editing. **Xiaohu Yang:** Methodology, Writing – review & editing. **Jinyue Yan:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare no competing interests.

Data availability

No data was used for the research described in the article.

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