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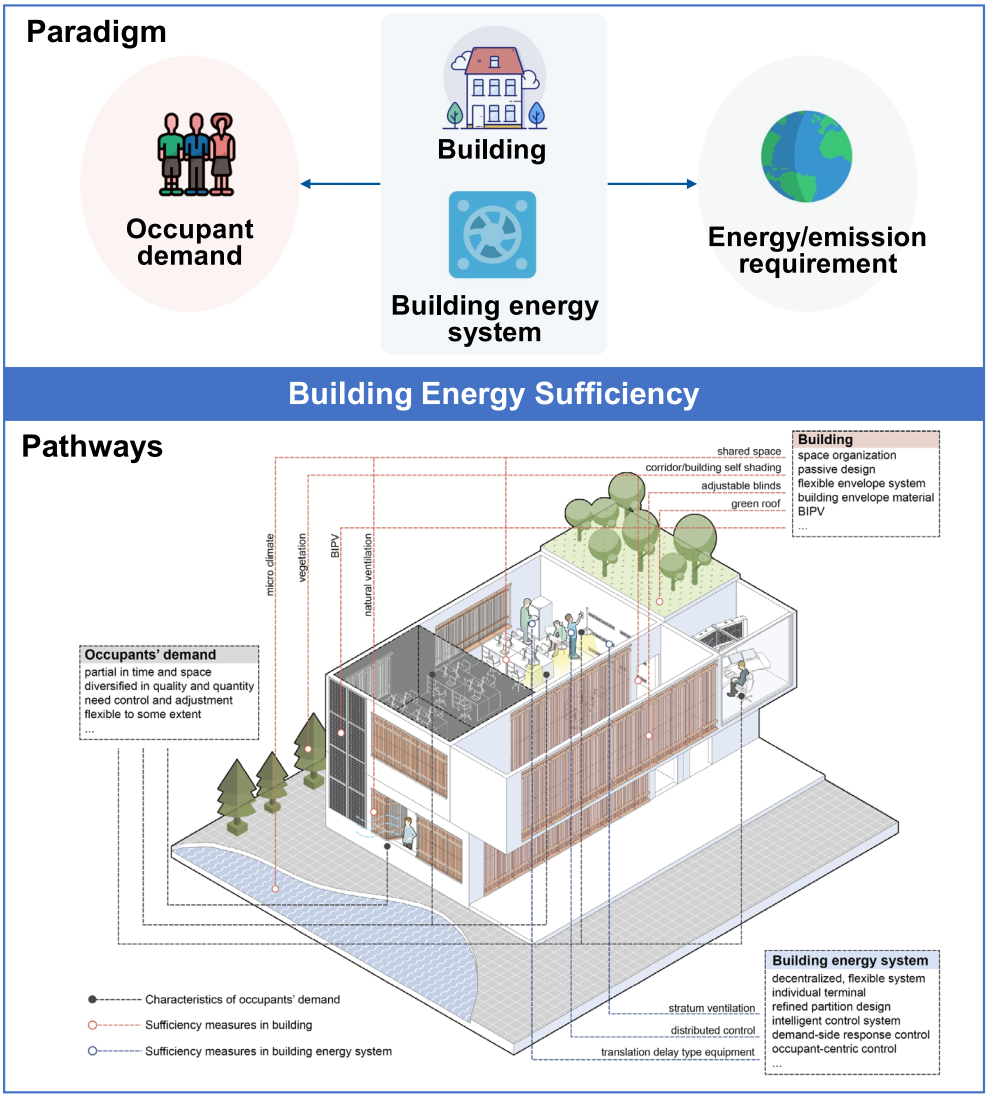
Graph abstract:



Abstract:

Among the sufficiency, efficiency, and renewable frameworks for reducing energy use and energy-related carbon emissions, Building Energy Sufficiency (BES) is gaining attention from policy makers and engineers. Despite the significant role of the building sector in the success of national energy and climate plans, there is a lack of research on the drivers, technologies, and effective policy instruments required to achieve BES in the building operational phase. To fill this gap, this study presents a systematic review of the definition and paradigm of BES and concludes that BES should address both occupant demand and energy or emissions requirements simultaneously. The characteristics of occupant demand in building services are divided into four dimensions: time and space, quality and quantity, control and adjustment, and flexibility. Technical options regarding the building architecture, the envelope system, and the building energy system are reviewed. Finally, policy implications and recommendations are discussed. The multiple benefits and multidisciplinary nature of BES justify further research and accelerated policy implementation in developed and developing countries.

Highlights:

- Building Energy Sufficiency(BES) are important to address building energy and climate issues, but research is lacking.
- Occupant demand for buildings has the following characteristics: partial occupancy in time and space, diversified and heterogeneous requirements in quality and quantity, and necessary for adjustment.
- Passive and flexible architecture, and building integrated photovoltaics are effective in reducing building demand at the building level.
- Decentralized, occupant-centric design and operation, and flexible terminals are sufficient measures from building energy systems perspective.
- Different policy pathways are recommended for different regions according to their own status.

Keywords: climate change mitigation; building; energy sufficiency; occupant behavior; climate policy

Word count: 9994 (excluding title, abstract, references, and figure and table legends)

1 Introduction

1.1 Building energy sufficiency towards climate targets

According to the International Energy Agency, global building operation accounted for 30% of the global final energy consumption and 27% of total energy sector emissions in 2021 [1]. It is clearer than ever that energy efficiency policy alone is not enough to turn around the rising global building energy demand[2]. Behavioral responses to energy efficiency improvements have offset potential energy savings and emissions reductions [3]. The Sufficiency, Efficiency, Renewable climate mitigation framework was introduced in the Intergovernmental Panel on Climate Change (IPCC) 6th Annual Report (AR6), in which building sufficiency was raised as a primary measure for the first time [4]. Sufficiency measures in the building sector are defined as a set of measures that avoid demand for energy, materials, land, and water while delivering human well-being[5,6]. Among all sufficiency measures, energy sufficiency is the most important, influencing both human well-being and energy and carbon emission boundaries [7]. According to the IPCC's scenario analysis results, these sufficiency measures could contribute to a 10% reduction in global building emissions [4]. An increasing number of bottom-up or hybrid studies have identified different levels of carbon emission reduction potential of sufficiency measures in both developing and developed countries [8,9]. According to International Energy Agency, buildings will remain off-track to achieve carbon neutrality by 2050 [10]. Given the importance of the building sector from energy and emissions perspectives [11], it is surprising that there are very few building sufficiency measures and policy instruments in the current policy framework [12]. There is an urgent need to understand the scope, objectives, drivers, and potential of BES.

1.2 Human well-being with building energy sufficiency

In addition to energy and climate targets, improving human well-being for all is the greatest challenge to improving sustainability. There is overwhelming evidence that, despite the promotion of new technologies that can improve energy efficiency, and generate renewable energy, poverty-stricken populations and disadvantaged communities have benefited far less than the wealthy populations [13]. Sustainable development is difficult to achieve without changes in lifestyles and high material, energy consumption and emissions, especially for high-income groups [9].Sufficiency measures in the building sector also provide the means to address inequality, poverty, and sustainability and ensure decent living standards for all [2,13].

The ultimate goal of sustainable development is to preserve both human life and environmental conditions[14]. Many studies have investigated the relationship between human well-being, energy consumption, and carbon emissions[15,16]. Mazur et al. [17] presented a non-linear relationship between energy consumption and lifestyle: increasing energy use was highly correlated with improved lifestyle and well-being at a low energy consumption level, but not at high levels. This non-linear pattern was later confirmed in various regions, such as Europe [18] and China [19,20]. Evidence from 93 countries from 1975 to 2005 has quantitatively proved the correlation and decoupling features between the human development index with energy and emissions [21]. A similar non-linear relationship has been found for building energy use. Guo et al. [22] analyzed data from 135 regions and revealed that higher building energy use may not bring more happiness. Hu et al. [23–25] analyzed the space heating energy use and satisfaction level of indoor service levels among 910 households, and indicated that centralized heating with “full time full space” mode slightly improved occupant satisfaction rate but significantly increased the energy use intensity.

Summarized from previous reviews, conceptual illustrations of building energy use intensity, human well-being, and sufficiency are presented in **Figure 1**. At the insufficient stage, building energy use intensity and human well-being are both low. Improvements in building energy use may significantly raise building service and comfort levels at the sufficient stage. At the sufficient stage, increasing building energy use has only a marginal effect on well-being. Finally, at the excessive stage, human well-being is decoupled from building energy use and the relationship becomes very weak. It is therefore possible to decouple energy and carbon emissions from human demand with BES strategies.

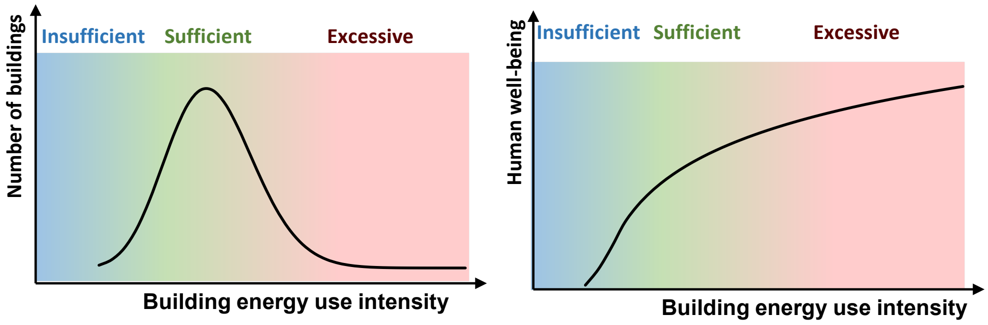


Figure 1. Conceptual illustrations depicting the relationship between building energy use intensity, sufficiency, and human well-being. *Left,* Relationship between building energy use intensity with the number of buildings. *Right,* Non-linear relationship between building energy use intensity and human well-being

Defining the range of energy sufficiency is key to addressing energy inequalities and excessive consumption. But the criteria for evaluating the "necessary need" or "reasonable" energy use intensity is difficult [13]. To overcome these key barriers, the Decent Living Standard was adopted as a universal set of service requirements essential for achieving basic human well-being [26,27]. However, dramatic gaps in energy consumption and emissions have been observed across countries and across different income groups within a given country [9,28]. BES cannot be measured only by the final energy use, but is also dependent on the choices of building occupants. Thus, it is possible and necessary to decouple energy and carbon emissions from human demand with BES strategies[29].

1.3 Content of this research

Previous original concepts and research papers have thoughtfully discussed BES in buildings and products from the perspective of end terminals [29,30,30,31]. Principally, four aspects have been considered in the literature [29]: space, design and construction, equipment, and building use. Subsequent studies investigated BES in building floor space [32], products [30]. A number of studies have discussed the concept of sufficiency at a broader level[29,31]. There are also existing modelling studies estimating the emission reduction potential of some sufficiency measures in the building sector, mainly on building floor area per capita and few on indoor temperature[33–36]. The research gaps in existing studies are:

- there is a lack of definition and framework for BES;
- drivers or influencers of BES are rarely discussed and mentioned, especially considering the importance of occupant demand and behavior;
- some common BES measures are listed, but a systematic framework is lacking, making the solutions included in BES inadequate;
- lack of policy recommendations considering different barriers for developed and developing regions.

In fact, as building envelopes and energy systems are optimized, the influence of occupant behavior on building energy performance increases [37]. Lifestyle and occupant behavior have been increasingly identified as significant factors influencing building final energy use [38,39]. Empirical evidence from surveys, monitoring, and simulations has revealed three- to five-fold differences in energy use for the provision of similar building-related energy service levels [40]. The differences in building energy use intensity across countries may largely be attributed to lifestyles and occupant behavior [41,42]. Therefore, the building service level reflected by occupant behavior is a fundamental driver of building energy use and is the key to addressing BES. In this systematic review, we aim to explore the paradigm, pathways, and potential of BES based on the core occupants inside buildings. The concept of an occupant-centric BES analysis framework is proposed, providing new insights into BES and its contribution to mitigating climate change while achieving sustainable development goals. The scope of this review pertains to BES measures on building architecture and energy systems primarily focused on building operation stages. First, in section 2, we summarized the concept of BES based on previous studies on energy and energy sufficiency and concluded the paradigm of BES. The factors influencing BES from the nature of occupant demand and behavior in buildings were concluded, in section 3. Then, the pathways and potentials of BES from the building and energy system level are reviewed by its scope, importance and state-of-the art. Finally, the policy implications for integrating BES into national energy and climate plans are discussed, taking into account the different levels of development and their main barriers for energy and climate targets.

2 The concept of building energy sufficiency

2.1 Definition of building energy sufficiency

Sufficiency is defined as "an amount of something that is enough for a particular purpose"; based on this definition, Fawcett et al. [31] established a definition of *Energy Sufficiency* as "a state in which the population’s basic needs for energy services are met equitably and ecological limits are respected”. Energy sufficiency is commonly confused with energy efficiency, which is a term representing the relative relationship between energy input and effect output; it is possible for a building to be both energy-efficient and energy consumption intensive. Historically, the synchronous growth of energy efficiency and energy consumption in the consumption sector has occurred in developed countries [22]. Energy sufficiency requires both reasonable services and absolute energy consumption within the limitations of environmental boundaries [31].

Specifically, Building Energy Sufficiency(BES) refers to building-related services that are provided in an equitable, reasonable, and ecological manner [29], as illustrated in Figure 2. The status of BES can be categorized as insufficient, sufficient, or excessive [13,29,31]. If building service is insufficient, then the energy usage and emissions would be low as well; however insufficient building services may cause a number of problems, including health risks to vulnerable populations from severe weather, indoor air pollution leading to illness, and other consequences [43,44]. On the other hand, if the demand for building services is too high, the resulting energy use and emissions would be higher than the limit, contributing to increased inequality and injustice.

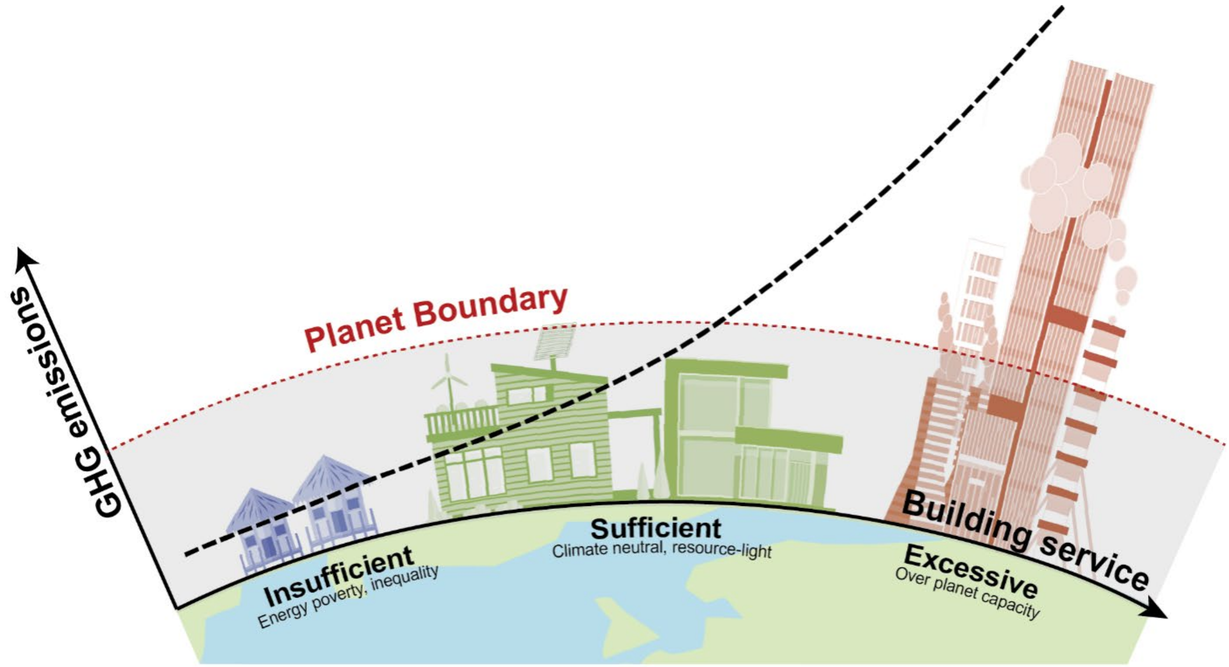


Figure 2. The concept of building energy sufficiency within limitation of planet boundary.

2.2 The paradigm of building energy sufficiency

From the perspective of occupants or building users, a building is a system that provides three types of services (see Table 1): (1) building space for occupants to live and work; (2) appliances for occupants to use to complete tasks, such as washing, cooking, or moving; and, most importantly, (3) comfortable indoor environments, including suitable temperature and humidity, low air pollution, and suitable lighting. The sufficient level of building service is subjective, individualized, diverse, and stochastic, because it is highly dependent on the occupants and can be different for different users, or even for the same user on different occasions.

Table 1. List of building services for occupants

Demand of building	Category	Target of service
Space	Space	Space
Activity	Domestic hot water	Hot water
	Cooking	Cooking activity
	Appliance	Life and work activities
	Elevator	Movement inside buildings
Comfortable indoor environment	Heating	Temperature and humidity
	Cooling	
	Ventilation	Air pollutant concentration
	Lighting	Lux

Figure 3 depicts the paradigm of occupant-centric BES. To achieve BES, the following two rules must be met simultaneously: (1) the needs of the occupants must be satisfied by the building and energy systems, and (2) the energy consumption of the building energy system must be limited to a certain level, which should be determined according to the energy and emission cap of the planet, nation, region, city, or community.

The first rule of sufficiency involves the relationship between occupant demand and building energy system supply: if the supply is less than the demand, the result is dissatisfaction and discomfort; on the contrary, the result is energy waste. In the case of equal supply and demand, BES is achieved only if energy use is less than the cap target; otherwise, the excessive energy use required by the demand would not be affordable or sustainable.

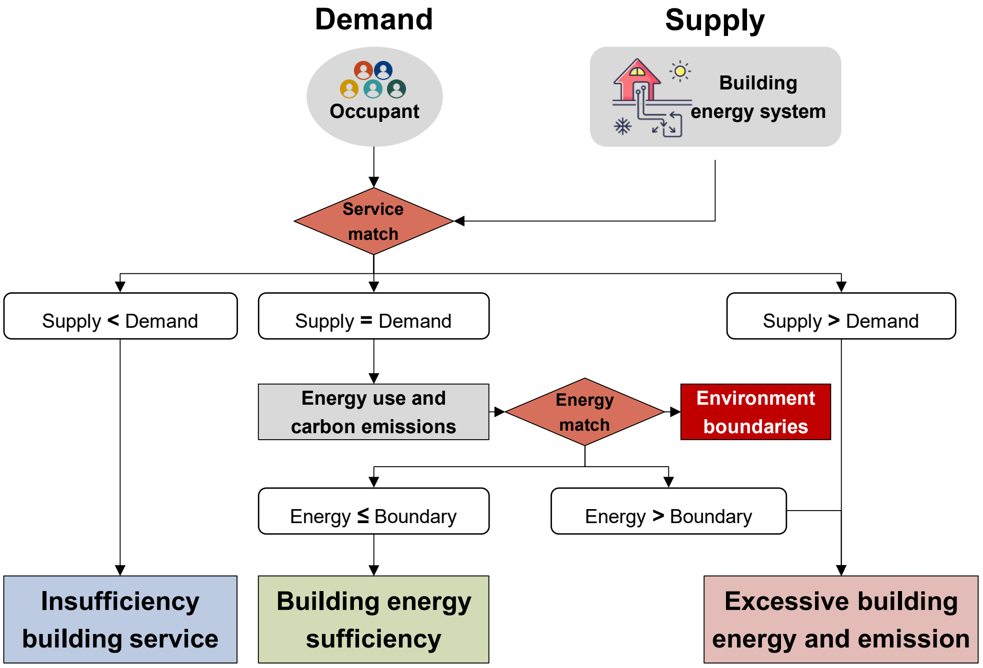
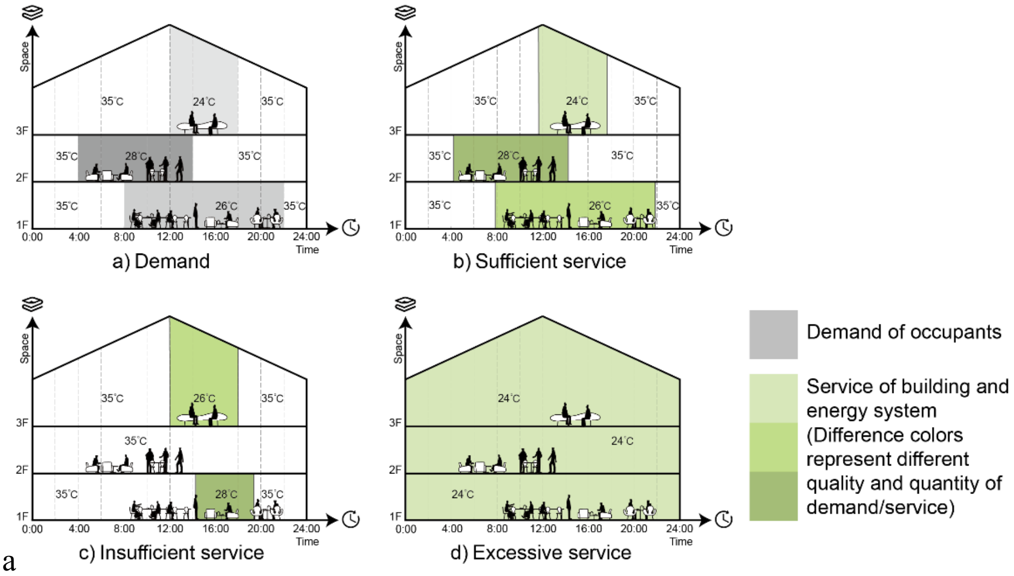


Figure 3. The paradigm of occupant-centric building energy sufficiency.

The match between occupant demand and the supply from building and energy systems falls into three categories: time and space of service, starting time and ending time of service, and quality and quantity of service. Sufficiency can only be achieved when the time and space, start and end time, and quality and quantity of the service match the demand, as shown in Figure 4b. Otherwise, if the service provided is shorter or smaller than the demand, or if the quality and quantity do not meet the demand, the service will be inadequate, resulting in occupant dissatisfaction (Figure 4c). Conversely, if time and space are covered by the highest demand requirement, as shown in Figure 4d, occupants will be satisfied; however, an oversupply cannot be avoided in this case.



a) Demand b) Sufficient service c) Insufficient service d) Excessive service

Figure 4. Matching the demand of occupants with building service.

a. Occupant's demand for air conditioning in terms of time, space and indoor temperature; b. building service is sufficient, indicating that the supply is perfectly matched to the demand; c. building service is insufficient, due to lack of supply for certain time and space, and mismatched temperature requirement; d. building service is excessive, as the building is supplied in full time and full space mode at the lowest temperature.

2.3 Framework for this review

Five basic scientific questions regarding occupant-oriented BES arise, as outlined in Figure 5:

1) Tailoring BES towards energy and climate targets;

2) BES drivers and influencing factors, and the threshold of sufficiency;

3) Pathways and potentials of BES measures in terms of energy use and emissions;

4) Simulation and modelling of BES across regions with different climates;

5) Intervention and policy designs for BES promotion.

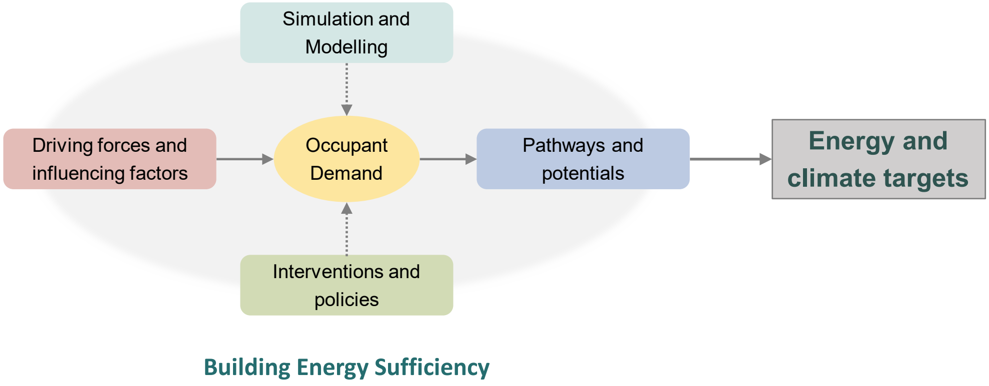


Figure 5. **Key research questions in the pursuit of building energy sufficiency.**

This study has reviewed the research progress on these issues, with a particular focus on drivers, pathways and potentials, and interventions and policies. Certain technological and non-technological measures that have been identified as effective in achieving BES are illustrated in Figure 6.

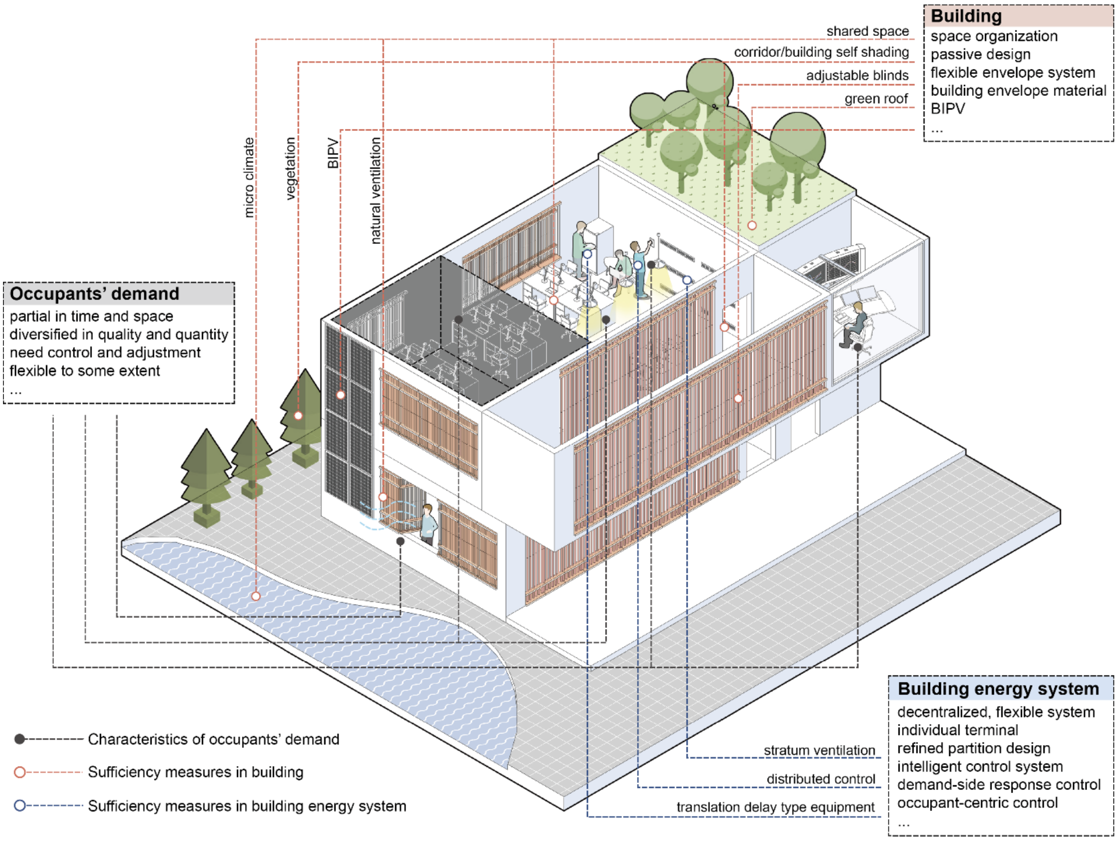


Figure 6. Building energy sufficiency measures to meet occupant demand.

Before proceeding review analysis, two clarifications should be made:

(1) The scope of this review focuses primarily on sufficiency measures influencing energy and emissions during building operational phase.

(2) Building energy efficiency measures are sometimes combined with BES measures, for example building envelope performance improvement. We categorize measures as BES measures if the primary intention is to reduce demand. For example, natural ventilation was categorized as a BES measure when it's intention is to extend the comfortable period without artificial space conditioning. But improvements in building insulation to reduce building energy consumption during the heating season were not included.

3 Factors influencing building energy sufficiency

The level of BES is strongly related to occupant demand and behavior, such as daily life routines, occupancy patterns, and occupant preferences regarding the quantity and quality of building services. The demand for building space or height and its diversity among populations has been investigated in previous studies [32,45,46]; therefore, here we focus on the influence of occupant demand on building energy services ranging from indoor environment to specialized equipment.

3.1 Partial occupancy in time and space

Humans tend to behave in particular ways at particular times; this is referred to as the regularity and periodicity of human activities [47–49]. At the same time, individual heterogeneity and the stochastic nature of humans lead to diversity and randomness in human activities[50,51].

Regularity and periodicity. Evidence from the Time-Use Survey (TUS) [52–55] and the Residential

Occupancy Pattern Survey [56,57] has shown that, occupancy (the presence and number of occupants) in residential buildings usually follows a pattern and changes periodically. The pattern of individual occupancy in public commercial buildings is not as obvious as that in residential buildings, but there are still common patterns of occupancy rate and density at the building level [58–61]. For example, the occupancy rate of office buildings is high during working hours, low during lunch breaks, and drops to almost zero during non-working hours[62]; however, the occupancy profiles are completely different between weekdays and weekends [63]. The difference in occupancy patterns between weekdays and weekends also occurs in both urban and rural residential buildings[50,51].

Diversity and stochasticity. Despite general patterns, there is still considerable diversity in the occupancy of different individuals, or even the same individual on different occasions. In residential buildings, different households have different work and rest schedules, and the occupancy pattern of a household varies greatly between weekdays and weekends, and on different occasions.

Partial in time and space. Most importantly, the regularity and periodicity, as well as the diversity and stochasticity nature of occupancy in buildings ultimately result in the proportion of occupied time and space being only one-quarter of the total time and space in residential buildings [23,64]; the proportion of occupied time and space is lower in office buildings [23].

Building services are delivered to occupants and are only effective when buildings are occupied. Therefore, centralized building energy systems (e.g. district heating), in which services are supplied continuously and to all spaces, will naturally result in an inevitable oversupply in terms of time and space. Conversely, decentralized building terminals offer the advantage of flexible adaptability to occupied rooms and spaces, and avoid services for unoccupied rooms and spaces. Furthermore, comparative studies of different buildings, in different seasons have shown that occupancy information offers significant energy savings potential of up to 50% [61,65]

3.2 Diversified service in quality and quantity

Although people have similar requirements for indoor environments, the definition of a satisfactory environment differs between populations. One of the main purposes of a building is to provide an environment that is comfortable and does not adversely affect the health or performance of its occupants [66]. Thermal comfort is an important parameter in the design of buildings and heating, ventilation, and air-conditioning (HVAC) systems [67,68]. For instance, ASHRAE Standard 55 specifies the conditions for acceptable thermal environments [69]. However, gender and other factors influence an individual's thermal comfort. The diversity of human thermal comfort has received increasing attention [70,71]. Humphreys and Nicol suggested that individual differences arise from phenomenological variances, including inter-individual differences, which represent the variance in thermal comfort between people, and intra-individual differences, which represents how an individual feels in the same environment on different occasions [72]. To address this variance, a paradigm shift from centralized to personalized space conditioning is underway [70].

People also have very different requirements for the amount of services they use. For example, there are obvious individual differences in the usage habits and consumption of domestic hot water among residents. Bathing via shower or tub significantly affects the energy consumption. A shower typically consumes 30–50 liters of water, while a bath typically requires 300–500 liters of water. Showering is the most common method of body washing in China [20]. Conversely, bathing is very common in Japan, and this lifestyle leads to much higher domestic water consumption in Japanese households than in Chinese households.

3.3 Willingness to control and adjust

In addition to diversified demands, occupants are also willing to adjust the indoor environment and control the building envelopes, for example through windows and HVAC terminals. Environmental psychologists have long known that human reactions to sensory stimuli are modified when a person has control over that stimulus [73]. With the ability to control and adjust the indoor environment, a wider range can be accepted by occupants, and in most cases, this leads to building energy savings. Moreover, within the expected waiting time, occupants can tolerate a reasonable delay in service after the request has been made. This is universally observed across different populations and building energy end-users.

3.3.1 Opening windows

Opening windows is a typical control behavior in a building. People all over the world have the habit to open windows. Glenn et al. conducted a national survey of 3800 individuals in the United States which showed that, including all seasons and geographic regions, 43.9% of the respondents said that at least one window was open[74]. Similar surveys have been conducted in China [23], and revealed that opening windows is a traditionalized behavior to maintain a suitable indoor temperature and air quality across climate conditions [75]. Results from 5731 valid samples from 12 provinces in China indicated that, in office buildings, more than 80% of occupants have window expectations; 30–40% of families keep at least one window open at home, even in winter. Window views are physically and psychologically beneficial to building occupants and can effectively reduce discomfort, according to a field study in the Netherlands [76]. Further research revealed that openable windows provide sufficient indoor space and allow exposure to external elements (e.g., air, sound, light, people outside), and allow the expression of personal control [77].

Natural ventilation through openable windows is also beneficial for indoor environmental control and building energy conservation. ASHRAE RP-884 [78] developed and analyzed a global database and found that occupants in naturally ventilated buildings accepted and preferred a significantly wider range of temperatures compared to occupants of centrally controlled HVAC buildings. One possible explanation is that naturally ventilated buildings afford occupants greater degrees of control, leading to a relaxation of expectations and a greater tolerance of temperature fluctuations [79]. Therefore, thermal environments in buildings with openable windows are typically more variable than the conditions found in fully air-conditioned buildings [80].

3.3.2 Controlling the building energy system

Owing to the differences between individuals, improvements in the adjustability of building services to better adapt to varying and random demand parameters may increase occupant satisfaction, even with the same physical parameters. Empirical research has been conducted to investigate the relationship between controllability and comfortable level. Field studies conducted in five office buildings in the Netherlands demonstrated that personal control is an essential factor for increasing occupant satisfaction in workplaces as it provides physical and psychological benefits [81]. Lee et al. adopted model research and showed that increased personal control over the physical workspace led to higher satisfaction [82]. Empirical studies on 600 Swedish households by Lindén et al. indicated that households could accept lower indoor temperatures during winter with individual and adjustable heating devices [83]. A field study in China showed that occupants with personal control had lower neutral temperatures in winter [84]. Experimental studies have shown that both psychological effects of perceived control and physical effects are both important for personal control of thermal comfort

[85]. Therefore, it is suggested that occupants be provided with opportunities to interact with the thermal environment, as it provides not only local heating and cooling, but also individualized feedback [86]. Personal service and control systems, including personal lighting control, can also achieve energy savings [62,87].

3.3.3 Waiting time

Waiting time is an important factor affecting all services, including food, transport, medical, and building services [88,89]. Empirical studies show that actual waiting time, perceived waiting time, and the disconfirmation are all related to satisfaction with the service [89]. In the building service context, while occupants put forward the demand for building systems, it is usually necessary to wait for the parameter to reach the desired state. There is an acceptable waiting time that occupants will tolerate; however, past a certain waiting time threshold, the dissatisfaction of occupants increases significantly. This phenomenon is typical for passengers waiting for buses [90]. Similarly, the elevator system faces the challenge of reducing passenger waiting times. Systems that enable passengers to pre-register elevator calls in some smart buildings can effectively reduce passenger waiting time [7]. Likewise, in HVAC systems, remote or pre-controlled cooling terminals during summer may effectively reduce the waiting cooling time of the cooling system. When provided with waiting duration information, subjects appear to maintain a sense of control while waiting, which in turn affects service quality judgements by increasing the acceptability of the perceived waiting time [89].

3.4 Flexibility

Although there are many constraints on occupant demand for building services, there is still considerable flexibility[91–94]. Building service demands from occupants are flexible in different dimensions including time of use, quality, and quantity. In other words, with the right incentives, occupant demand for building services can be avoided, shifted, and improved under certain circumstances.

Occupant-centric demand is flexible in terms of the parameters and time of use [95]. Building indoor environment control is aimed at a relatively wide range of comfort rather than a specific value. Unlike accurate environmental control for industrial production, there is no strict or precise parameter requirement for building service supply because of the adaptable nature of humans. According to the ASHRAE Standard 55-2017, the recommended temperature range is 67°F to 82°F, and the recommended relative humidity range is 30% to 60%.

The time of use of home appliances and hot water is sometimes flexible for some end-users [96]. Space heating or cooling can be switched on before occupation by pre-heating or pre-cooling to achieve a suitable temperature during the occupied period and to avoid peak electricity demand. Another example is that home appliances, such as washing machines, dish washers, and domestic water heaters, can be reserved to work during valley hours to take advantage of lower electricity prices without affecting users' activities [31,97–99].

Traditional building energy control systems typically use a constant indoor service level without input from real occupants. The control strategy from the central control center allows limited flexibility to meet real occupant demand and reduce energy consumption [100]. To satisfy the needs of building occupants while decreasing building energy consumption, occupant-centric building design and occupant-centric building controls (OCCs) have been promoted [41], to ensure that building energy services are provided only at the right time, in the right place, and in the right quality and quantity as required by occupants [100]. In addition, the flexible nature of occupant demand and building energy systems with OCCs provides opportunities to avoid peak periods or increase the use of renewable electricity in the grid[95].

In summary, the characteristics of occupant demands inside buildings can be summarized as follows: (1) partial spatial-temporal dimensions; (2) inter-individual and intra-individual differences; (3) preference to control and adjust, preference not to wait; and (4) some degree of flexibility in terms of time of use and amount of service. Thus, it is essential to explore and understand the requirements of each individual and match the diversified requirements as much as possible; the target is a match between the occupant demand with the systems' supply. It is also important to take advantage of the flexibility of occupant demand to achieve energy efficiency and lower carbon emissions.

4 Pathways and potentials from building level

4.1 Scope and aims

4.1.1 Scope

Firstly, architectural design mainly considers how to partition the overall space to reflect the differences in the needs of different subspaces to provide corresponding services in a targeted manner. In addition to spatial design, another major focus of architectural design in terms of BES is to use various passive design methods to extend the time period in which the building can meet occupant demands, on the premise of reducing the intervention of the active energy system as much as possible.

4.1.2 Aims

1) Time and space

The energy intensity of the main space can be reduced by classifying spaces and using transitional and passive spaces, while space sharing reduces the area of space that requires active environmental adjustmen. in terms of time, the main purpose is to enhance the indoor-outdoor connection through various passive design means, and to extend the period during which the building can passively maintain a comfortable indoor environment.

2) Quality and quantity

In architectural design, passive adjustment methods, such as enhancing natural ventilation and the clever use of natural lighting, should be used as much as possible to reduce the intensity of active energy use. In addition, compared with the active control method, passive control methods generally result in wider comfort zones as the quality provided by the environment is different, which is conducive to reducing energy consumption.

3) Control and adjustment

By using openable windows, adjustable shading, phase-change materials et al., the supercooling and overheating conditions caused by random weather or building thermal disturbances can be reduced, thereby extending the time during which the building does not use active energy.

4) Flexibility

The flexibility of occupant demand offers advantages that can be flexibly applied in architectural design, providing new opportunities for energy saving and emission reduction. For example, architectural design, and the characteristics of occupant needs are combined to rationally optimize the activities of occupant under extreme temperature adjustment and use the comfort tolerance range of occupants as much as possible to reduce active energy intervention.

4.2 Importance

Occupant behavior and occupant needs in buildings are often ignored or simplified during architectural design. Consequently, the indoor environment often fails to meet individual needs, which in turn leads to inappropriate changes to the architecture due to dissatisfaction with the building environment, resulting in energy waste and even potential safety hazards. Therefore, taking occupant factors into consideration during architectural design, implementing behavior-guided space design methods, enhancing the interaction between occupants and nature through passive design, and considering the diversity of people as much as possible can effectively improve occupant satisfaction, enhance building quality, and increase building energy efficiency.

4.3 State-of-the-art

4.3.1 Space organization

By setting reasonable floor space per capita and combining ingenious space divisions, combinations, and connections, an activity space suitable for diverse personal and functional needs can be formed. This can extend the time for which users are within the thermal or visual comfort zones and reduce energy consumption.

Huebner et al. [101] proposed that the floor area is a key variable affecting building energy consumption. Jones et al. [102] realized that because of the extra space for installing more electrical appliances, a larger floor area usually implies a higher level of electricity usage. Kang [103] proposed that for energy consumption per floor area, units in multi-unit residential buildings consume less energy than single detached houses. Moreover, designing pleasant shared space can reduce the need for individual volumes [104]. Marín-Restrepo et al. [105] proposed that occupants of shared spaces have a wider comfort range. Mofidi et al. [106] also suggested that designers can reduce energy consumption by considering the thermal and visual comfort preferences of different occupants and setting positions to suit their preferences. For example, if an occupant prefers a darker environment and the visual tolerance of the occupant is high, the brightness can be adjusted to a range closer to the visual comfort zone of other workers who prefer a brighter environment.

In general, different methods of space organization can affect not only the indoor thermal environment but also the thermal comfort threshold and user behavior. Some studies have also examined the impact of differences in the arrangement of occupants in space on energy consumption; however, there are few studies on how to increase the comfort range of residents and reduce energy consumption in a specific spatial organization mode. The impact of space organization on energy consumption can be continued in this direction in the future.

4.3.2 Building passive design

As can be seen from the discussion in Section 3.4, occupants need to regulate windows and building envelopes. Therefore, most buildings are designed with openable windows. On this basis, existing research has explored how further passive design can be achieved.

At present, the vigorous advocacy of concepts such as energy-saving buildings, green buildings, and low-carbon buildings has led to the wide use of passive building designs. The main idea of passive building design is to reduce the energy consumption for lighting, heating, and air conditioning through the architectural design itself, rather than the use of mechanical equipment.

Liu et al. [107] realized the time-varying effectiveness of passive design strategies in responding to future climate change in hot and humid climates. The three most effective parameters for building thermal performance, namely, shading devices, natural ventilation, and thermal insulation, were investigated in a temperate climate in a study by Mushtaha et al. [108]. The findings suggest that the implementation of such passive design parameters can reduce building energy consumption by 59%. Jung et al. [109], conducted a multi-objective optimization of a passive design strategy for multi-storey residential buildings in South Korea. Through the optimization of the passive design parameters, the energy, environmental impact, and economic feasibility was improved by 52.7%, 39.5%, and 36.9%, respectively.

It is worth noting that the specific scheme of architectural passive design and its effectiveness depend on the building type, climatic characteristics, architectural form, etc. It is impossible to apply a general passive design scheme to all buildings, which is one of the reasons why this research has become a hot topic in recent years. Researchers with different cultural backgrounds in different regions need to conduct optimization research on passive design for specific cases in order to realize the high efficiency and sustainability of buildings that perform better in hot and dry climates.

4.3.3 Flexible envelope system

A flexible envelope system is a new building envelope structure based on intelligent adjustment and dynamic response. Compared with the traditional stable envelope system, the optimized flexible envelope system can better meet the dynamic response of outdoor environmental changes and meet the thermal environment needs of occupants, which is the key to the realizing energy-saving work of the building through the interaction of the indoor and outdoor environments.

Through a systematic review, Cui and Overend [110] classified switchable thermal insulation technologies into three categories based on their heat transfer and switching mechanisms: density transitions, mobility transitions, and energy transitions. Dabbagh and Krarti [80] evaluate a prototype of dynamic insulation systems suitable for switchable building envelopes to minimize heating and cooling thermal loads while maintaining indoor thermal comfort, and the experimental testing showed a significant reduction of over 50% of the wall R-value. Dehwah and Krarti [111] demonstrated that the deployment of an integrated adaptive envelope system alone enabled homes in the United States to achieve near net-zero energy designs, particularly in mild and hot climates; the primary contribution was from movable photovoltaic-integrated shading devices, followed by attic and wall-integrated switchable insulation systems.

In terms of the adjustable ventilation envelope, common measures include natural ventilation control, such as variable-size windows [112,113], adjustable double-skin curtain walls, and ventilation walls [114]. In recent years, new materials have also been introduced in ventilation design to improve flexibility. Formentini and Lenci [115] innovatively applied shape memory alloys to a ventilated facade. The adjustable ventilation façade worked without any mechanical or electronic equipment or external energy supply, thus contributing to energy savings and increased reliability.

Although the concept of an adjustable building envelope is novel and has great application prospects, the existing research is currently concentrated in European and American countries. Most of the research is conceptual and is still at the stage of design, simulation and preliminary experimentation.

4.3.4 Building envelope materials

Recent years have seen the rapid development of new building envelope materials as the materials sector has evolved. These materials have improved the performance of buildings and have expanded their flexibility to cope with climate change.

Passive cooling techniques, such as nocturnal radiative cooling and phase-change material (PCM)-based free cooling of buildings, have also attracted the attention of researchers for their energy-saving potential [116]. Vukadinović et al. [117] analyzed the influence of PCM on detached residential buildings with a sunspace and a thermal storage wall. They found that the total energy requirement was reduced by approximately 2.4% with the appropriate use of PCM. For a detached residential building in a warm, humid climate, a reduction in the energy performance index of approximately 34% was made possible by applying a cool roof, and a reduction of approximately 32% was achieved with a green roof [118].

Radiative cooling provides a new path to address the challenges of the energy crisis and global warming. Researchers have demonstrated that, compared with ordinary roofs, radiant cooling roofs have higher solar reflectance and mid-infrared emissivity, which can not only reduce building cooling loads but also significantly alleviate urban heat island effects [119][120]. Fang et al. [121] proves that the cooling load reduction from utilizing the cool roof resulted in cooling electricity savings of 113.0–143.9 kWh/m^2/year compared with a shingle roof.

Research into transparent radiation-cooling materials has expanded the application of this technology in architectural windows. Metamaterial glass can be divided into two main types: using transparent radiative cooling film [122] and adding a transparent coating on the surface of the glass material [123][124]. Studies have shown that the indoor air temperature under metamaterial glass can be reduced by about 3.6°C compared to ordinary glass [125].

4.3.5 Building-integrated photovoltaics

Building-integrated photovoltaics (BIPVs) are multi-functional systems that generate electricity from photovoltaic panels while being part of the building material. BIPVs are economical and play an important role in building design. BIPVs also help to create an eco-friendly image for the building and its occupants.

The main energy-related features of BIPV modules and systems were reviewed by Martín-Chivelet et al. [126] and are grouped into thermal, solar, optical, and electrical aspects. Some researchers have attempted to integrate solar cells into window glass, which not only retains the function of traditional windows but also provides other benefits, such as power generation and thermal insulation (reviewed by[127]. Existing research results show that the total heat gain of BIPV windows in summer is lower than that of traditional windows; therefore, the electricity used by air conditioners is reduced. In addition to the electricity generated by BIPV windows, there is a huge potential to significantly reduce building energy consumption in hot climates. Wijeratne et al. explored a multi-objective optimization method [128] in which the seven best roof shingle and the 14 best skylight BIPV design solutions were compared by considering factors such as life cycle cost, payback period, et al. Karthick et al. [129] developed a BIPV-PCM module to improve the performance of BIPV systems by using a PCM to regulate the photovoltaic cell temperature. The experimental results revealed that the electrical efficiency of the BIPV-PCM was increased by 10% compared with the reference BIPV module, while its surface temperature was reduced by 8°C.

In principle, BIPVs also impart the property of productivity through the building envelope to generate more energy without affecting occupant demand. However, it should be noted that BIPVs themselves may also affect the characteristics of the building envelope, which in turn affect the power generation efficiency of the BIPVs. With the application and promotion of BIPVs, these issues have attracted increasing attention and research.

5 Pathways and potentials from building energy system level

5.1 Scope and aims

5.1.1 Scope

The building energy system plays a role in regulating indoor temperature and humidity, providing clean air, and other functions to meet the working and living needs of occupants. Matching building energy system controls to actual energy usage behavior is an effective way to reduce energy consumption without sacrificing occupant comfort and system functionality. Previous studies [61,130] have shown that significant improvements in energy efficiency can be achieved if building energy systems are controlled according to actual occupant use.

5.1.2 Aims

1) Time and space

Diversity of occupancy may lead to lower energy efficiency, as the load on unoccupied spaces may still be considered part of the actual demand of the building energy system [131]. Moreover, when the service object of a building energy system has multiple relatively independent demands, the start and end times of these demands are often not synchronized. Through the improvement of reasonable equipment systems and design schemes, matching the distribution characteristics in time and space is a major focus for achieving sufficiency in building energy systems.

2) Quality and quantity

Achieving sufficiency in the energy system is also crucial. Building energy system faces several independent demands with different qualities, which are often asynchronous. In an energy system, a reasonable distribution of quality and quantity should be carried out in terms of energy quantity and quality.

3) Control and adjustment

However, the energy consumption characteristics of different systems and service modes, and the energy costs to reduce dissatisfaction are very different. How to choose an appropriate energy system, based on the premise of meeting occupant needs without introducing excessive energy consumption and carbon emissions, is one of the important considerations.

4) Flexibility

In the process of system design and regulation, it is necessary to fully recognize the flexibility of occupant demand and to make reasonable use of this characteristic. This flexibility can be combined with the system design and system optimization operation to stimulate the best way of matching supply and demand, thus achieving a win-win situation of comfort improvement, energy saving, and emission reduction.

5.2 Importance

5.2.1 Building energy system operation in relation to occupancy

Based on the discussion in section 3.2, buildings are occupied only a fraction of the time [57].In a building energy system affected by demand diversity , it is often difficult to transfer the number of occupants in the space, heat generation, and other conditions of the building energy system. As a result, it is difficult to predict the service volume required in a given room (cooling capacity, heat supply, etc.), and it is also impossible to judge the moment when the end demand appears. Therefore, considering the sufficiency of occupancy in the room, the service scope of the building energy system can be greatly reduced in terms of regulation area and regulation time to meet the needs of occupants and contribute to energy conservation and emission reduction.

5.2.2 Building energy systems respond to diverse needs and quality

The supply side of the building energy system often reduces the dissatisfaction rate of indoor users by increasing the service volume, extending the service time, and improving the control capability of the terminal, resulting in oversupply at most terminals.

Existing studies have shown that high-efficiency technology cannot save energy if the building energy system does not match the demand characteristics. Therefore, to analyze whether a technology saves energy, it is necessary to comprehensively consider the local climate and resource conditions, building characteristics, and system characteristics as well as the demand characteristics and usage patterns of occupants. In this way, the benefits of high-efficiency, energy-saving technology can be fully exploited, and the green lifestyle and use mode of occupants can be maintained to achieve the energy-saving goals of buildings.

5.2.3 Opportunity brought by demand flexibility

Demand flexibility not only brings challenges to the regulation of building energy systems, but also offers new opportunities for energy savings and carbon reduction. First, energy consumption can be reduced by reducing the amount of service through demand-side management and behavioral energy savings. Second, based on the flexibility of the user-side demand characteristics, user-side-powered demand-side management is an important source of power system flexibility. Meanwhile, in the context of reducing carbon emissions, new energy based on wind power and photovoltaics will become the main source of new power supplies. To ensure the balance of power supply and demand on different time scales and the high-level consumption of new energy, we must improve the flexible adjustment capability of the new power system, which includes taking advantage of the flexibility of occupant needs and adopting appropriate demand-side management and response measures.

5.3 State-of-the-art

5.3.1 Decentralized system and individual adjustable terminals

To achieve sufficiency, an increasing number of building energy systems tend to adopt decentralized adjustment building service systems, and the service terminals can be adjusted freely according to the needs of the occupants. Under this control method, if the user's enthusiasm for adjustment can be fully mobilized, the supplied energy will completely match the user's actual demand and sufficiency can be achieved. Common decentralized adjustment mechanisms include charging methods (charging by area or consumption), peak and valley electricity prices, and reward and punishment systems.

Rehman et al. [132] compared centralized and semi-decentralized solar district heating systems in Finland, and showed the decentralized system can reduce the life cycle cost by up to 35%. Compared with decentralized systems, centralized systems have 12–40% higher losses. Weinand et al. [133] proposed that the performance optimization and equipment selection of a decentralized energy system should be based on the user's cooling and heating needs in space and time.

5.3.2 Refined partition design of HVAC systems

The refined operation management of classification, time sharing, zoning, and quality of building energy systems is an effective measure to match occupant needs and achieve BES. Riffat et al. [134] conducted experimental tests on displacement ventilation systems, and have shown lower vertical air temperature differences and higher ventilation efficiencies when they are used in combination with underfloor heating systems.

Zhang et al. [135] compared three ventilation modes, and showed that in offices stratum ventilation can save 20% and 40% of energy throughout the year without providing solar energy, compared to displacement and mixing ventilation, respectively. For classrooms and retail stores, stratum ventilation provides annual energy savings of approximately 25% and at least 37%, respectively, with solar energy compared to displacement and mixing ventilation.

Abdollahzadeh et al. [136] proposed that the optimal design of partitions is critical for improving solar performance. By increasing the partitions' reflectivity by 20% and the reduction of the partitions' height by 0.2 meters, the autonomous sunlight in the space was increased by 9.47% and 4.36% respectively, and the energy consumption of artificial lighting was reduced by 10.01% and 6.27% respectively.

5.3.3 Intelligent control systems

Distributed control is considered an effective means of improving the energy efficiency of building HVAC systems. Occupant-centric building control has attracted the attention of scholars worldwide, and the IEA Annex79 has conducted research specifically on this topic. Wang et al. [137] used a hierarchical structure with multiple layers to describe the tree structure of various HVAC systems. A hierarchical alternating direction multiplier method was proposed to solve the overall optimization problem in a layer-by-layer recursive manner. The results showed energy and computational time savings of approximately 5% and 70%, respectively, compared to the centralized control approach.

Wang et al. [138] proposed a novel decentralized sensor fault detection and self-correction method. This method matches the terminal characteristics with occupant diversity and meets the key points of sufficiency. Simulation results and hardware platform tests of an actual HVAC system illustrate the effectiveness of the proposed method. Similarly, inspired by the advantage of emerging decentralized systems, Feng et al. [139] implemented a fully decentralized architecture for intelligent buildings to improve the building operation performance. Based on a comparison with related state-of-the-art methods, experimental results highlight the superiority of the approach, which provides high accuracy, plug-in capability, and strong adaptability.

5.3.4 Demand-side response and energy flexibility

Demand-side flexibility is an important sustainable measure that allows demand to change over time and space to address supply and demand matching [140]. Demand-side response (DR) improves the flexibility of the demand side by encouraging power users to participate in the demand response market, changing their inherent habitual electricity consumption patterns, reducing or shifting the electricity load for a certain period of time, and responding to the power supply, thereby ensuring the stability of the power grid and restraining the short-term behavior of rising electricity prices [98].

There are two main types of DR programmes: price-based and incentive-based. Typical price-based programmes include time-of-use, real-time, and critical peak pricing [98]. Participants in such DR programmes benefit from savings on electricity bills. In incentive-based schemes, DR resources can often be directly controlled by the system operator for a specified period of time, sometimes without prior announcements [97]. In some programmes, DR participants can respond to requests to increase or decrease their power consumption for a specific period. In return for participating in these programs, owners of these DR resources receive payments based on the response time and response duration [107].

In the future, under a high proportion of renewable energy structures, building energy flexibility will also respond to the trend of synthetically applying four technologies: photovoltaic, energy storage, direct current, and flexibility in the building field. Electric appliances in buildings can be divided into three types according to their adjustment performance and methods: translation delay, variable power, and load cutting. Translation delay-type equipment includes hot water storage tanks, air-conditioning ice/water cold storage systems, refrigerators et al. Optimal planning within a given period can avoid operation during periods of power shortage and redirect electricity usage during periods of excess power as much as possible. Variable power-type equipment includes electrical equipment that can be adjusted by frequency conversion or other means, such as split air conditioners. These devices have their own control and regulation, which can change power consumption through frequency conversion or other methods. Load-cutting equipment can reduce power consumption by cutting off after the busbar voltage drops to a preset value. Thus, modifying the control strategy of the product and changing the DC interface can generate electrical equipment suitable for use in the energy system.

A good regulation strategy does not affect the function and use of the energy system itself, but has the ability to flexibly adjust the power consumption, thereby increasing system flexibility or reducing the demand for battery capacity under the same system flexibility. This is also an economic benefit that can be obtained through reasonable demand-side response-control strategies.

6 Policy implications for building energy sufficiency

After defining BES and reviewing the potentials of BES from building and energy system level, the purpose of this section is to highlight the priority of BES for different regions, in order to provide more specific suggestions to policy makers.

Suitable interventions to individuals and integrated BES policy frameworks are essential to finally achieve energy and climate targets. The integration of BES measures into existing building energy policy clusters is urgently needed. Therefore, in this section, we have divided regions into three types, which is building energy insufficient zone, building energy sufficient zone, and building energy excessive zone. Towards unique barriers of these three zones, distinguished targets and measures were discussed, which is explained in section 6.1. Then in section 6.2, how to integrate specific measures into current energy and climate targets and instrument were discussed. The challenges and opportunities were given in section 6.3 for future perspective of BES implementation.

6.1 Policy priorities and pathway design

Considering the nonlinear relationship between building energy services and their energy and emissions (Figure 7), a suitable BES policy should focus on the development status of the nation/region/population.

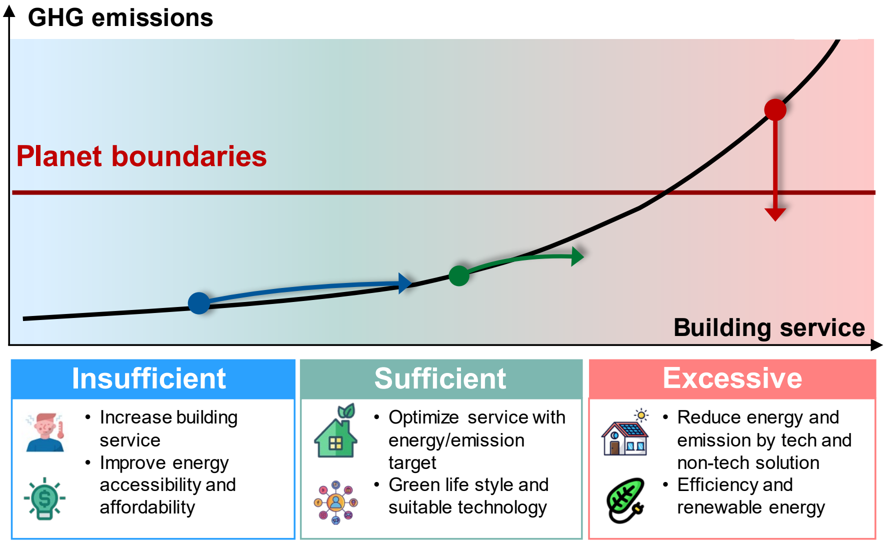


Figure 7. Suitable selection of building energy sufficiency pathways.

6.1.1 Building energy insufficiency

For regions or population groups located in insufficient zones, the priority should be building service improvement, as indicated by the blue arrow in Figure 7. In this zone, inadequate levels of building services create discomfort and even health problems for the occupants. Lack of energy access and affordability for lower-income groups or regions can trigger serious social problems. Even in developed countries, it is possible to reach inadequate status during during extreme weather conditions or during an energy crisis. In this situation, the BES policy should be designed: (1) identify the most serious deficiencies in building services; (2) consider passive, low-cost, and non-technological measures to provide natural-based solutions with very little energy and emissions; (3) artificial systems should only be used when absolutely necessary, in which case energy efficiency measures and renewable utilizations are recommended. This concept has been thoroughly implemented in the India Cooling Action Plan (ICAP) released in 2019, which prioritises the reduction of cooling demand through passive and low-cost measures[141].

6.1.2 Building energy sufficiency

For regions or populations that are in a sufficient zone, which is the ideal state, priorities should include both service level improvement and emissions reduction simultaneously, as indicated by the green arrow in Figure 7. With technological innovation and rising environmental awareness in society as a whole, there will be incremental potential for service improvement and energy/emission reduction. With total energy use and carbon emissions reaching the boundary, the primary targets include: (1) the explicit energy consumption and carbon emissions of society and each sector by top-level planning and in-depth research, (2) the regulation of building energy use and emissions by both improving building energy efficiency and building energy conservation, and (3) the improvement of building indoor services, social equity, energy security, and resilience through technological innovation and the promotions of green lifestyles. To meet China's overall energy consumption and intensity control and dual carbon emission targets [142], China has adopted this concept, and shifted its traditional focus on prescriptive standard to the holistic control of energy use through the Standard for Energy Consumption of Buildings [143].

6.1.3 Building energy excess

For regions or populations where service levels are already well above the threshold, energy efficiency measures are urgently needed to reduce final energy consumption and emissions,, as indicated by the red arrow in Figure 7. Green lifestyles and voluntary energy saving behavior should be encouraged from a societal perspective to further reduce building service-related environmental impacts. Reduction in per capita primary energy consumption could be achieved in high energy-consuming countries with little or no loss of health, happiness, or other outcomes, with the great benefit of reducing energy demand and increasing equity[144]. Given the strong lock-in effect on both the building systems and occupant lifestyles, economic incentives to leverage retrofitting, awareness-raising campaigns, and public education to nudge voluntary lifestyle transformation are the most important sufficiency measures to be taken not only in the building sector but also in all aspects of life. The European government has taken these actions. I 2022, European countries encouraged a 15% reduction in heating demand by reducing indoor temperatures and adopting local heating devices(such as heated blankets and portable heaters) to address the energy crisis caused by the reduction in natural gas supply from Russia [145].

6.2 Combining building into energy policy packages

6.2.1 Building energy modelling and scenario analyses

First, BES measures should be paid attention to by energy modellers, and should be integrated into future scenario analyses, which is not always the case currently [146]. BES measures should be considered in national or regional building energy and emission modelling, scenario design, and pathway selection. Most importantly, the quantitative potential of lifestyle and behavioral changes should be highlighted more prominently in these scenarios. Owing to the strong coupling of occupant behavior and technology choices, BES and changes in lifestyle should be embedded, discussed, and integrated with unique technology decisions adapted to demand characteristics[147]. A few scenario analyses considering these BES measures have illustrated huge energy and emission gaps between sufficient and insufficient pathways, as well as obvious capacity reduction of energy system and cost. Compared with excessive scenario which adopted centralized heating and cooling system, sufficient scenarios by implementing "part time part space" behaviour could save 66% heating energy demand[148], and 45% cooling energy demand[149] in China. Analysis in Germany indicated a significant impact (9.4% to 20.5%) of demand reduction on renewable capacities and system cost by behaviour-based demand reduction including heating sufficient measures[34]. Similar conclusion were found by low energy demand scenario analysis in Ireland[35]. The systematic impacts on land use, building waste, energy consumption in industry sector were identified by introducing sufficiency in net-zero scenarios of France[33].

6.2.2 Sufficiency measures from all societies

Empirical evidence has revealed that the rebound effect of energy efficiency is typically 30% [3,150,151]. Although energy sufficiency is introduced as a measure to offset the rebound effect of energy efficiency, there are limited studies that have shown modest (<10%) indirect rebound effects from sufficiency actions[152], include (1) indirect rebound effects (cost-saving from BES actions may be re-spent on other services or goods, which require more energy to provide), (2) spill-over effects ("moral-licences" gained from BES were moved to other services or goods, which are even more energy intensive), and (3) time-use rebound effects (time saved was used on other activities that require energy to participate). Therefore, BES requires raising awareness and changing the actions of society as a whole, and incorporation as key elements in general energy and climate policy packages. To meet sufficient emissions reductions requires culture of sufficiency and efficiency, rather than excess and waste, as well as integrate efforts from all human activities[153]. This is already happen in some government policy documents, such as the Energy Plan 2020-2030 of the State of Genève [154], French Law for Energy Transition [155], and suggested in several other policy documents.

6.2.3 Building energy sufficiency policy instruments

It is already widely recognised by researches that energy sufficiency is an option which must be considered through enhanced policy tools such as standard and regulation[30,36]. However, there are very few building sufficiency policy instruments can be found around the world [12]. Zell-Ziegler et al. [12] systematically reviewed 230 sufficiency-related strategies in the National Energy and Climate Plans and long-term strategies of European countries, found most sufficiency policies were set in the transport sector[12]. Reasons for the absence of BES may include low acceptance of sufficiency approaches or a lack of suitable policy instruments. Therefore, toward different policy priorities discussed in section 6.1, BES policy instruments are recommended in Table 2, for three types of regions or populations, with the framework of regulations, information, and incentive tools similar to previous reviews [38].

Information tools, such as public awareness-raising campaigns, capacity building, and labelling and disclosure, are the most powerful policy tools. Insufficient zones should pay more attention to passive strategies, nature-based solutions, and public health. Maintaining traditional lifestyles and energy-saving behavior is most important for sufficient zones, while public propaganda for voluntary energy saving and environmental protection is encouraged in excessive zones.

Economic incentives or pricing schemes that push all market participants have proven to be effective globally and include energy and carbon taxes, personal/building-level carbon allowances, and feed-in tariffs [156]. Subsidies for infrastructure construction and high-cost technology implementation are effective measures to be implemented in insufficient regions but may not lead to BES in other zones. Pricing or taxes for energy and carbon emissions, subsidies for retrofitting, and poverty groups should be considered by policy designers in sufficient and excessive zones.

Table 2. **Building energy sufficiency policy suggestions for different regions/groups.**

	Urgent priority	Policy Goals	Policy instruments		
			Regulatory	**Information**	**Incentives**
Insufficient zones	Increase building service to prevent social issues	**Primary:** building service access and levels **Secondary:** building energy and emissions	• Standard for indoor comfortable requirement • Prescriptive building design code to meet efficiency requirement while providing service	• Education for all on improving building comfortable level and public heath with minimal energy cost • Minimum energy performance standard (MEPS) and related labelling instruments	• Subsidies for building infrastructure construction and promotion • Incentives for technology adoption, such as of high efficiency products and systems • Incentives for low-energy-cost, natural-based solution promotion
Sufficient zones	Optimize building service without increasing building energy use and emissions	**Primary:** building energy and emissions, **Secondary:** building service levels	• Prescriptive building design code to meet efficiency requirement while providing service • Outcome oriented standard to control building energy use and emissions	• Raising awareness to maintain traditional culture and green lifestyles • Minimum energy performance standard (MEPS) and related labelling instruments • Labelling for top-runner products of high energy efficiency, or building with good energy performance • Disclosure for high energy/emission buildings	• Tiered energy pricing scheme to discourage energy intensive consuming • Energy/carbon taxes • Subsidies for building retrofitting • Targeted poverty alleviation
Excessive zones	Reduce building energy and emissions with technology and non-technology measures	**Primary:** building energy and emissions, **Secondary:** building service levels	• Outcome-oriented standard to control building energy use and emissions • Prescriptive building design code to meet efficiency requirement while providing service	• Raising awareness and public propaganda on energy conservation and environmental protection • Labelling for top-runner products of high energy efficiency, or building with good energy performance	• Tiered energy pricing scheme to discourage energy intensive consuming • Energy/carbon taxes • Subsidies for building retrofitting • Targeted poverty alleviation

6.3 Challenges and opportunities

Building energy policy tools are typically integrated and coupled. A set of integrated policy packages is required to decarbonize the building sector. Developed countries with higher building energy intensity and carbon emission intensity face great challenges owing to the lack of building sufficiency measures. BES practices can be found principally in European countries; for example, France improved building energy codes by involving bioclimatic design requirements and extending the lifetime of appliances, and Germany intends to reduce floor area per capita by home sharing [157]. Fortunately, the multiple benefits of BES, as well as climate mitigation pressure, have accelerated the design and implementation of BES policy clusters. BES is also promoted as effective measures to cope with the health threats posed by extreme weather events and to alleviate the energy crisis and energy security issues. In 2022, facing the worst heat wave and drought in six decades, cooling demand reduction measures were adopted to overcome the accompanying severe electrical shortage [158]. Similarly, building energy heating sufficiency measures have been promoted in European countries. Given the majority of building construction takes place in developing countries, BES policies are also important for developing countries because they synchronously provide solutions for inequality, poverty, and justice transition.

Challenges remain from a policy and technical perspective. Research gaps still exist in the BES with regards to quantitative descriptions, targets and thresholds, drivers and influencers, potential assesment, and effective interventions. Nevertheless, digitalization, the circular economy, and the sharing economy have opened up huge opportunities for BES. Advances in 5G internet and personal mobile terminals enable behavioural change for individuals and operators, and smart control of building and energy systems allows for easy and remote adjustments. The circular economy and sharing economy have great potential to stimulate a sustainable economy and social development, as well as BES level optimization [159].

7 Conclusions

Energy sufficiency is one of the most important policies for addressing climate change mitigation and global carbon emission targets. A number of studies discussed the concept of sufficiency from broader level, as well as modelling research estimated emission reduction potential of some sufficiency measures in building sector, mainly building floor area per capita and few on indoor temperate. However, there are still lack of systematic framework to reveal the paradigm and influencing factors of BES. This hinders a comprehensive overview on the potential and measures of existing BES, and development of future pathways. To address these research gaps, the concept and paradigm of BES has been proposed from the perspective of occupant demand and planet limitation. Then, this study reviewed BES measures and policies to reduce building operational energy and related carbon emissions.

This systematic review work has revealed the following characteristics of occupant demand in buildings: partial occupancy in time and space, diversified and heterogeneous requirements on quality and quantity, and necessary control and adjustment with flexibility. Towards these demand features, energy sufficiency measures have great potential to reduce energy use and carbon emissions. Flexible floor planning envelope systems, passive strategies for architecture design and building material adoption, and BIPVs are available technical solutions that can be applied to architecture. Decentralized building energy systems, refined partition designs, occupant-centric designs and operations, as well as flexible and individual adjustment terminals, are the most useful BES measures to better satisfy occupant demand while lowering energy use and carbon emissions.

Despite the great potential of BES in developed and developing countries, there is still a lack of consideration in policy planning and implementation of effective policy instruments. Incorporating BES into scenario analysis and policy framing of nnational energy and climate plans and long-term strategies is strongly recommended. During this process, possible negative effects of BES, such as rebound or spill-over effects, should be considered and avoided by economy-wide and cross-sectoral actions. Distinguished policy priorities and predominant instruments are recommended for insufficient, sufficient, and excessive zones according to their own situation of building services and emission levels and unique barriers for justice transitions. Given the multiple benefits of BES, such as its ability to reduce energy and emissions, adapt to severe climate conditions, and achieve sustainable development and justice transition, it is strongly recommended that BES should be included in future energy policy packages.

More research and development on BES is still needed, but opportunities lie ahead. In particular, with the trend of digitalization, the circular economy, and the sharing economy, there are unprecedented opportunities for data collection, properly intervention of occupant demand, and intelligent control of the buildings and energy systems. Quantitative simulation and modelling of different BES measures, and appropriate BES interventions to accelerate BES evaluation and implementation, would be the most urgent needs for next step research.

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