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ABSTRACT

Demand side energy flexibility is increasingly being viewed as an essential enabler for the swift transition to a low-carbon energy system that displaces conventional fossil fuels with renewable energy sources while maintaining, if not improving, the operation of the energy system. Building energy flexibility may address several challenges facing energy systems and electricity consumers as society transitions to a low-carbon energy system characterized by distributed and intermittent energy resources. For example, by changing the timing and amount of building energy consumption through advanced building technologies, electricity demand and supply balance can be improved to enable greater integration of variable renewable energy. Although the benefits of utilizing energy flexibility from the built environment are generally recognized, solutions that reflect diversity in building stocks, customer behavior, and market rules and regulations need to be developed for successful implementation. In this paper, we pose and answer ten questions covering technological, social, commercial, and regulatory aspects to enable the utilization of energy flexibility of buildings in practice. In particular, we provide a critical overview of techniques and methods for quantifying and harnessing energy flexibility. We discuss the concepts of resilience and multi-carrier energy systems and their relation to energy flexibility. We argue the importance of balancing stakeholder engagement and technology deployment. Finally, we highlight the crucial roles of standardization, regulation, and policy in advancing the deployment of energy flexible buildings.

1. Introduction

Historically, the operation of the electric power and energy system has relied on large centralized power plants, where centralized decision and control systems are deployed to commit and dispatch conventional and typically fossil-fuel, generation resources. However, in order to increase the integration of renewable energy sources (RES) and achieve low-carbon energy systems, the intelligence for keeping the balance between energy supply and demand must include the demand side (e.g., in buildings). This is because future low-carbon energy systems based on wind and solar are weather-driven and largely inflexible (i.e., the power production is dependent on weather conditions). The management of a

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weather-driven energy system, therefore, is decentralized and implemented across both the supply- and demand-side, including a plethora of residential and commercial building stocks.

To ensure a continuous balance with the instantaneous and increasingly variable energy production, energy flexibility in buildings is an attractive but underemployed resource to modify energy demand. Energy flexibility is defined by the International Energy Agency (IEA) as "the ability for a building to manage its demand and generation according to local climate conditions, user needs, and grid requirements" [1] and is characterized by changing the magnitude and timing of building energy use in response to system costs, emissions, and/or operational requirements. From the work in IEA-EBC Annex 67 and 82 [1], it became clear that energy flexibility of buildings must be harnessed across a cluster of buildings or at a district scale to provide an aggregated amount that is sufficiently impactful for the operation energy grids. This paper, therefore, does not focus on single buildings, but discusses all questions on a building cluster level.

Compared with the more established term demand side management (DSM), energy flexibility is a building-centric term describing the capability of buildings to respond to the needs of energy grids, including power grids and other types of networks (e.g., district heating [2,3]) and is inclusive of DSM. Energy flexibility is an emerging field of research based on knowledge and analysis of building physics and energy systems to study capabilities with real-world fidelity, including building thermal dynamics, service systems and appliances, occupant influences, and weather impacts, with different temporal considerations for different types of grid services. Energy flexibility (also called demand flexibility in some publications) is often considered within a broader DSM context, where DSM strategies can be broadly categorized as energy efficiency, demand response (DR), and energy flexibility measures [4,5]. Energy efficiency measures are characterized by reductions in energy consumption with respect to a reference system or baseline. These can be achieved either through improved building envelope or energy conversion systems, enhanced control algorithms, or building system optimization measures [4]. DR that curtails building electrical demand during times of grid stress can be viewed as a specific strategy for harnessing energy flexibility in buildings (or other end-use categories) without the need for significant capital investment, which can offer flexibility to the power grid [6]. Energy flexibility, in turn, is characterized by the shifting of energy demand profiles to satisfy grid and local objectives, including energy availability, cost management, and carbon reduction, and is typically executed in a planned and optimized manner [7]. Within the building energy sector, energy flexibility measures can include the incorporation of on-site renewable energy options, such as solar electric or solar thermal systems, to offset central energy supply systems. Other measures include the re-scheduling of heating, ventilation, and air conditioning (HVAC) systems [8,9], utilization of active energy storage systems [10], exploiting passive building thermal mass [11,12], harnessing appliances, or shifting occupant demand by influencing associated behavior [6]. Lastly, modern HVAC systems that operate along a continuous capacity scale such as variable refrigerant flow, variable air flow, and variable-speed vapor compression systems offer part-load performance characteristics that can be favorably exploited to offer energy flexibility [13].

Despite the potential benefits of energy flexibility to energy systems and energy providers, a number of technological and policy developments are needed for widespread deployment. For example, new methods and approaches for quantifying and harnessing energy flexibility, and increasing end-user acceptance and engagement; business models that enable sharing the benefits among stakeholders; and policies and regulations that encourage new business development and reduce investment and operational costs of demand side management. The aim of this paper is to discuss some of the challenges for enabling energy flexibility services that individual buildings and clusters of buildings can deliver to different types of energy networks, including technological approaches, stakeholder involvement, business models, and regulations and policies.

2. Ten questions

2.1. Q1. How can building energy flexibility contribute to a low-carbon future energy system?

Energy flexibility has the potential to be a cost-effective solution which enhances and strengthens the operation of the energy system, while integrating a larger share of renewables. From this perspective, the existing thermal energy infrastructure within buildings and associated energy supply networks represent a considerable asset for flexibility [16,17]. Recent advancements in smart sensing and metering, smart appliances, electric vehicles, and energy storage technologies facilitate energy flexibility in buildings and can help energy supply systems improve operational management by optimizing flexible loads [18]. At the single building level, the increasing use of smart sensing and metering, smart appliances, electric vehicles, and energy storage technologies, all enhance the energy flexibility offered by buildings and can help energy systems improve operations [4,17]. At a building cluster level, inter-building cooperative energy flexibility measures have the potential to provide greater degrees of energy flexibility within a single localized operational framework [19–21].

The deployment of energy flexibility can yield significant economic and environmental gains. The European Commission developed the Smart Readiness Indicator (SRI) to promote smart buildings with the capability of providing energy flexibility and estimated that mandatory implementation of the SRI by linking it to the energy performance certificate (EPC) could reduce final energy consumption up to 198 TWh by 2050 and avoid 32 million tonnes of GHG emissions per year [22]. Similarly, Satchwell et al. found \$100-\$200 billion in US power system cost savings and a 6% reduction in US power sector emissions from efficient and flexible residential and commercial buildings by 2030 [23].

As peak-load generators are commonly fossil-fuel units, environmental gains appear with peak-load shedding that positively impacts GHG emissions cuts. Although a systematic quantitative analysis on building stocks still needs to be conducted, a few relevant studies can provide some insights into this benefit. Stentoft et al. [25] found that flexible management of a wastewater aeration system using a control strategy based on electricity production GHG emissions data resulted in 14–43% lower emissions than the other control strategies. Larger inter-diurnal differences in GHG-emissions generally led to larger savings. This suggests that the current potential might increase in a future energy context with more fluctuating energy sources [25]. A study of meat factories in Spain suggested up to 3% and 5% of CO2 emission reductions by participating in balancing markets and secondary regulation, respectively [26]. In addition, energy flexibility can provide additional solutions to counterbalance the shortfall in generation due to the expected phase-out of fossil fuel or nuclear power plants [27].

Customers are also expected to benefit from energy flexibility. For example, the TABEDE project modeled a district consisting of 66 residential buildings with seven archetypes including apartment buildings and terraced houses in Cardiff, UK, and estimated up to 30% in energy cost savings and up to a 25% increase in the penetration of distributed RES [24]. A study of a community with 498 all-electric homes showed that with the increase in energy flexibility by using home energy management systems (HEMS) and batteries, homeowners can reduce their electricity cost by \$590/year [4]. The full benefits to individual households are difficult to quantify, however, as there are also qualitative factors such as the empowerment of controlling one's own energy use and the awareness of contributing to a greener society. Still, with recent and substantial increases in energy prices worldwide, the economic benefits to some individual households may become a decisive factor to participate in energy flexibility programs.

Despite the fast advancement of technologies to deploy energy flexibility (e.g., see details in Q2-Q5), social, economic, and policy developments are necessary to remove barriers and constraints (e.g., see details in Q6-Q10) to increase the impacts and role for energy flexibility in a low-carbon future. Furthermore, residential user engagement is typically a complex process involving several issues that are generally specific to each end-user. These issues include financial motivation, familiarity and trust, perceived risk and control, complexity and effort, interaction with routines and programs, and user characteristics [28].

2.2. Q2. How can energy flexibility be quantified?

Existing literature shows that most quantification methodologies focus on the building sector [18]. This observation may reflect the relatively high contribution of the sector to energy consumption (e.g., the building sector accounts for 40% of total primary energy consumption in the U.S. and E.U [29]) and the opportunities arising from the possibility of controlling the operation of specific systems without decreasing the quality of the provided services and within acceptable user comfort levels. Li et al., in a wide-ranging review, concluded that resources and technologies providing energy flexibility could be organized according to four main categories, namely: i) thermostatically controlled loads; ii) electrical or thermal energy storage devices; iii) electrical appliances; and iv) multi-energy consumption devices [18], which, unlike the previous categories, do not provide energy flexibility by modification of their demand profile, but instead switch between energy carriers during flexibility events.

Despite the types of exploitable resources and technologies, energy flexibility is often quantified according to two distinct approaches. In the first, existing flexibility can be quantified by key performance indicators (KPIs) describing its impact on different performance metrics, such as peak to average ratio [30] or electricity costs [31]. Simulation or measurement campaigns used to obtain the baseline scenario, which are needed to compute the referred KPIs, must therefore respect the same constraints (e.g., users' comfort needs) considered during the utilization of the available energy flexibility. In the second approach, energy flexibility is directly quantified by metrics related to the modifications imposed to the demand profile, such as the power demand increase or decrease that can be sustained over a specific period of time [32] or a combination of several metrics as described by the Flexibility Function developed in IEA-EBC Annex 67 [15]. The Flexibility Function quantifies the response of the controlled system to a specific incentive variation (e.g., electricity price) and is suited for data-driven applications where only the incentive signals and the energy consumption profiles are available (e.g., as shown in Ref. [33]). Additionally [15], proposed a Flexibility Index, which assesses the benefits of using energy flexibility given a specific incentive signal that could come from the grid to motivate a response. This index belongs to the first type of approaches and provides a single number that can be used to guide how to optimally design the buildings for a particular area and climatic zone.

The Energy Performance of Buildings Directive (EPBD) [34] requires the development of a rating system for the smart readiness of buildings, termed the Smart Readiness Indicator (SRI) [22]. The SRI allows the rating of the smart readiness of buildings to be quantified, and leads, for example, to a rating of the capability of a building to adapt its operation in response to signals from the grid, which can be used as an additional possibility to characterize existing energy flexibility. However, energy flexibility is a dynamic phenomenon and therefore the SRI will only provide an indication of the approximate potential to react to the referred signals. Additionally, the SRI is only applicable to buildings while other methodologies, such as the Flexibility Function [15], can be used for all flexible assets including water towers [32], and wastewater treatment plants [25].

Since energy flexibility is not an invariant intrinsic parameter of buildings (e.g., energy flexibility varies at different times limited by the available controllable devices at the time) and its use depends on specific objectives to be achieved, quantification methodologies should allow real-time updates according to any performance metric of interest, including different user comfort needs. Therefore, when applying an energy flexibility quantification methodology to a specific case study, one must take into consideration the respective needs and limitations and, if possible, test several candidates (e.g., Reynders et al. assessed several methodologies using a common case study [35]).

This underscores the need for a generic energy flexibility characterization methodology, which should be simple to apply and useable by different stakeholders, where adequate interoperability among different decision-making levels is instrumental for the effective use of the characterized energy flexibility. Potential user comfort impacts and other aspects related with the quality of the service provided by the flexible systems should also be taken into consideration. A possible solution is to use a hierarchy of controllers that we discuss in more detail in Q3. Additionally, given that metering and sensor technologies that allow real-time data collection are becoming increasingly available, it is evident that larger efforts should be allocated to the development of data-driven characterization methodologies. In this context, IEA-EBC Annex 82 will continue the development of the data-driven Flexibility Function developed in IEA-EBC Annex 67 with the main objective of extending its application to an aggregated level, while facilitating its application by different stakeholders.

2.3. Q3. How can energy flexibility be harnessed?

Unlocking energy flexibility consists of connecting flexibility providers (e.g., a cluster of buildings) to a utility operator or an aggregator in need of flexibility with the objective of altering energy demand. Multiple control architectures and DR programs have been studied, with advantages and disadvantages in terms of reliability, scalability and implementation cost. Control architectures are classified either as centralized, decentralized or distributed systems (see Fig. 1) depending on decision-making roles (e.g., utility, aggregator or end-users) and whether end-users share information with other stakeholders [36].

In centralized architectures, a single entity communicates and directly controls the flexible devices (see Fig. 1-a). The main advantage of centralized approach is a control close to optimal as the entire system is under the supervision of a single entity [37,38]. However, there are some scalability and computational issues especially when controlling a large number of assets [36].

In decentralized architectures, end-users share only selected information (e.g., power consumption profile) and the management strategy is decided locally. The simplest form of decentralized architecture consists of broadcasting either a price signal to end-users [35,39] or by issuing an optimal load shaping signal that buildings actively track as closely as possible by locally shaping device control strategies [19–21] (see Fig. 1-b). In price-based DR-programs, customers are encouraged to participate in a time-varying pricing scheme and their reward depends on the flexibility offered [40–42]. This type of architecture is suitable for scaling to building clusters, but may not lead to optimal control over the entire asset [43].

To improve cooperation or enhance competition, two types of distributed approaches exist: hierarchical and non-hierarchical (see Fig. 1-c and 1-d). The global control strategy is divided into various subtasks in the hierarchical architecture, whereas a direct communication between end-users enhances interaction in the non-hierarchical architecture. An increased research trend for both types of architecture has been recently observed [36]. An example of hierarchical architecture is proposed by Ref. [44], with a combination of high-level markets with a hierarchy of controllers. To address coordination at scale in non-hierarchical architectures, various methods have been developed from classical optimization techniques to multi-agent systems [36,38]. Classical optimization methods include techniques such as stochastic optimization and mixed integer linear programming, but are limited at scale. Multi-agent systems include mathematical and heuristic methods that can be further divided into game-theory based and reinforcement-learning based [45,46]. In these different optimization

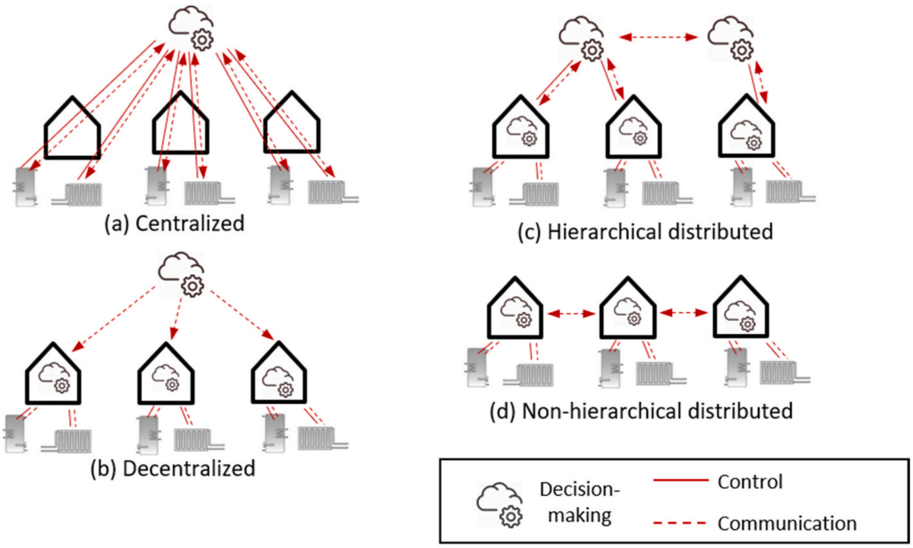

Fig. 1. Control architectures for cluster of buildings.

algorithms, the major challenge is the accurate evaluation of uncertainties from occupants and buildings [43].

At the building level, in case of decentralized or distributed architecture, a local controller is necessary to define a set-point temperature, a charging strategy or a time of activation. This controller might be located at the device level (e.g., smart appliances) or integrated in a building management system [47]. Three types of control strategies can be identified: manual control by end-users, automated rule-based control, or advanced optimization techniques (e.g., MPC) [48]. Automatic control can reduce user fatigue and improve participation in DR programs [49] and optimization allows building and equipment dynamics to be taken into account as well as addressing multiple objectives. It should be highlighted that end-users often prefer a degree of autonomy over their energy use (e.g., by opting out or overruling the controller) [50,51] and therefore, for the design of local control systems, a balance should be found between robustness, effectiveness and simplicity, as well as user preferences. Q7 offers more discussions on end-users.

In all of the aforementioned architectures, communication is the cornerstone of DR programs. It can be one-way or two-way communication, wired or wireless and exploit smart-meters, the internet or home area networks [47]. The adoption of protocols and standards is necessary to enhance the development of DR programs at large scale (e.g., NIST smart-grid standard [52], OpenADR [53], SG ready label from the German Heat Pump Association [54]).

Various challenges remain in the development of solutions for harnessing energy flexibility. Improved coordination is necessary to alleviate the peak rebound issue and improve the economic benefits of both utilities and end-users. The development of local production and storage systems will also reinforce the need for coordination and flexibility in distributed systems [43]. Moreover, there is a need to better integrate end-users in DR programs that balances adequate incentives, acceptable level of service and equity [134,135].

2.4. Q4. How do multicarrier energy systems contribute to energy flexibility?

Multicarrier energy systems combine different energy vectors, such as electricity, gas, oil, biomass, and heat to provide services (e.g., heating, cooling, ventilation, appliances) to end-users [55]. Any large-scale energy system (e.g., countrywide or energy market) can be seen as a multicarrier system, as electricity and fossil fuels (e.g., gas, oil) are typically present. The multicarrier energy systems that can contribute to energy flexibility are characterized by redundancy in providing selected energy services from different carriers (e.g., space heating from electricity or from biomass) (see Fig. 2). They are sometimes referred to as “Multi-energy” systems, or less frequently as “hybrid energy systems” [56]. Another typical multicarrier scenario is an electrically driven air-source heat pump heating system combined with a natural gas fired boiler, normally provided as insurance during very cold weather periods; the boiler can be preferentially engaged during electric grid stress events.

The redundancy between different carriers to provide a specific energy service renders multicarrier systems inherently flexible. Specifically, switching between fuels allows them to respond to the needs of the energy grids while maintaining the same level of service to the end-user. This flexibility potential can be leveraged at the district level, as discussed below, but also at the single building level. In the Canadian province of Quebec for example, a “dual energy” electricity rate encourages switching from electric heating to an alternative heating source (e.g., gas) when the outdoor temperature is below −12 °C [57]. This basic fuel-switching control strategy provides flexibility during typical winter peaks caused by electrical heating. D’Ettore et al. [58] analyzed the flexibility offered by hybrid heating systems combining an air-source heat pump with a gas boiler and highlighted the importance of using and correctly sizing a buffer tank to operate the heat pump more efficiently and benefit from energy flexible buildings [16,56]. Combined heat and power systems and power-to-heat conversion are the main tools to convert energy between different carriers, and to utilize thermal energy storage in order to increase flexibility [10,59].

At the community (or district) level, district energy systems are excellent candidates to provide flexibility for the electric grid and achieve a larger share of variable renewable energy in their energy supply [44,60]. Indeed, district energy systems can utilize the thermal storage in the network itself for short-term storage, and they are often equipped with thermal storage tanks providing flexibility for several hours [61]. Many district heating systems also include long-term (seasonal) thermal storage when they are designed to integrate RES such as solar thermal [62]. District energy systems themselves can benefit from the decentralized storage present in connected buildings to leverage flexibility in the heating supply [3]. This “heat” flexibility can then be harnessed to optimize the operation of the district energy system and/or to provide “electric” flexibility with power-to-heat conversion systems such as heat pumps.

Historically, multicarrier systems have been modeled and analyzed with the objective of reducing primary energy use, emissions, and cost [63]. Recent research addresses designing and operating multicarrier

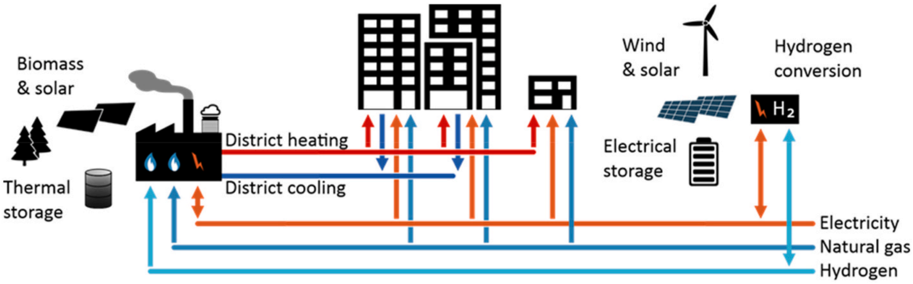

Fig. 2. Multicarrier energy systems can provide the same energy services from different energy vectors (e.g., heating from electricity, district heating, and natural gas). Energy flexibility can be harnessed from buildings themselves (e.g., via thermal mass, decentralized storage) and from centralized systems to maximize renewable energy integration and minimize greenhouse gas emissions.

energy systems for maximum flexibility to enable a higher integration level of variable RES at the neighborhood or urban level [64], in isolated systems [65], and at the country level [66]. Flexibility can also help integrate waste heat recovery and promote heat-sharing within a multicarrier system [67]. Achieving cost-efficient multicarrier energy systems requires coupling the different sectors not only at the energy level, but also at the market level, which can be realized efficiently in a centralized market or with a decentralized market per energy carrier [68,69]. Multidisciplinary research programs are required to address their technical complexity (design and control), economic challenges (market integration), and societal challenges (policies, regulations, and social equity), as discussed further in Q7-9.

2.5. Q5. Can energy flexible buildings contribute to energy system resilience?

Resilience is defined as the ability to be prepared, absorb, adapt and quickly recover from an adverse event [70]. An emergency or an adverse event is understood as a temporary event that poses additional stress to the urban energy systems. High stress can be observed directly in buildings during extreme climate events (e.g., heat waves [71], cold snaps or storms [72]). Adverse events may also affect grids with increased magnitude and duration of the peak loads, reduction of renewable energy generation and degradation or "interruption" of conventional energy supply systems. Increased stress can lead to a system failure (i.e., a "shock" or "short-run shock" event), a blackout or power outage, that may have important effects on day-to-day living and in the longer term the economy [73]. In this context, survivability is adopted as an indicator that expresses the probability that a building can be continuously powered from locally produced and stored energy during a grid failure. Broadly speaking, emergency situations that may drastically affect access to energy and well-being in our societies, especially to vulnerable populations, are the climate or health crisis [74], which have different spatial or temporal scales than local short and extreme shocks.

In future low-carbon energy systems, energy flexible buildings, ranging from individual buildings to clusters of buildings, need to adapt their operation to a range of environmental variations including the needs of the grid. Flexible buildings are naturally more resilient by providing habitable indoor conditions for longer periods of time under adverse or emergency events [75]. The enhancement of flexibility based on management of passive and active thermal storage, on-site renewable generation and demand controllable facilities increases the resilience of the systems.

Resilience, especially when assessed in terms of survivability, is typically associated with the building's ability to change the electricity use during a demand-response or adverse weather event. If a building can maintain occupant comfort, known as passive survivability [76], during a power outage, it will obviously be capable of lowering its electricity use during the same period. Local energy storage, whether thermal or electrical, is the key factor enabling both flexibility and resilience. There is a close and often inverse relationship between resilience and flexibility, since control strategies aiming to increase resilience (i.e., reserving battery capacity for backup) can decrease the flexibility the building can provide. For example, the control strategy adopted for a photovoltaic system with battery storage will have an impact on the upward flexibility (ability to use more electricity) and on the downward flexibility (ability to use less electricity or no electricity at all), the latter being closely related to survivability and resilience [77, 78]. Weather-related power outages can often be predicted [79], so control strategies could be adapted from "maximum flexibility" to "maximum resilience" in some cases.

Increasing building resilience without limiting energy flexibility may be accomplished beyond individual buildings supplied by only one energy carrier to multi-carrier energy systems or groups of buildings at community scale. In the case of multicarrier energy systems, the energy flexibility comes from redundancy between energy vectors to provide the same energy service (e.g., electric heating and gas-fired heating). In these systems, energy flexibility and resilience go hand-in-hand if the considered outage only affects one of the energy vectors. These systems are necessarily associated with higher capital costs to provide the redundancy, but their economic viability could be improved if the economic value of resilience was considered in the analysis [80].

Moving from the single building scale to the building cluster scale, several studies show the benefits that control strategies aiming to increase demand flexibility and resilience under extreme events may achieve. Nik and Moazami [81] investigated how the implementation of collective intelligence, that controls groups of buildings in Stockholm, is effective to decrease energy demand up to 44% and absorb the shock during extreme weather events compared with the case without intelligence. Mar et al. investigated management strategies to maintain user's needs in an energy community with PV generation and houses with non-controllable and controllable devices while maintaining the community network operation during temporary reduction of available grid power [82].

2.6. Q6 Who are the stakeholders involved in energy flexibility?

Numerous stakeholders are involved in the nexus of energy flexibility and buildings. The stakeholders range from the large central energy utilities, grid operators and downstream through distribution system operators (DSOs) to individual consumers. With the transition to a smart energy system, including the development of new energy flexibility services, the emergence of new market actors such as distributed services aggregators, decentralized energy producers (e.g., prosumers), and services market operators is unfolding [83]. In addition, as the energy sector is highly regulated, policymakers, such as national governments, and supranational entities, such as the EU, also play a key role in defining the framework conditions for the development within the energy sector. For example, an EU regulation that requires unbundling of energy supply and generation from transmission networks, and third-party access [84]. Another trend is the decentralization of energy production, especially within the electricity sector, which drives a transition to a less hierarchical organized energy system and gives rise to a more diverse and complex set of stakeholders [85]. Other stakeholders include distributed services aggregators and energy service companies (ESCOs) that further complicate stakeholder interactions [86].

The complexity of stakeholders increases further if one considers end-users because energy consumers represent a diversity of conditions and motivations for participating in energy flexibility services. Consumers differ in terms of their size of consumption and how large their potential for supplying energy flexibility are, as well as in terms of ownership and organization. Consequently, the conditions differ highly between commercial, public and private households; within these types of consumers there is a wide variety of types (e.g., between office buildings and industries for the commercial consumers, or between apartment buildings and individual detached homes for residential consumers [87,88]).

An effective utilization of energy flexibility in buildings will require an alignment across stakeholders with regard to technical and commercial activities. This will require moving beyond the tendency of stakeholders to mainly pursue their own interests and existing business models to the active involvement of policymakers through regulation, as well as to enhanced collaboration between stakeholders on creating shared visions and understanding of the future energy flexible system [86]. The discussion of extracting values for different stakeholders from energy flexibility is continued in Q9.

2.7. Q7 What new approaches to the design of energy flexibility solutions can increase user engagement?

Two different, and partly competing, conceptualizations of the role of the energy consumer in the future flexible energy systems exist within the smart energy field [89,90]. One emphasizes the *active* participation of energy consumers, who are expected to adjust the timing of their consumption on a continuous basis (e.g., according to price signals from the grid). The other emphasizes that demand response should be executed through automated solutions and/or remote control by grid operators or others, and the energy consumer is seen as a *passive* participant, who is primarily involved when accepting the control program. Both conceptualizations have opportunities and limitations. First, the idea of active participation of energy users opens for a broader application of flexible energy use, as the range of consumption types available for automated or remote control is limited. Often, there is a close link between energy consumption and performance of practices (e.g., cooking), which makes active participation of consumers necessary. However, studies have also demonstrated that it is difficult to ensure consumers' long-term participation in demand response programs [91]. Second, automation or remote control may enable customer response to more granular locational and temporal pricing.

Evidence shows that voluntary active participation by energy consumers does happen in certain situations (e.g. for households with micro-generation such as rooftop solar PV). Such households are often named "prosumers", and studies show that micro-generation motivates many households to optimize their utilization of their own energy through time shifting, i.e., changing the time of their consumption [92–96]. Monetary savings play a role here, but also other elements are important, such as the positive feeling of consuming one's own energy, energy independence and concerns for the environment [94,95,97]. The latter supports the critique raised by Strengers [98] that existing approaches within smart energy tend to exaggerate the importance of economic motivation in their (often tacit) assumptions about energy consumers' behavior. Therefore, many smart grid designs are guided by a misleading understanding of the individual energy consumer as "an efficient and well-informed micro-resource manager who exercises control and choice over his consumption and energy options'' (ibid.: 34–35). In addition, there seems to be a "strong engineering bias with a focus on new information and communication technologies, disregarding their interaction with other technological and social aspects of local energy systems" [99]. This leads to technical designs that do not fit well with the needs and practices of the users (see also [100]). Instead, these authors argue for a broader understanding of the energy practices, which also takes into account how the behavior of energy users are dependent on material elements (such as the design of buildings), the users' competences and the meanings associated with energy-consuming practices and new habits of demand response (e.g. Refs. [90,98]). This is in particular important to consider for those solutions aimed at involving energy users as active participants in demand response actions.

Researchers have suggested involving users more actively by applying co-design methods in the designing of smart grids and energy flexibility solutions (e.g. Ref. [101]). Even if users are partly involved in the design phase of some smart grid developments, the more *systematic and comprehensive involvement* of them is still rare [99]. Therefore, methods from co-creation and participatory design methods are worth considering. The core idea of these design approaches is to involve the prospective users of a given technology much more extensively in the design phase than is typically done today [102]. For instance, this can happen through a series of co-creation workshops with participation of designers, technology developers *and* users. Often, such design events involve the use of tools like design probes etc. to facilitate the process. Through this, end-users are engaged as active "co-creators" of innovations [103]. The main goal of applying such methods is to integrate the perspective and needs of end-users in the final solutions and in this way ensure that these will fit with their daily habits and needs [104]. A limited number of studies apply co-creation and participatory design methods in the design of demand response solutions. Among the studies are experiments where researchers have involved citizens actively in changing their energy consumption patterns through changes in their everyday routines and practices. For example [136], developed a solution combining digital feedback and automatic heating control with simple "low-tech" material designs such as "heating bags", which included heat-retaining pouches affixed to the radiators. The latter complemented the automated control with the possibility for the participants to maintain thermal comfort during periods with heat setback. Another example is the use of a social practice theory-inspired living lab approach by Ref. [137] that changed practices of doing laundry and maintaining comfort through challenging people's established routines and norms. A third example is how participatory design methods were used to establish continuous communication between technical developers and the local community in a Chilean microgrid project and ensuring that the final technical solution was tailored to the local context and needs [138]. However, as these limited examples indicate, attempts to more specifically apply co-creation and participatory design methods in developing demand response solutions is an opportunity for further exploration.

2.8. Q8 How should energy performance standards and requirements be adapted to support building energy flexibility?

Energy performance goals have historically been based on targets for energy reductions and optimal design of systems. There is a need to modify existing goals or develop new ones to avoid penalizing energy flexibility that may not necessarily result in net reductions in energy consumption over certain timescales. Energy flexibility is also affected by the operation of energy systems and not only relative to simulated levels. Energy efficiency and energy flexibility are two targets that have to be viewed as complementary and deployed in an integrated strategy to address energy and climate challenges [5,7]. A recent study showed that the co-deployment of energy efficiency and flexibility measures in building yields large reductions in peak electricity demand [7]. Although efficiency may reduce the load available for shifting to low emission hours, it also reduces the need to use fossil fuel plants to supply peak demand. The two measures combined can help grid operators avoid or defer investments in new fossil-fueled plants and energy storage deployments to support the integration of variable renewable energy [7]. Accordingly, future buildings and districts have to be designed with a focus on both energy efficiency and flexibility [14,15]. Therefore, it is important to develop solutions and standards that focus on reduction of greenhouse gas emissions as a common target.

Most energy performance standards focus on the static energy needs in buildings in terms of an annual energy requirement. Even though many countries base their energy performance calculations on dynamic simulations, the end result is still an annual energy requirement (i.e., no time dependency of the energy use) [105]. Energy performance certification (EPC) of buildings is most often based on the calculated performance according to the standards. However, some countries base their EPC on measured energy, and in these cases, flexibility offered to the energy supply may influence the EPC in any direction.

There are limited examples of energy flexibility in building codes and standards. The ASHRAE 90.1 standard includes an "Energy Cost Budget" method to demonstrate compliance [106]. If cost accounts for a "penalty" similar to the flexibility penalty, that is an indirect way to include energy flexibility in the building's energy performance. Additionally, the EU Energy Performance of Buildings Directive (EPBD) defines an optional smart readiness indicator: "*The smart readiness rating shall be based on an assessment of the capabilities of a building or building unit to adapt its operation to the needs of the occupant and the grid and to improve its energy efficiency and overall performance*" [34s]. The intent of the smart readiness rating is to ensure that future buildings and buildings undergoing major renovation can provide some kind of flexibility to connected energy supply systems. There is, however, no indication of how this can and should work in conjunction with the building energy performance requirements.

Therefore, there is a need to ensure that requirements, energy performance standards and energy flexibility complement each other to achieve a low-carbon future [133]. Solutions may include strategies, controls, and technologies that can address competition with existing energy performance requirements and changes to energy performance assessments and/or codes and standards that incorporate energy flexibility. One such solution could be a shift towards CO2 emission requirements rather than energy performance requirements in the operational phase of a building's life. This goes hand in hand with emerging requirements for life cycle CO2 emissions (Life Cycle Analyses, LCA) from a building over its lifetime (i.e., the construction, operation, and demolishing phase of a building's life). The CO2 emissions during a building's operational phase will be influenced by its flexibility to energy in periods with low CO2 emissions from the connected grids. Flexible buildings should thus have an advantage from non-flexible ones in terms of CO2 emissions during the operational phase. Such emerging requirements are seen in several countries [131,132] and suggested in a recent proposed recast of the European EPBD, to be decided upon in late 2022. These initial CO2 requirements are based on static estimates of the CO2 emissions during the operational phase. Therefore, a shift towards rewarding and incentivizing flexibility is needed to push increased deployment in buildings.

Introduction of price signals, and controls that are able to react intelligently on the signals, will be valuable tools to achieve the goal offering flexibility from buildings to the energy supply. Additionally, carbon-neutral goals established for a portfolio of electric and non-electric resources can support energy flexibility in district heating systems or broader beneficial electrification [107]. Finally, the development and adoption of interoperability standards, especially at the semantic level, is necessary to reduce the costs of energy flexibility-enabling technologies and the complexity of managing energy performance and flexibility from multiple end-uses [108].

2.9. Q9 What business models can successfully develop and utilize energy flexibility?

Successfully engaging consumers to realize the benefits of building energy flexibility will require several different entities to form business models that manage specific financial and performance risks and profit from the financial opportunities. Entities that are likely to play an important role in delivering energy flexibility solutions to customers include electric utilities, district heating companies, ESCOs, and aggregators [109]. Electric utilities, particularly DSOs are often the primary interface for customer energy consumption and management and are increasingly offering energy flexibility products, as well as data and communications services that support energy flexibility [110]. District heating networks do in many respects have the same challenges as electric grids, but with a built-in storage capacity and with peak loads primarily dictated by weather, which can be foreseen. There are though large saving potentials in operating with the lowest possible flow temperature at any time [111,112]. In addition to electric utilities, ESCOs deliver and finance a range of building energy management solutions that increasingly include renewable generation and energy storage [113] and aggregators typically specialize in assembling a portfolio of energy flexibility resources from multiple customers and bid flexible load into electricity markets similar to traditional power plants [114].

The opportunities for businesses to profit from energy flexibility typically arise from addressing the complexities and risks of energy management, which produces customer financial and operational benefits (e.g., bill savings, improved productivity). For example, entities may provide software and advisory services to customers to design optimal energy flexibility systems and integrate complex technology and controls systems, as well as directly control building loads and bid into wholesale electricity markets. Additional financial opportunities for energy flexibility business models include managing changes in market rules and tariffs, minimizing penalties for under-performance, and enrollment and participation in incentive programs.

Energy flexibility business models are generally characterized by their value proposition, value creation and delivery, and value capture [115]. The value proposition is defined by the energy flexibility objective (e.g., customer bill savings, grid-connected resource for managing distribution network, increased customer resilience) and includes the scope and type of energy flexibility solutions that are offered (e.g., energy shifting and load shedding capabilities, integrated building and distributed generation/storage), as well as customer segments. Value creation and delivery is based on strategies for responding to grid and/or price signals (e.g., shifting load from peak price periods to low price periods) with important consideration of roles and responsibilities (e.g., customer interface, building controls management). Finally, the extent to which customers capture value depends on how successfully the business model employs energy flexibility strategies and the sharing of costs and benefits between customers and businesses based on revenue models, customer remuneration, cost structures, and asset ownership [116].

Energy flexibility business models rely heavily on customer building technologies and customer economics are driven by the high-upfront costs of building control technologies and efficient end-use appliances that typically result in long-term payback periods [117]. Business models that can scale across multiple buildings, energy flexibility technologies (e.g., integrated buildings and storage), and services may solve customer adoption challenges by reducing certain costs and maximizing, or more widely distributing, value. For example, multi-building approaches can achieve capital cost savings through bulk purchasing and streamlined installation, as well as increased revenues by enabling participation in multiple market products and opportunities (e.g., wholesale capacity markets, ancillary services markets) [118]. Aggregators may communicate grid signals from system operators to multiple buildings, thereby absorbing and managing the transaction costs and operational complexity that the system operator would otherwise incur when interacting with numerous individual buildings [119]. Relatedly, aggregators may offer customers energy market hedging services to minimize price risks and stabilize customer energy costs and bundle services across electricity and other energy markets [114]. Utilities may also successfully scale services to increase energy flexibility deployment especially when complementary to existing services (e.g., adding customer financial incentives for building load flexibility technologies and measures to existing energy efficiency programs) [120].

2.10. Q10 How can policy evolution support the future deployment of energy flexibility?

Policy support is necessary to increase energy flexibility deployment and realize its societal and economic benefits, and may include building technology performance standards, mandated targets and goals for flexible grid resources, and funding mechanisms for basic research and design or to increase customer adoption, among many others. Decision-makers, including policymakers and regulators, therefore, play a critical role in creating and sustaining energy flexibility opportunities.

A wide array of approaches is necessary given the breadth of institutional contexts and activities that govern energy systems [47]. At the supranational and national levels, policymakers may establish explicit goals and targets for energy flexibility deployment. As examples, the US Department of Energy aims to triple both the efficiency and flexibility of residential and commercial buildings by 2030 relative to 2020 levels [23]. Likewise, the European Union has a binding target for 2030 to have at least 40% renewable energy in the energy mix, which needs to be accompanied by increased flexibility to take up variations in production [121]. Additionally, energy flexibility has been identified as a key strategy to meet national net zero GHG emissions targets (e.g., UK goal to reach net zero emissions domestic economy-wide by 2050 relative to 1990 levels) [122].

Given the highly-regulated nature of electricity systems, especially at the state and municipal levels, there are several areas in which regulators can address barriers to energy flexibility deployment. For example, in the US, some states have building energy codes and appliance and equipment standards that incorporate flexibility [123] and are often more ambitious than minimum codes and standards established at the national level. Regulatory processes for electric utilities are also an important context, especially in the US that does not have overarching policy for or regulation of retail electricity markets. For example, state utility regulators can authorize time-varying retail electricity prices that increase the value of energy flexibility for customers [124]. Pricing reforms that reflect the costs of environmental externalities and/or carbon intensity of energy may facilitate energy flexibility programs for both economic and environmental improvement [125]. Other electric system regulatory processes that can address barriers to energy flexibility include incorporating energy flexibility into electricity system planning, time-sensitive economic valuation of energy flexibility, and authorization of advanced metering infrastructure that enables two-way communication between buildings and electricity system operators [123].

The most successful policy evolutions to date are regulatory and/or market designs that establish explicit opportunities for energy flexibility and incentivize aggregators, utilities, developers, and other entities to deliver energy flexibility. For example, the Texas wholesale electricity market has separate balancing services products that enable participation of building end-uses with asymmetrical capabilities for balancing up and down [126]. California state utility regulators created the Demand Response Auction Mechanism to create retail market opportunities for energy flexibility companies with a minimum 100 kW scale of aggregated resources, including flexible building technologies, behind-the-meter storage, and electric vehicles. The mechanism has been successful at attracting new companies and developing opportunities for aggregating residential customer energy flexibility resources, which is an emerging opportunity [127].

Finally, decision-makers can support energy flexibility deployment through regulatory and policy approaches that reduce the costs of controls, packaged solutions, and other emerging building technologies (e.g., thermal energy storage). There are complementary effects of supportive policies and technological improvements that can drive cost reductions via technology interoperability and economies of scale [128]. Additionally, investments in customer automation and control technologies can enhance the value of flexibility for distribution systems [129]. Novel financing mechanisms that overcome high upfront capital costs have attracted significant loan volume for energy efficiency [130] and could be leveraged to increase adoption of energy flexibility technologies.

3. Conclusions

Energy flexibility promises to be a cost-effective solution to enhance and strengthen the operation of the energy system by facilitating a greater penetration of renewable energy resources. To that end, a wide range of thermostatically controlled loads, electrical or thermal energy storage devices, electrical appliances, and multi-energy consumption devices are available to unlock energy flexibility in buildings. In terms of their ability to be prepared, absorb, adapt, and quickly recover from adverse events, flexible buildings offer higher levels of resilience, as they are designed to manage their systems and storage facilities to adapt to several objectives. The most promising opportunities for energy flexibility are in clusters of buildings and multicarrier energy systems. Based on the questions and answers discussed in this article, we identified the following research opportunities to enable widespread deployment of energy flexibility.

1. Extension of existing data-driven energy flexibility characterization methodologies to an aggregated level, considering the requirements from different stakeholders.
2. Supervisory controls that can respond to grid signals to avoid unintended consequences (e.g., peak rebounds, reduce occupancy comfort) at the building- and grid-levels.
3. More sophisticated building modeling and control algorithms that integrate efficiency and flexibility, and also incorporate uncertainties in load, distributed (behind-the-meter) generation, and customer behavior.
4. Multidisciplinary approaches to address the technical, economical, and societal complexity of multicarrier energy systems and stakeholder relationships, and exploit their full potential to harness energy flexibility.
5. Design of flexible buildings systems and controls that may contribute to more resilient systems when it is needed.
6. Policy/regulatory frameworks that modify existing or create new energy performance standards that do not penalize flexibility.
7. Business models that can scale energy flexibility across multiple buildings and technologies.
8. Policy support to reduce technology costs (e.g., either through direct R&D funding or economies of scale).

4. Expertise of the authors

The authors are key collaborators in the IEA EBC Annex 82 project. Dr. Li leads IEA EBC Annex 82 "Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems." Mr. Satchwell researches utility regulatory and business models that achieve greater deployment of energy efficiency, demand flexibility, and other distributed energy resources. Prof. Finn investigates demand response measures in the residential and commercial building sectors. Senior researcher Christensen researches the role of users in smart energy solutions and low-carbon energy transitions. Prof. Michaël Kummert's research focuses on modeling and control of building-scale and community-scale energy systems to optimize energy flexibility and resilience. Dr. Le Dréau researches energy flexibility of buildings both at building and district scales, develops occupant behavior models and prediction techniques related to flexibility. Dr. Lopes is involved in two international projects funded by the European Union's H2020 programme where he is developing and applying energy flexibility characterization methodologies and optimization algorithms in several demonstration activities. Prof. Madsen leads a national research project 'Energy Flexible Denmark' and he focuses on grey-box modeling, digital twins, forecasting and control for smart buildings in smart grids. Dr. Salom research works focus on zero/positive energy buildings and districts and their interaction with energy infrastructures being involved in several international projects. Prof. Henze researches model predictive and reinforcement learning control and data analytics for the integration of building and district energy systems with the electric grid. Mr. Wittchen research works focus on zero/positive energy buildings and districts and implementation of European legislation on building's energy performance.

CRediT authorship contribution statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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