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Building decarbonization based on building loads flexibility and clusters' collaboration

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The decarbonization of the building sector is crucial for global sustainable development because it is responsible for about 40% of global carbon emissions and has been growing continuously at a rate of 2% to 3% per year [1]. Over time, significant energy-saving milestones have been achieved through technologies such as improving equipment efficiency, building envelope performance, and utilization of sustainable resources. As energy consumption transitions shift towards low-carbon solutions with increased utilization of renewable energy, focusing on maximizing the use of renewables is pivotal in reducing building carbon emissions. However, wind and photovoltaic power have strong volatility and intermittency. Substantial evidence has supported the notion that adequate flexibility is necessary as renewable energy becomes predominant; otherwise, it may quadruple the comprehensive cost of energy use and even trigger energy insecurity [2]. Therefore, the building sector to adapt to an unstable energy supply through building loads flexibility and clusters' collaboration drive the further development of building decarbonizing.

The concept of building energy flexibility refers to the ability to manage its demand and generation according to local climate conditions, user needs, and energy network requirements, according to International Energy Agency (IEA) Annex 67 project [3]. According to this definition, it is obvious that almost all electrical appliances in buildings can be subject to varying degrees of load adjustment through energy storage, frequency modulation, human behavior regulation, and delayed start. Besides, it is equally important to note that building components that do not directly consume electricity can still impact energy consumption and create energy flexibility [4], such as the building envelope, external shading, and curtains. Energy flexibility from buildings can play a critical role in the ongoing energy transition and hold tremendous short-term regulatory value in future energy systems [5]. It is almost the most cost-effective method to match the actual energy generation and consumption [6]. The rational use of flexible building loads in a beneficial interaction with the power system is possible to decrease CO_2 emissions by 80 million tons annually before 2030 [7]. Figure 1 summarizes the regulation modes, sources, and evaluation indicators of building energy flexibility.

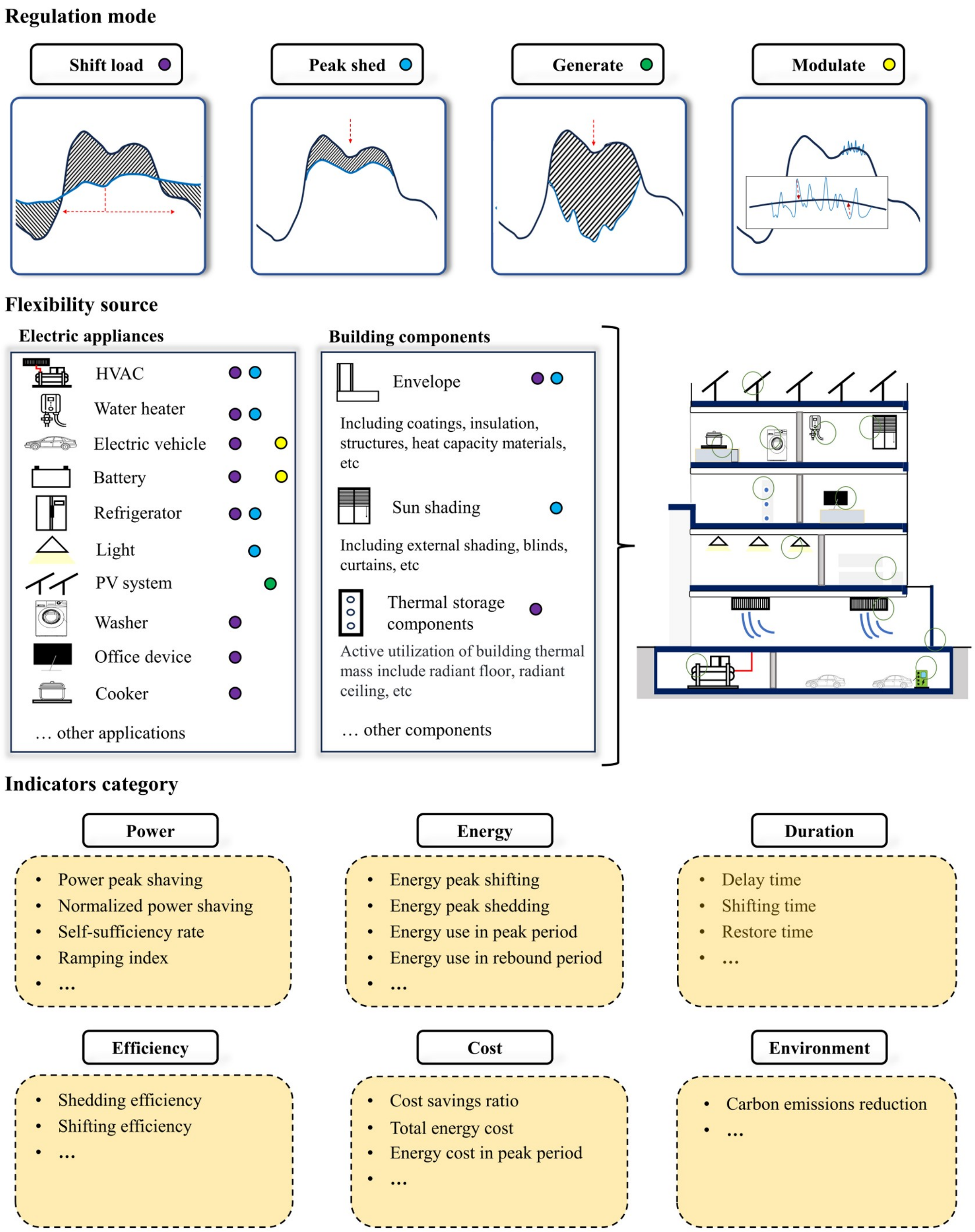

Figure 1 Building flexibility sources, regulation modes, and evaluation indicators.

The energy flexibility modes in buildings can be classified into four categories based on their response time and regulation method: load shifting, peak shedding, generation, and frequency modulation [8]. Load shifting can be achieved at negligible cost by HVAC systems and hot water loads through pre-start and thermal energy storage via inertia thermal mass. It is noteworthy that the National Renewable Energy Laboratory in the US has underscored the significant potential for energy flexibility and cost-effectiveness of building thermal loads [9]. Research findings demonstrate that effectively harnessing thermal load flexibility can underpin a 100% renewable energy scenario within the building sector. Furthermore, due to the thermal storage capability, cooling and heating devices like heat pumps in HVAC systems and refrigerator can operate at their peak performance during appropriate time periods. With the increasing adoption of electric vehicles, optimized charging and discharging strategies offer significant opportunities for power frequency modulation and energy peak valley transfer [10]. Household appliances like washing machines, cooker and even office devices can also shift their energy usage time through user behavior or delayed start programs. Peak shedding can be achieved through lighting frequency conversion and temporary adjustments to the set temperature of air conditioning, domestic hot water and refrigerator. In addition, technologies that do not consume electricity, such as passive radiative cooling, building envelope insulation, and external shading, have the potential to reduce the peak energy load. On-site generation in buildings can cover the energy consumption of the building itself and even distribute excess electricity to surrounding buildings through the local power grid. Batteries equipped with intelligent inverters can also enhance the efficiency of building energy usage through bidirectional load adjustment within seconds and minutes. Owing to the abundance of energy flexibility resources present within buildings, it is very important to undertake more precise quantitative assessment of the energy flexibility capabilities of various appliances and building components.

The quantitative assessment of building flexibility plays a crucial role in facilitating the implementation of auxiliary electricity regulation in buildings. Researchers have proposed indicators and methodological systems to evaluate flexibility quantitatively, focusing on aspects such as power, energy, duration, energy cost, efficiency, and environment [11]. Among these indicators, the peak shifting indicator is the most used. It measures the ratio of energy consumption shifted from peak to off-peak periods compared with a baseline scenario [12]. Power indicators, such as net load power and its derived metrics, are often employed to assess the efficiency of on-site renewable energy consumption in buildings [13]. Delay time and energy costs are also applied in different scenarios. These indicators and methods provide valuable insights into the energy flexibility of buildings, enabling policymakers and stakeholders to make informed decisions regarding energy management and grid integration.

Achieving energy flexibility in buildings requires a collaborative interaction between the physical systems of devices, parameter sensing systems, control systems, and the energy management awareness of occupants. Most devices already have the capability for energy flexibility, needing only the addition of control systems. For instance, electric water heaters could be programmed to delay the heating cycle start, scheduling heating during times of lower energy demand. Similar adjustments are necessary for devices such as electric vehicle charging stations and air conditioning units. Currently, the adoption of variable-frequency lighting is not widespread, indicating that enhancements to the physical systems are still needed. In addition to equipment modifications, establishing an energy flexibility management system with a user-friendly interface, along with effective incentive and feedback mechanisms, is essential. Such systems help occupants understand the potential of energy demand management to reduce costs and minimize environmental impact. Besides, different building types often require tailored strategies and technologies for energy flexibility due to variations in their function, occupancy patterns, energy usage, and equipment.

The aggregation of the interactions between building devices and components can give flexibility abilities for single buildings, and correspondingly, aggregation of single buildings' flexibility grants tremendous

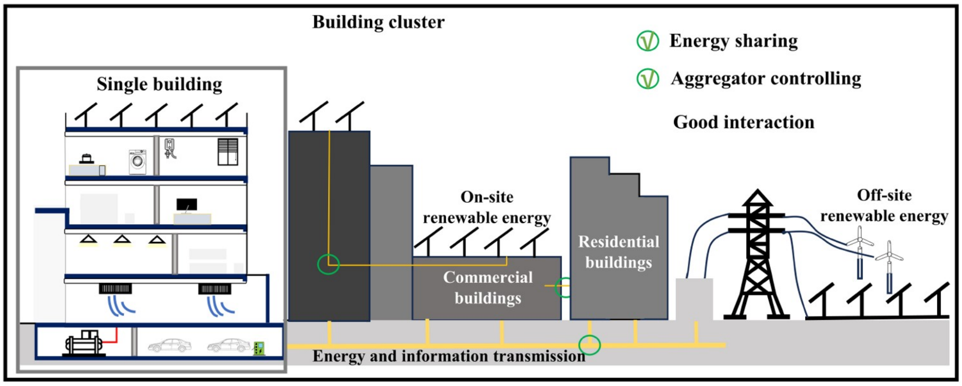

Figure 2 Energy flexibility of building cluster level.

flexibility capability of building clusters (see Figure 2). It is important to note that the buildings can either be located physically next to each other or not be physically connected, which depends on whether the same aggregator controls their energy flexibility. A building with a cluster interconnected to the same energy infrastructure could share excess energy with others to meet their energy needs through regional electricity trading. For example, without additional energy storage, the self-use rate of a single building's household photovoltaic system cannot exceed 40%, while that of a multi-story residential building is only about 18% [14]. Fortunately, researchers [15] have validated the significant positive impact of PV production through building clusters' collaboration. The energy collaboration among different types of buildings at the cluster level can also enhance the overall energy stability of energy consumption [16]. Different buildings in the cluster may have diverse energy needs and characteristics to realize energy complementarity. For example, commercial buildings and office buildings are likely to have peak electricity loads during the day, while residential buildings tend to display peak energy usage in the evening. The uncertainty of energy flexibility was less than 10% when about 700 households were aggregated [17]. However, as mentioned above, the connection of microgrids between groups of buildings has a very small share. According to the information available, microgrids currently serve less than 1% of the US electricity demand [5].

Through centralized management and integrated control systems of the building cluster, the overall energy usage of the entire building cluster can be monitored and optimized. Ref. [18] propose an information-sharing strategy based on linked data for information exchange among building prosumers and consumers, as well as other relevant stakeholders. An investigation in Colorado, involving 498 residential units showed that rational energy management in building clusters is expected to save homeowners up to $590 annually on electricity bills due to improving community load flexibility [19]. A project modelled a district in Cardiff, UK, consisting of 66 residential buildings with seven archetypes, including apartment buildings and terraced houses, estimating up to 30% in energy cost savings and up to 25% increase in the penetration of distributed renewable energy resources [20]. An aggregator has the potential to offer the market the same flexibility in terms of capacity with the largest battery project in the Netherlands (10 MWh capacity) by managing 17 reference-type office buildings [21]. Through energy aggregation management among clusters of buildings, abundant energy flexibility resources can be integrated and accommodate the demands of various stakeholders, such as users and the power grid [22]. But, time variation of energy prices remains the primary incentive for building energy flexibility. To effectively harmonize the application of demand response strategies across buildings within a community, it is imperative not only to enhance the interconnectedness of the hardware infrastructure but also to elevate the sense of collaboration between building occupants and electricity operators. Subsequently, the incentive systems must be refined to guarantee the allocation of dedicated funds.

In our opinion, the efficient utilization of energy flexibility, which is bolstered by the adaptability of building loads and the cooperation among clusters, holds considerable importance for the ongoing phase of decarbonization within the building sector. Although there are some inadequacies in research and challenges in application, it is clear that the way toward a future where buildings are not just passive consumers of energy but active participants in the energy landscape, effectively balances their needs with the fluctuations of renewable energy generation.

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Author contributions

J.G. proposed the topic of the perspective, led the revising of the manuscript, and provided resources for the manuscript. G.L. conducted the literature review, led the drafting of the manuscript, and designed the figures. J.T. helped with visualization and revised the manuscript. K.Z. discussed and revised the manuscript. All authors have given approval to the final version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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