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Evaluating the cost of energy flexibility strategies to design sustainable building clusters: Modelling and multi-domain analysis

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ABSTRACT

The increasing complexity of urban distributed energy systems demands effective strategies to tackle design and operational challenges. This study presents a framework for evaluating energy flexibility strategies in building clusters, aiming to minimize costs across various domains. By analysing thermostat adjustments and load adaptations, the study assesses the economic and non-economic costs, namely energy expenses and variation in occupant thermal comfort. A simulation platform has been developed to carry out multi-domain analyses, aiming to enhance the utilization of renewable energy and manage grid power demand. The model integrates detailed building energy models with a district grid model in co-simulation mode, augmenting the capabilities of current energy models in capturing multi-domain aspects of the design, such as occupants' response to flexibility events. The model integrates distributed renewable energy sources and energy storage systems aggregated with different building typologies forming energy communities. Proof-of-concept simulations are conducted, showcasing the multi-faceted costs of implementing energy communities, including photovoltaic, battery energy storage, and a building cluster composed of residential, office, and service buildings. Sensitivity analysis evaluates the impact of flexibility strategies on renewable energy consumption and occupant comfort. The results of the study help to understand and quantify the impact of measures encouraging the engagement of citizens in such communities' response programs and inform the design and operation of such strategies. It is demonstrated that for the case study, the use of BESS in demand management raises the utilization of renewable energy by up to 25 %, while load adaptations lead to an 8 % increase in renewable energy consumption. The maximum variation in thermal comfort sensation is achieved adapting setpoint at lower aggregate load thresholds. Compared to previous district grid models, this framework provides a more comprehensive evaluation by quantifying the specific effects on renewable energy use and occupant comfort through detailed dynamic building simulation.

1. Introduction

The transition towards a more sustainable and resilient energy system is a global priority, and the development of *renewable energy communities* (RECs) is one of the most promising solutions to achieve this goal (Di Silvestre et al., 2021). RECs are clusters of consumers and producers (people or organizations) that come together to develop and implement renewable energy projects in their local communities (Ceglia et al., 2022). Introduced by the RED-II (European Directive 2018/2001/EU (Directive EU, 2018), RECs aim at generating societal benefits, rather than solely focusing on financial profits. By prioritizing the interests of the whole community, RECs can help to foster a more sustainable and equitable energy system that benefits all stakeholders, rather than just a few individuals or organizations. This can include reducing greenhouse gas emissions, increasing energy security and independence, and promoting local economic development (Musolino et al., 2023).

The increasing in renewable energy sources (RES) integration in the energy system and urban areas pushes the electrification of heating and

Abbreviations: BCVTB, Building Controls Virtual Test Bed; BEM, Building Energy Modeling; FMI, Functional Mock-up Interface; GDM, Grid dispatching model; GHG, Greenhouse gas emissions; HVAC, Heating Ventilation and Air Conditioning; MPC, Model Predictive Control; REC, Renewable energy community; RED, Renewable energy Directive; RES, Renewable energy source.

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Symbols

A_{module}	Area of a PV module
A_{tot}	Total area of the photovoltaic field
c_{EC}	Total costs of the energy community
c_{loss}	Loss coefficient
C_{max}	Maximum battery capacity
E_{ex}	Excess energy
E_s	Stored energy
E_{sc}	Energy self-consumed
G_{inc}	Incident solar radiation
I_{cl}	Clothing insulation
$k(t)$	Time-dependent fractional schedule for lighting
L	Building load
M	Metabolic rate
p_a	Indoor air pressure
$P_{BESS,in}$	Battery energy storage system input power
$P_{BESS,load,threshold}$	Power demand threshold for BESS operation
$P_{BESS,max}$	Battery energy storage system maximum power
$P_{BESS,out}$	Battery energy storage system output power
$P_{equipment,d}$	Design equipment power
P_{grid}	Power supplied by the grid
$P_{lights,d}$	Design light power
PMV	Predicted Mean Vote
$P_{peak,module}$	Peak power of a PV module
P_{RES}	Power produced by renewable energy sources
$s(t)$	Time-dependent fractional schedule for equipment
sc	Self-consumption
SOC	State of charge
ss	Self-sufficiency
T_{in}	Indoor air temperature
T_{mr}	Mean radiant temperature
$T_{set,d}$	Setpoint temperature
u_n	Price of energy from energy providers
u_{NUP}	Electricity feed-in tariff
u_{sc}	Energy community incentive
v	Air speed
v_i	Economic incentives
v_s	Revenues from energy sales
$z(t)$	Additional temperature signal
ΔPMV	Change in Predicted Mean Vote
Δt	timestep.

transportations (Johannsen et al., 2023). Therefore, urban systems are about to become *smart* and more and more interconnected such that operation is increasingly complex and ensuring stability, resilience and limiting costs are of great concern (Barone et al., 2023a). Solutions to improve the *smartness* of urban energy system need to encompass many aspects in an holistic way (Zheng et al., 2024).

In this context, the demand for grid services, and, in general, for demand flexibility, is likely to increase in the future, switching from the Zero Energy to Zero Power buildings concept (Bilardo et al., 2024). This is driven by the escalating burden on energy transmission and distribution infrastructures (Minuto and Lanzini, 2022), along with the cost benefits that such measures can provide both to infrastructure managers and end users (Förster et al., 2024).

Small clusters of users such as RECs have the potential to unlock flexibility and demand-response at small scale (Backe et al., 2022) if designed to *"adapt/manage its short term (a few hours or a couple of days) energy demand and generation"* (Jensen et al., 2017). The deployment of energy flexibility in energy communities can bring about significant economic and environmental benefits (Barone et al., 2022). One way to achieve this is through the shedding of peak loads, which can lead to a positive environmental impact by reducing greenhouse gas (GHG) emissions since the peaking supply is often fossil fuel-based (Angizeh et al., 2022). Furthermore, flexibility based on energy storage systems enable the coordination of energy usage among multiple buildings, energy demand can be more effectively managed and optimized with higher renewable energy self-consumption (Li et al., 2022; Pompei et al., 2023a). To undertake a flexibility program, effective communication and information exchange between the utility and flexibility providers (demand-response events, pricing signals, etc.) are necessary (Kaspar et al., 2022). At building level, local controllers are needed to define set-point temperature, battery charging / discharging strategy or device activation time. Control strategies can be manual, rule-based (Maturo et al., 2022), or optimized through predictive modelling (Li and Wang, 2022).

Given its inherent complexity, the design and operation of energy communities require the consideration of all interconnected factors, such as the energy demand and supply of the community, the availability of renewable energy sources, power grid constraints, and data and communications services that support energy flexibility (Li et al., 2023). However, flexibilities at the building scale may influence other aspects that are difficult to assess in the design stage and can create barriers to the effectiveness of energy flexibility strategies. For example, occupants' behaviour has a significant impact on building energy consumption patterns (Chen et al., 2021). During demand-response events, building occupants may experience discomfort, or other liveability standards may be disregarded (Kazemi-Razi et al., 2021). Consequently, measures aimed at influencing occupants' behaviour and encouraging cost reduction may also prove unsuccessful. Indeed, a flexible operation should not *"jeopardize building occupants' needs"* (Li et al., 2021).

In this context, planners and designers may face challenges in implementing smart and flexible energy communities considering their complexity. Quantifying all costs and balancing them may streamline the actual implementations and operation. An analysis framework and models capable of capturing these effects and informing the design are of utmost importance.

1.1. Literature review

Modern urban energy systems are inherently complex, demanding a cross-sectorial approach to identify the optimal production and management system. Reference (Ceglia et al., 2020) comprehensively reviews Smart Energy Communities (SECs) and the interconnected aspects associated with their energy production and management schemes. The key actors in establishing energy communities include energy production assets, prosumers and consumers, energy sharing schemes, sensing and communication technologies, the energy market, utility services, transportation systems, and storage technologies.

SECs, but in general building clusters, exhibit various sources of flexibility, such as architectural measures that exploit the thermal capacity of buildings, building or district equipment, and electric vehicles. A recent review article (referenced as Le Dréau et al. (2023) discusses the challenges associated with implementing energy flexibility in urban clusters and also reviews the planning and design tools currently adopted in the early phases, including recent software kits such ad CitYBES (Hong et al., 2016), URBANopt (El Kontar et al., 2020), etc. The lack of comprehensive tools is identified as a barrier in developing flexibility strategies for clusters of buildings, as professionals need to assess the flexibility potential of projects even when limited data are available. In this phase, costs and impacts analysis are of great importance to assess feasibility and for value engineering. The development of multi-domain design tools is advocated along with improvement in whole-building energy control and modelling oriented to load flexibility may boost the diffusion of grid-interactive efficient buildings (GEBs) (Roth and Reyna, 2019).

In general, increasing modelling capabilities may inform on the costs that flexibility inherently possesses.

1.1.1. Assessing the costs of demand flexibility

Analysing the impact of building energy flexibility, studies primarily focus on the **economic costs** associated with the operation of demand-side management schemes, considering both the user side and the infrastructure side.

In reference Harder et al. (2020), it is demonstrated that this results in positive costs for aggregated energy demand of households. The study formulates a control problem as a generic flexibility quantification methodology which is applied to showcase different scenarios both at building and aggregate scale. Different models are developed to estimate this specific aspect of flexibility (Ma et al., 2023). An important consideration is defining a price for flexibility to appropriately reward flexibility providers (Holweger et al., 2023). As a matter of fact, energy flexibility can yield significant cost benefits in urban areas, extending to various sectors such as transportation. For instance, in metro railway systems, flexible operation has the potential to reduce annual power demand by up to 40 %, with a correlated cost reduction of 26 % (Kumar and Cao, 2023).

Multi-domain costs are analysed when focusing on a single building. The authors of reference (Pallonetto et al., 2021) studied the impact of advanced control algorithms for a residential building that provide flexibility to the power grid. Specifically, the study presents the distributions of thermal comfort scores (i.e., Predicted Mean Vote, PMV) for two different algorithms, which do not exhibit significant variations compared to the baseline. As thermal comfort introduces a new degree of flexibility in the context of smart building aggregates, it is crucial to consider such variability in optimization frameworks (Seyednouri et al., 2023). The authors of reference (Xiao and You, 2024) analyse the control of indoor comfort in grid-interactive communities. A community consisting of five identical buildings was simulated as a case study to test an innovative day-ahead energy dispatching and comfort control system. The study demonstrates a cost reduction of up to 40 % and a significant increase in comfort indices.

The study in reference (Ghasemnejad et al., 2024) adopts thermal comfort as a constraint in a robust optimization model for Citizen Energy Communities (CECs). The comfort constraints are introduced to ensure the comfort of prosumers during flexibility events in the energy management scheme proposed by the authors. While the study evaluates comfort among community members, it does not estimate the cost of flexibility in terms of thermal comfort.

Existing literature establishes that flexibility brings about various impacts beyond purely economic considerations. Thermal comfort is a notable aspect in this regard, as adjusting thermostats is one of the main sources of flexibility, with studies predominantly focusing on control mechanisms to mitigate any adverse effects on occupants' thermal comfort. Despite the current emphasis on promoting distributed energy sharing paradigms (Barabino et al., 2023), the implementation of advanced control strategies, which consider occupants' dimensions, becomes challenging when establishing energy communities with multiple users and diverse building types. This complexity arises due to the need to coordinate distributed decision-making (Li et al., 2022). Consequently, there is a growing realization that flexibility strategies can be effectively adopted by individual users within these communities. These users make decisions to participate in demand flexibility based on a balanced consideration of concurrent needs, such as energy cost reduction and thermal comfort, thereby maximizing the overall benefits of the energy community they belong to. Indeed, the proper design of energy communities is crucial for ensuring effective and flexible operation.

1.1.2. Modelling flexibility of building clusters

Capturing the interconnection of energy systems while modelling building energy consumption is fundamental for energy modelers, planners, and designers (Pompei et al., 2023b). However, the authors of reference (Wetter and Sulzer, 2023), identified gaps in designing properly configuration of equipment and networks under consideration of dynamic operation for grid-interactive buildings. The authors foresee that if no actions are taken to adapt the modelling approach to the increasing complexity, the industry might fail to address decarbonization targets. A platform-based design applied to the concept of energy hubs may be a valuable strategies to innovate energy systems at different scales (district, city, etc.) (Sulzer et al., 2023). This process is based on integrated energy models that are modular, reusable and allow holistic design.

Actual energy forecasting for building clusters are based on both detailed modelling (Ceglia et al., 2023) or data-driven approaches (Manna et al., 2023; Petrucci et al., 2022). A combined approach is also adopted, which is a fusion of these two methods. It utilizes grey-box models, which are low-order models retaining the physics behind predictions but with a lower computational burden (Petrucci et al., 2023). This approach is widely used in flexibility studies as it is easily coupled with Model Predictive Control (MPC) (Maturo et al., 2023).

In building modelling, *co-simulation* involves the parallel simulation of buildings and other models, such as district systems. It is performed at the time-step level and more accurately captures physical dynamics among the simulated models (Abugabbara et al., 2020); the tight coupling of models allows information exchange, which is fundamental for flexibility controls. Co-simulation is mainly used for thermal district system simulations, i.e. fifth generation district heating and cooling (Allen et al., 2022). Two main approaches are adopted for co-simulation of district energy systems: exploiting a middleware software such as Building Controls Virtual Test Bed (BCVTB) (Angizeh et al., 2022; Wetter, 2011), and the using Functional Mock-up Interface (FMI) (Wang et al., 2017; Cucca and Ianakiev, 2020; Elhefny et al., 2022).

Detailed modelling may require more time and computational resources than large data-driven simulations, but it has the potential to provide a test bed for designing demand flexibility strategies for building clusters, a detailed approach allow investigating more complex effects and unlocking the use of existing building digital twins (developed for building design) (Song et al., 2023). This approach can also help to increase the adoption of such models among designers and district energy planners, as it allows for a more accurate representation of the complexity of building energy system. Furthermore, it can enable the evaluation of different energy management scenarios and the comparison of different demand-response strategies in a controlled and realistic environment, ultimately leading to more efficient and sustainable energy systems.

1.2. Aim of the study

The aim of this study is to address challenges related to the design and operation of distributed energy systems in urban contexts. Focusing on building clusters as energy communities, the study introduces a comprehensive modelling framework to assess and develop energy flexibility strategies. The primary objective is to evaluate the cost of flexibility, encompassing both economic expenses related to building-grid interaction and the impact on occupants, particularly in terms of thermal comfort. The paper provides a framework analysis that can be adopted by those attempting to answer the question: *"What is the overall costs of flexibility strategies on energy community members?"*. "Cost" is meant in terms of net economic expenses related to the community-grid interaction and the impact of flexibility strategies on building occupants, specifically by assessing the variations in the thermal comfort sensation index due to energy demand adaptation.

To achieve this goal, a simulation platform integrating detailed Building Energy Models (BEMs) with a district grid model is developed to facilitate multi-domain analyses. The renewable energy community investigated in this study consists of different building typologies (residential, office, and service buildings), simulated as prototype BEM models. The district system model, developed as an external computational model, assesses the energy production of RES and energy storage systems, simulating economic and energy flows within the energy community. Connected in co-simulation mode with the BEMs, it captures the physical connections between demand and district systems during flexibility events, enabling to assess the mutual influence between the building occupants and district system. Simulations are conducted to perform a sensitivity analysis on key parameters involved in the energy management schemes of the flexible energy community such as battery capacity, battery power threshold for peak shaving and building load adaptation strategies.

1.3. Contribution of the current study

The current study contributes to two key areas, enhancing the overall understanding of complex energy systems in small-scale urban clusters and their modelling for design and operational purposes:

i) Firstly, the study introduces a novel perspective by evaluating multi-domain costs associated with energy flexibility. While existing literature has predominantly focused on economic considerations (Harder et al., 2020; Ma et al., 2023; Holweger et al., 2023), this research delves into the multifaceted impacts, considering both economic and non-economic domains. The evaluation of these multi-domain costs provides a comprehensive framework for assessing the true implications of energy flexibility strategies in urban clusters and small-scale energy communities, the diffusion of which is strongly incentivized. Pivotal in both centralized and decentralized decision-making schemes (Li et al., 2022). Estimating the overall costs will help to define strategies to mitigate expenses and increase overall benefits.
ii) Secondly, the study provides a comprehensive approach to energy community design and modelling. By creating tight coupling between physics-based models to simulate district energy systems, the simulation platform is valid for testing and optimizing energy flexibility at the small scale of energy communities and evaluating multi-domain impacts, which are missing in the current literature (Le Dréau et al., 2023; Roth and Reyna, 2019). Furthermore, the results obtained through the proposed approach may be more detailed and accurate compared to those based on grey-box or data-driven modelling (Maturo et al., 2023), as it allows for deeper investigation inherent in white-box modelling (e.g., EnergyPlus models).

With the new thinking approach proposed to model modern energy hub-based systems on an increasing scale (i.e., from building equipment level to city level) (Sulzer et al., 2023), depending on the level of abstraction or refinement, certain modelling capabilities are required for the tools adopted, such as modularity, scalability, and reusability. As also explained in (Wetter and Sulzer, 2023), the complexity and interconnection of urban energy systems increase, so the energy modelling industry needs to be adequate to face this complexity. By using established whole-building energy simulation tools, coupled with district models in co-simulation mode, the modelling framework developed in this study has a greater potential to become a widely used tool among designers.

2. Materials and method

The proposed approach for modelling energy communities (ECs) and investigating user demand flexibility involves a simulation platform developed to integrate detailed Building Energy Modelling (BEM) tools and a District Energy System (DES) model in co-simulation mode. The platform is developed in the MATLAB/Simulink environment coupled with Functional Mock-up Units (FMUs) of EnergyPlus building energy models. The adopted method allows for the representation and simulation of the physical coupling between the building energy systems and the DES, enabling complex and multi-domain analyses to support the design of flexibility strategies for ECs. As illustrated in Fig. 1, the simulation platform is utilized to investigate two aspects of the energy community under analysis. From a system perspective, an Energy and Economic (EE) analysis is conducted, while from an occupants' perspective, the thermal comfort of the indoor environment is analysed.

At a higher level, the DES considers the energy demand and supply of the community, the availability of renewable energy sources, and power grid constraints. The DES model manages energy fluxes within the district grid. At a lower level, the BEM models contain detailed information about the building envelope, internal loads, lighting, and HVAC systems, simulating the thermal and electrical fluxes of the buildings in the district.

DES and BEMs are integrated into a co-simulation platform, allowing the simulation of the entire energy system and community energy flexibility strategies through the FMU protocol, enabling online data exchange between BEMs and DES simulation models. The energy flexibility strategies considered in the simulation platform encompass energy management through battery storage, load adaptation and thermostat adjustment to reduce peak loads. Advanced BEM tools facilitate the analysis of a wide range of building archetypes and HVAC energy management systems.

2.1. Developing of district energy system model (DES)

The district systems model is structured as shown in Fig. 2. The EC's users aggregations, energy storage units and RES-based generators forming the EC's physical assets, and the power grid interact by each other through the virtual dispatching node of the energy community (red dotted line in Fig. 2) and the district flexibility control which received signals from the virtual dispatching node and sends signals to users and the energy storage technology. Considering the virtual dispatching node, the energy balance of the node itself is calculated by the Eq. (1) which is then characterized according to the considered node features.

$$L_i + P_{RES,i} + \frac{E_{s,i}}{\Delta t} + P_{grid} = 0 \tag{1}$$

Eq. (1) represents the generic energy balance equation of a virtual dispatching node that, in an EC adopting *virtual* distributed energy sharing schemes (Minuto and Lanzini, 2022), is used to account for self-consumed energy. The equation involves the required electrical load per each *i-th* building L_i, power produced by renewable energy sources $P_{\mathrm{RES},i}$, stored energy $E_{s,i}$, and power supplied by the grid P_{grid}.

Once the energy flows from and to the power grid are defined, the share of energy that is *virtually self-consumed* (E_{sc}), and therefore the excess energy (E_{ex}), are evaluated per each simulation timestep, as per Eq. (2). This value is crucial as the economic incentives acknowledged by public authorities to EC organizations aim at favouring renewable energy self-production and self-consumption as a founding principle of RECs (Magni et al., 2024). However, the specific enabling framework adopted depends on the Member State's transposition of the European Directive RED II (REScoop.eu., 2023).

$$\begin{cases} E_{sc} = \min\left(\sum_i P_{RES,i}\cdot\Delta t, \sum_i L_i\cdot\Delta t\right) \\ E_{ex} = \left(\sum_i P_{RES,i}\cdot\Delta t - e_{sc}\right)^+ \end{cases} \tag{2}$$

In this setup, all electricity stored or generated locally is fed into the virtual dispatching node (physically into the power grid). Simultaneously, users draw electric energy from the same node to fulfil their demands. Therefore, no physical self-consumption takes place between the shared power or storage plant of the EC and its members.

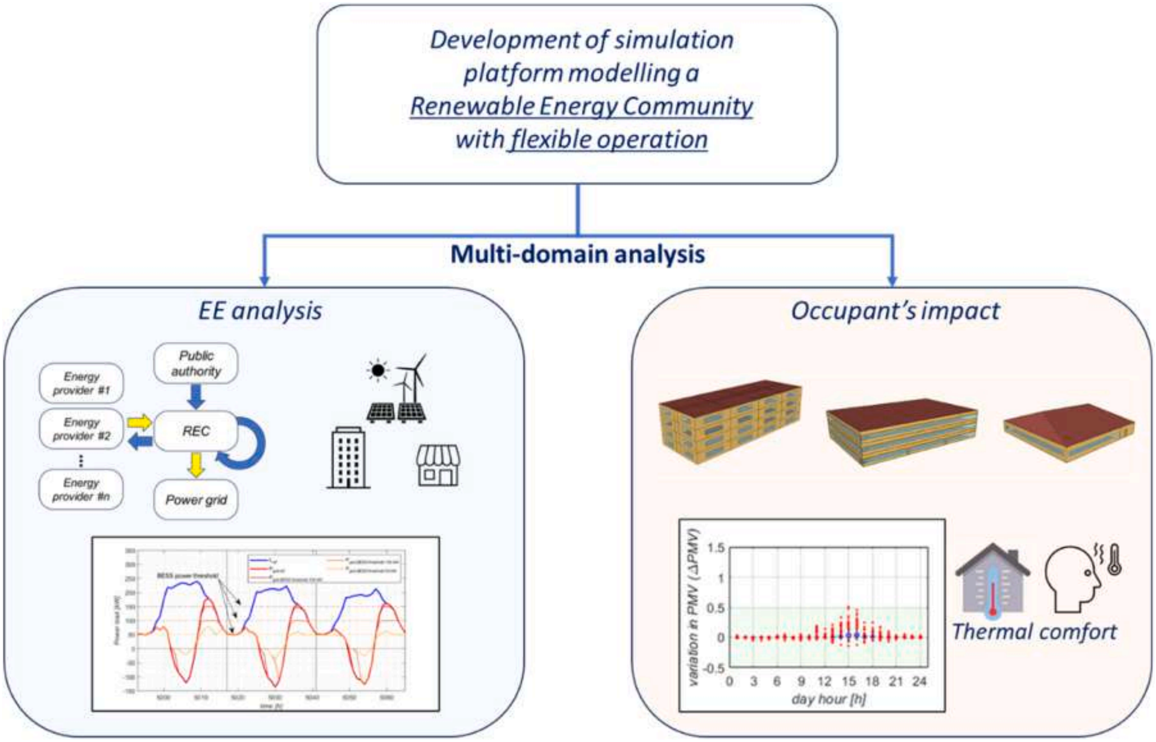

Fig. 1. Schematic representation of the method adopted to carry out the study and analyse the impact of energy flexibility on energy community members.

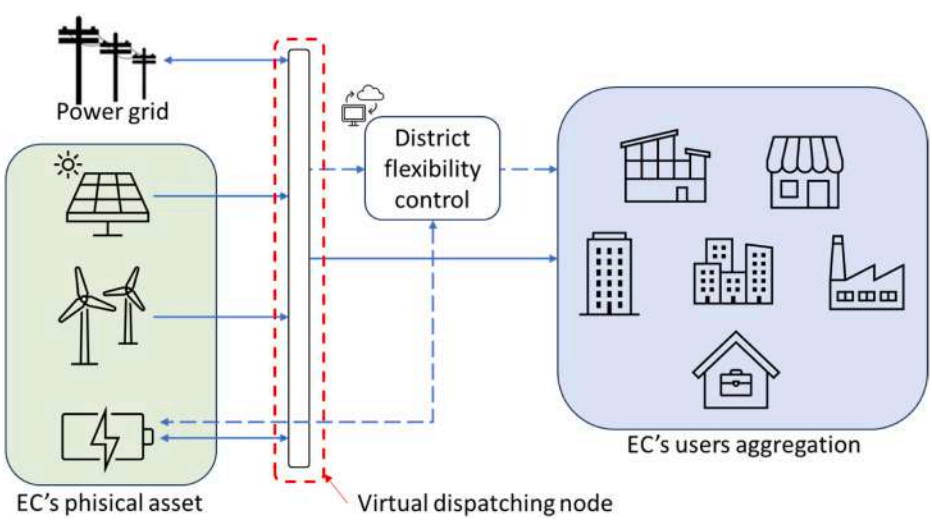

Fig. 2. District energy system model and object interactions: Continuous lines represent energy exchange, while dotted lines represent logic signals.

Each term of the equations is calculated according to the established energy management strategy, which considers the availability of renewable energy sources, energy storage units, and the power grid. Each object of the DES model is provided with suitable operation controls. The energy required from the electricity utility is assessed as the remaining power required by the district when no renewable energy or stored energy is available, assuming that the power grid can always supply the required loads.

2.2. Developing of building energy models (BEM)

Building energy models are essential tools for predicting and optimizing building energy performance. These models are developed using building simulation software such as EnergyPlus, which is a widely used building simulation engine capable of simulating the thermal, lighting, and HVAC performance of buildings.

To develop a building energy model, an Input Data File (*idf*) must be created. An *idf* is a text file that contains all the necessary information about a building's geometry, construction, materials, and systems. This file is then processed by EnergyPlus to simulate the building's energy performance.

There are many software tools available for creating *idf* files, both proprietary and open source. The choice of software tool depends on the specific modelling intent and the level of detail required. The *idf* file must include information related to data exchange interface for the subsequent Functional Mock-up Unit (FMU) export.

The developed building energy model (shown in Fig. 3) can be used to evaluate the energy performance of a building under different

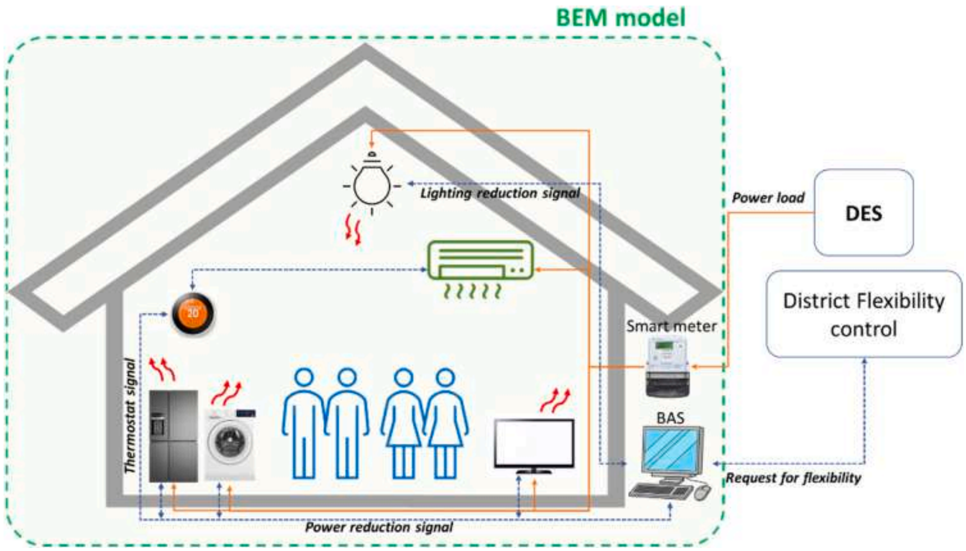

Fig. 3. Schematic visualization of a BEM model with externally controlled inputs related to lighting, equipment, and thermostat.

scenarios and to optimize the design and operation of building systems to reduce energy consumption and costs.

In order to investigate flexibility strategies, the building energy models (BEM) adopted in this study were designed to include data exchange interfaces for equipment, lighting, and HVAC setpoint controls. This allows for adaptation and load changes based on external signals from the BEM models, which is essential for implementing effective flexibility strategies.

The external interface developed to allow external model communication is based on time-dependent *fractional schedules* (*k(t)*, *s(t)*) and *additional temperature signal* (*z(t)*), updated at each simulation time step as described in Eq. (3).

$$\begin{cases} P_{lights} = k(t)\cdot P_{lights,d} \\ P_{equipment} = s(t)\cdot P_{equipment,d} \\ T_{set} = z(t) + T_{set,d}(t) \end{cases} \quad (3)$$

Where $P_{lights,d}$, $P_{equipment,d}$, and $T_{set,d}$ are the design light power, equipment power, and the setpoint temperature, respectively. The actual power loads and setpoint temperatures of the buildings are calculated according to external model information. All buildings' thermal zones are characterized by Eq. (3). The details of these data exchange interfaces and their importance in enabling flexibility are discussed in Section 2.3.

2.3. Developing of the BEM-DES interaction

In order to enable the interaction between the BEM and the DES, a specific interface is developed to link the BEM models, which are generated by EnergyPlus and exported as FMUs, to the DES. The interface is built in MATLAB/Simulink which is a widely used software for scientific computing and data analysis, while FMUs are exported through EnergyPlusToFMU.

EnergyPlusToFMU is a Python-based software package that allows buildings modelled in EnergyPlus to be exported as Functional Mockup Units (FMUs) for co-simulation using the Functional Mockup Interface (FMI) standard. Therefore, FMUs are implemented by a Python routine developed for the BEM models representing the building systems comprising the district under investigation.

To establish the interaction between the BEM and the DES, an interface consisting of a set of MATLAB functions that are responsible for exchanging data between the BEM and the DES are developed. The data exchanged includes information about the current building energy load, available on-site power generation, and the demand response signals generated by the DES.

The data exchange is based on a signal-passing architecture, where the BEM and the DES exchange signals through the interface. The signals contain information about the current status of the BEM and the DES, and are used to update the BEM model input signals in real-time.

Specifically, as discussed earlier in Section 2.2, the energy flexibility strategies are implemented at the district level to reduce and control the loads. This is achieved by controlling the lighting and equipment demand, and the HVAC setpoint temperatures.

In particular, as shown in Fig. 4, the fractional power coefficient signal is used to modulate the lighting and equipment power consumption. This allows the district centralized controller to adjust the power consumption of lighting and equipment to match the available energy supply, thereby reducing overall energy consumption.

Similarly, the thermostat set-point temperatures are also adjusted according to the flexibility signals sent from the DES. This helps in reducing the energy consumption of the HVAC system, as set-point temperatures can be dynamically adjusted based on the available energy supply.

The rule-based control implemented is described by Eq. (4) which is used to calculate the *schedules* (*k(t)*, *s(t)* and *z(t)*) introduced with Eq. (3). It is based on adjustment of the time-dependent *design schedules* ($k_d(t)$, $s_d(t)$ and $z_d(t)$) through parameters *r*, *v*, and *a*. The parameter values depends on specific strategies adopted and are described in Section 2.5.3. Specifically, it depends on whether P_{grid} is higher or lower than $P_{demand,threshold}$, representing the power request to the grid and the power demand threshold set as the limit above which flexibility from users is required.

$$\begin{cases} k(t) = r\cdot k_d(t) \\ s(t) = v\cdot s_d(t) \text{ if} P_{grid} \geq P_{demand,threshold} \\ z(t) = a \end{cases}$$
$$\begin{cases} k(t) = k_d(t) \\ s(t) = s_d(t) \text{ if} P_{grid} < P_{demand,threshold} \\ z(t) = 0 \end{cases} \quad (4)$$

Data exchange occurs at a fixed timestep Δt during the simulation. Simulink supports FMU import and manages data synchronization between the DES platform, developed in the Simulink environment, and the EnergyPlus FMUs.

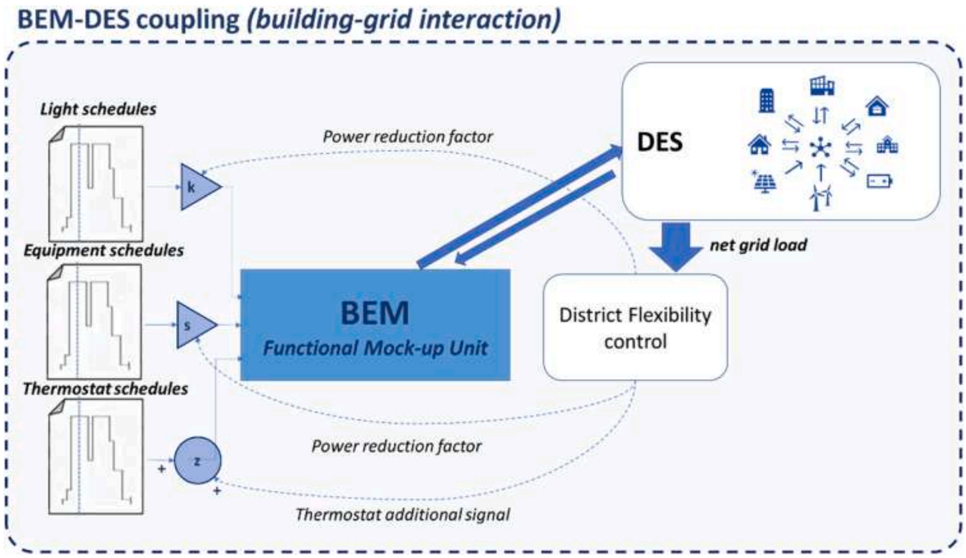

Fig. 4. Logical coupling between BEM and DES models which represent the physical building-grid interaction with flexibility control.

The DES model calculates the r, v, and a parameters to adjust the design schedules of the BEM FMUs. Consequently, the FMUs perform building load calculations, and the signals are directed back to the DES model. Both the DES and FMUs operate on the same timestep, set at 10 minutes (600 s).

2.4. Multi-domain analysis

This section provides the calculation framework for conducting the energy and economic assessment of the described system, as well as the variation in thermal comfort indices. The economic calculation is carried out considering the Italian context and the rules set to incentivize energy communities, based on the energy balance between power injected into the grid and power withdrawn by the users in a virtual self-consumption scheme (Minuto et al., 2024). While the analysis is based on the specific regulatory and economic frameworks currently in place in Italy, it is important to note that similar principles are applied in other regions to incentivize self-consumption and self-production of renewable energy. Therefore, whatever incentive schemes are adopted (different feed-in tariffs, reimbursements on energy shared, etc.), they will likely reduce costs for renewable energy utilization. The modelling framework will remain valid with appropriate context-specific adjustments. Results may be influenced by the specific economic incentives considered. However, the flexibility strategies analysed, which aim to increase local self-consumption of renewable energy within the community, will similarly provide improvements in the cost of flexibility, with trends observed in this study expected to be consistent.

2.4.1. Energy and economic analysis

Energy performance is primarily evaluated through energy flows calculated by the equations in Section 2.1. Additionally, two key indices, namely *self-consumption* (sc) and *self-sufficiency* (ss), serve as metrics to assess the proportion of energy produced and directly consumed by the REC and its independence from external sources. sc and ss are defined by Eqs. (5) and (6), and evaluated over a one-year time span (T=8760 h), accounting for both renewable energy injected into the grid directly and from the storage system.

$$sc = \frac{\sum_{t=1}^{T} E_{sc,t}}{\sum_{t=1}^{T}\sum_{i} P_{RES,i,t}\cdot\Delta t} \tag{5}$$

$$ss = \frac{\sum_{t=1}^{T} E_{sc,t}}{\sum_{t=1}^{T} P_{grid,t}\cdot\Delta t} \tag{6}$$

The economic flows related to energy purchasing of EC members from their own energy providers depend on the price of energy (u_n) that each energy provider ensures to clients. The total cash flow from the EC members to EPs is calculated according to Eq. (7), considering the power load request (L) of the *n-th* user.

$$c_b = \sum_{n} L_n \cdot u_n \tag{7}$$

Economic flows of incentives (v_i) and revenues from energy sales (v_s) both guaranteed by the public authority responsible for providing provisions to ECs based on demand and production data received. Total flows are calculated by considering the incentive recognized per unit of virtually self-consumed energy (u_{sc}) and the electricity feed-in tariff (u_{NUP}), assumed to be as high as the National Unique Price (NUP), according to the RECs enabling framework adopted in Italy. Such economic flows are calculated according to Eq. (8).

$$\begin{cases} v_i = E_{sc}\cdot u_{sc} \\ v_s = (E_{sc} + E_{ex})\cdot u_{NUP} \end{cases} \tag{8}$$

The total costs of the EC (c_{EC}) are calculated as a balance between ingoing and outgoing financial flows, as indicated in Eq. (9).

$$c_{EC} = c_b - v_i - v_s \tag{9}$$

The actual price experienced by each community member over time is determined by Eq. (10), which varies hourly.

$$u_{e,EC} = \frac{c_{EC}}{\sum_{n} L_n} \tag{10}$$

2.4.2. Occupant's impact

The methodology employed for evaluating occupants' thermal comfort involved leveraging the EnergyPlus integrated calculator, which incorporates the Fanger's model to assess thermal comfort indicators such as the Predicted Mean Vote (PMV) (Barone et al., 2023b).

The PMV depends on several parameters. Eq. (10) describes *PMV* as a function of the main variables involved in the calculation. Detailed equations involved in the calculation are not provided for the sake of brevity; however, readers may refer to the complete EnergyPlus documentation for further information on the simulation approach (EnergyPlus).

$$PMV = f(T_{in}, T_{mr}, v, p_a, M, I_{cl}) \quad (10)$$

where T_{in} is the indoor air temperature, T_{mr} is the mean radiant temperature, v is the air speed, p_a is the indoor air pressure, M is the metabolic rate, and I_{cl} is the clothing insulation.

PMV is calculated dynamically by the EnergyPlus integrated calculator, considering factors such as indoor temperature, clothing insulation, metabolic rate, and air velocity.

For each scenario analysed, PMV was computed over time to capture variations in thermal sensation. The *ΔPMV* was then calculated by comparing the PMV values obtained in each scenario (PMV_{flex}) to those in a baseline scenario without building load adaptations (PMV_{ref}), namely the scenarios in which there is no cooling thermostat setpoint adjustment. Therefore, *ΔPMV* index served as a measure to quantify the impact of flexibility strategies on occupants' thermal comfort. It is calculated according to Eq. (11).

$$\begin{cases} \Delta PMV = +\left|PMV_{flex} - PMV_{ref}\right| \text{if} PMV_{flex} > PMV_{ref} \\ \Delta PMV = -\left|PMV_{flex} - PMV_{ref}\right| \text{if} PMV_{flex} < PMV_{ref} \end{cases} \quad (11)$$

By assessing how different strategies affect the *ΔPMV*, insights into the level of thermal comfort achieved under various conditions could be gained. Overall, this approach provided a systematic means to evaluate and compare the thermal comfort implications of different energy flexibility strategies in building clusters.

2.5. Simulation experiment

The district electric network model developed as proof of concept consists of the objects shown in Fig. 5. Specifically:

- A residential building.
- An entertainment building.
- An office building.
- A virtual dispatch point which represents the interface node between the local virtual network of the EC and the power grid.
- A renewable energy system, namely a photovoltaic field (PV).
- An energy storage system, namely a Battery Energy Storage System (BESS).

Simulations were performed assuming the local weather condition of Naples, Italy. Therefore, solar radiation and outdoor temperature time series are gathered from the EnergyPlus Weather (epw) file of the specific site location (EnergyPlus). The considered location experiences a peak of around 1000 Wh/m^2 of global horizontal radiation, resulting in an annual radiation of roughly 1600 kWh/m^{2}year. Additionally, Naples is characterized by 1034 Heating Degree Days (Barone et al., 2023c).

Each object of the scheme shown in Fig. 5 is characterised by a suitable model reflecting the node behaviour, i.e, building energy models (as FMUs), photovoltaic systems and battery energy storage. They are implemented as model block within Simulink, developed as MATLAB functions.

2.5.1. Building modelling and simulation

The building models was implemented by means of the EnergyPlus simulation software. Specifically, prototype building models developed by the Pacific Northwest National Laboratory (PNNL) (PNNL, 2023) were used as the basis for the simulation. Some of these prototype buildings are derived from commercial reference building models developed by the United States Department of Energy (DOE) and are modified by PNNL as ASHRAE Standard 90.1, and International Energy Conservation Code (IECC) evolve.

The building models forming the virtual district energy system of the EC, selected for this study, are illustrated in Fig. 6 and sourced from the DOE's repository. These models include both commercial buildings and mid- to high-rise residential buildings (PNNL, 2023). The decision to use DOE prototype models and select these three specific building typologies is based on two key reasons: i) these models are thoroughly reviewed and provide high-fidelity simulations results, accurately representing groups of buildings with similar characteristics; ii) assessing flexibility strategies in community energy aggregations requires diverse load profiles, which these different building types provide.

The selected building types—mid-rise apartment, medium office, and sit-down restaurant—are commonly found in urban environments, making them ideal for this study. Furthermore, the authors found these building prototypes suitable for the analysis carried out for the specific case study considered.

The *mid-rise apartment* building has a total area of about 3100 m^2 and features a 20 % window-to-wall ratio on all sides. Each floor of the four-stories building have eight apartments, except the ground floor which has seven apartments and an office. The heating system utilizes gas boilers, while cooling is provided by split systems (one per apartment). The cooling setpoint temperature is set to 24°C.

The *medium-office* building has a total area of 5000 m^2 and a 33 % average window-to-wall ratio on all sides. Three floors are divided in four perimeter zones and one central zone on each floor.

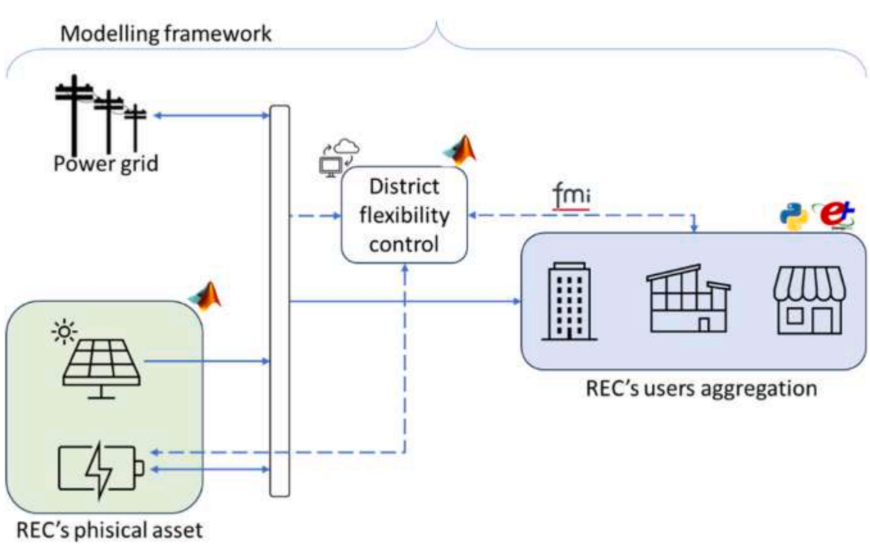

Fig. 5. Diagram of the model developed for the simulation experiment.

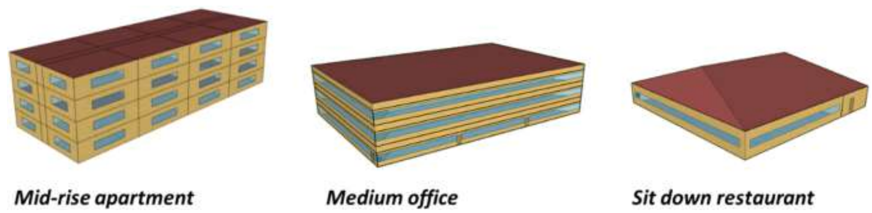

Fig. 6. EnergyPlus models comprising the virtual District Energy System selected from the PNNL library (PNNL, 2023).

The heating system is composed of gas boilers coupled with packaged air conditioning unit that supply also cooling to spaces. The cooling thermostat setpoint temperature is set to 24°C during occupied time while setback temperature is set to 27°C in the rest of the day.

The sit-down restaurant has a total area of 500 m^2 and a 28 % average window-to-wall ratio on the South facade, 0 % on the North facade, and 20.22 % on the East and West facades. It is a single-story building divided into a kitchen and dining area. Heating and cooling systems are similar to the ones of the medium office building with the only difference of the setback temperature value which is 30°C during non-occupied time.

For thermal comfort calculations, the building models described include information regarding activity levels, from which the metabolic rate (M) of people is derived, air speed (v), and clothing insulation (I_{cl}). Additionally, the simulation model dynamically calculates other environmental parameters such as indoor air temperature (T_{in}), mean radiant temperature (T_{mr}), and indoor air pressure (p_a). Specifically, v is set to 0.2 m/s, while I_{cl} is set to 1 for the period from January 1st to April 30th and from October 1st to December 31st, and to 0.5 during hotter season (from May 1st to September 30th). The activity level is set to 95 W/m^2 and 120 W/m^2 for the mid-rise apartment model and the medium office and sit-down restaurant, respectively. Further information on building model assumptions is available in (PNNL, 2023).

The building models presented have been adjusted to ensure efficient external interface communication for lighting and equipment operating schedules, as well as schedules related to cooling thermostat setpoints. So that, external interface systems can interact with lighting, equipment, and HVAC systems in co-simulation mode to make building energy demand flexible to power grid needs.

2.5.2. Power supply and energy storage modelling and simulation

As a renewable energy producer, a photovoltaic field was considered and modelled as a MATLAB function. The input parameters required for the model are the ambient temperature, the area of the photovoltaic field, and the direct and diffuse radiation on the normal plane. The output parameters include the incident solar radiation on the panels and the electrical power produced by the photovoltaic field.

The incident solar radiation, G_{inc}, was evaluated by considering the surface inclination and azimuth, as well as the location of the photovoltaic field (Naples) expressed as latitude and longitude degrees (Latitude: 40.842, Longitude: 14.259). The sun path has been simulated in order to assess the actual incident solar radiation of the sloped surface taking into account the horizontal solar radiation gathered from weather data file of the site. Specifically, the analysis considers south-facing solar panels with an azimuth angle of 0 degrees and a slope angle of 30 degrees, utilizing commercial photovoltaic modules rated at 315 W per module (1.65 m^2 each). The electrical power produced by the photovoltaic field was calculated by Eq. (12):

$$P_{pv} = G_{inc} \cdot A_{tot} \cdot c_{loss} \tag{12}$$

where A_{tot} is the total area of the photovoltaic field, varied to analyse different plant sizes; while c_{loss} is a coefficient that accounts for the efficiency of the panels, as well as any losses due to shading or external losses related to cables and inverters. This coefficient is assumed to be 0.78. These assumptions are based on a previous analysis carried out for the same location as the current study (Buonomano et al., 2023).

Whenever there is an imbalance between the energy production and demand of the building, the grid is utilized to supply the required power (P_{grid}).

The BESS is modelled with a drainage loss ($c_{BESS,loss}$) of 0.95 (Barabino et al., 2023). The MATLAB function takes into account the state of charge (SOC), the required input and output flows, and maximum power of the battery ($P_{BESS,in}$, $P_{BESS,out}$, and $P_{BESS,max}$). The battery has limited power on both charging and discharging, which depends on the current and voltage values supported by the cells, and has a maximum capacity (C_{max}), see Eq. (13). Thus, the function returns the actual input and output flows along with the charge level and state of charge. SOC_{t-1} refers to the state of charge at the previous timestep. It is assumed that the battery cannot discharge more than 10 % and can reach 100 % charge capacity. The state of charge is calculated as according to Eq. (13).

$$SOC_t = SOC_{t-1} + \left(P_{BESS,in,r} + P_{BESS,out,r}\right) \cdot \Delta t / C_{\max} \tag{13}$$

The energy management of the BESS is described by Eq. (14), where the conditions for charging and discharging are defined. Specifically, BESS charging is permitted whenever the power production from renewable energy sources (P_{RES}) is higher than building loads (L). Additionally, BESS can discharge only if grid demand surpasses a specified load threshold ($P_{BESS,load,threshold}$), representing the power levels at which the BESS attempts to shave peak loads. This threshold depends on the specific energy management strategy adopted by the energy community. The values used are defined in Table 1 in Section 2.5.3.

$$\begin{cases} P_{BESS,in,r} = \min\left(P_{BESS,in}, P_{BESS,\max}\right) \text{if} P_{RES} > L \\ P_{BESS,out,r} = \min\left(P_{BESS,out} \cdot c_{BESS,loss}, P_{BESS,\max}\right) \text{if} P_{grid} \geq P_{BESS,load,threshold} \end{cases} \tag{14}$$

2.5.3. District energy community simulation platform and modelling assumptions

The platform consists of several modules that simulate the different components of the district energy system, including the FMUs for

Table 1
Summary of parameters adopted for the simulation experiment.

Module	Modelling approach	Adopted parameters	Notes
BEMs	Co-simulation with EnergyPlus through Functional Mock-up Interface	Geometry; Envelope; Systems.	Modelling assumption at reference (PNNL, 2023).
PV	Sun path simulation and PV plant power production calculation	$P_{peak,module}$= 315 W; A_{module} = 1.65 m^2; c_{loss} = 0.78.	Eq. (12)
DES	Energy balance calculation based on pre-defined grid topology	r= 80–110 %; v = 80–110 %; a = 3.	Eq. (4)
BESS	Energy balance calculation and rule-based control	C_{max} = 100–1000 kWh; $P_{BESS,load,threshold}$=50–150 kW.	Eqs. (13) and (14)

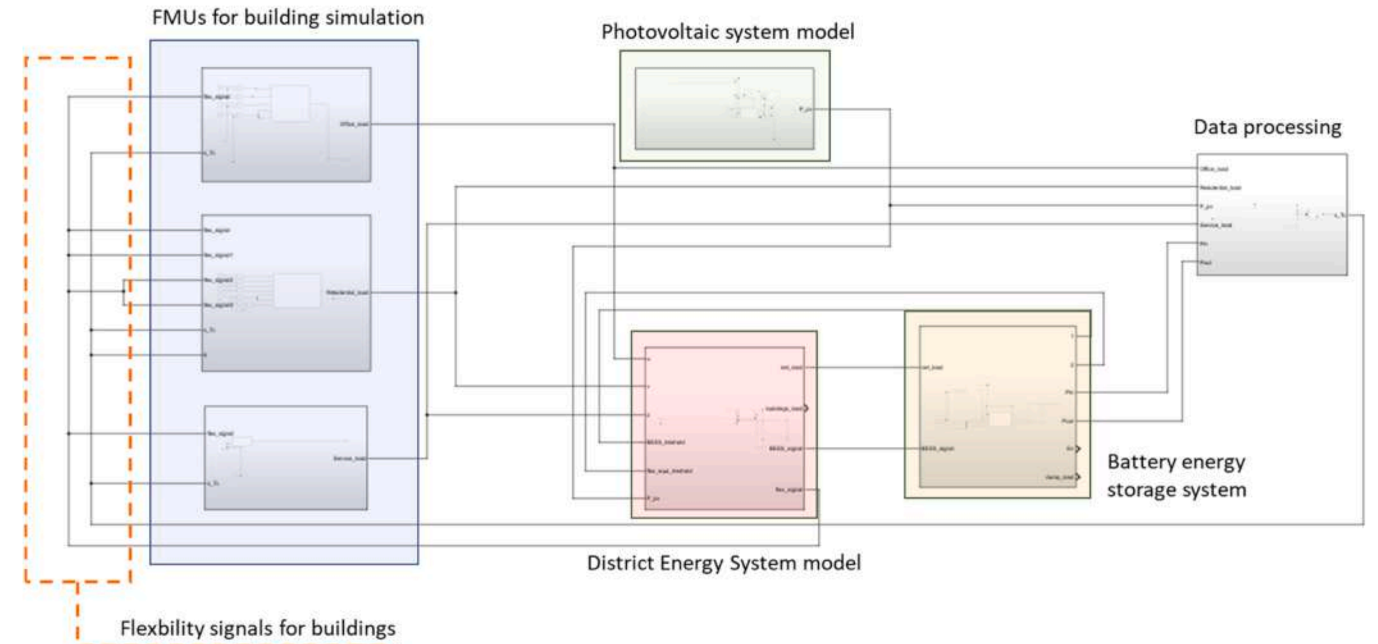

Fig. 7. Simulation platform developed in Simulink for district energy flexibility simulation. The platform includes interface for detailed building simulation (FMUs), photovoltaic system, District Energy system, battery energy storage system models and multi-domain analysis data processing.

building simulation, photovoltaic system, district energy system model, and the battery energy storage system. Fig. 7 shows the simulation platform developed in Simulink for district energy flexibility. The figure provides an overview of the model architecture, highlighting how the different simulation models interact simultaneously. While PV, DES, and BESS are simulated within the Simulink environment, FMU blocks call the EnergyPlus simulation engine in real time during the simulation. The simulation experiment carried out to test the modelling approach and analyse the main factors influencing demand flexibility of energy communities are reported below, in Table 1,

3. Results

This section is dedicated to results obtained, showcasing the effectiveness of flexibility strategies, such as the utilization of energy storage systems and energy demand adaptation, within the virtual district energy system outlined in Section 2.5. This system features an energy community (EC) that adopts a virtual distributed self-consumption scheme. A sensitivity analysis is conducted to assess the impact of various design and operation parameters on the EC members. Specifically, BESS capacity and BESS power threshold are investigated, analysing how these factors influence the flexibility potential that such technology may confer on the district energy system (DES) energy management. Moreover, to enhance flexibility, occupant response strategies are explored, evaluating different flexibility power thresholds. These thresholds represent the limits above which occupants attempt to adjust their electricity demand. The evaluation is carried out through modifications to building equipment schedules and thermostat adjustments. The latter involves changes in thermal comfort within buildings of the EC, and the impact related to this aspect is considered.

In the following, the dynamic behaviour of the EC is first analysed in different scenarios, intending to provide a comprehensive understanding of the fluctuations in electricity demand. Subsequently, the annual results are presented, identifying key indicators for the EE analysis, as well as assessing the impact on occupants.

In the following sections, the dynamic behaviour of the energy community (EC) is analysed across various scenarios to provide a comprehensive understanding of the fluctuations in electricity demand.

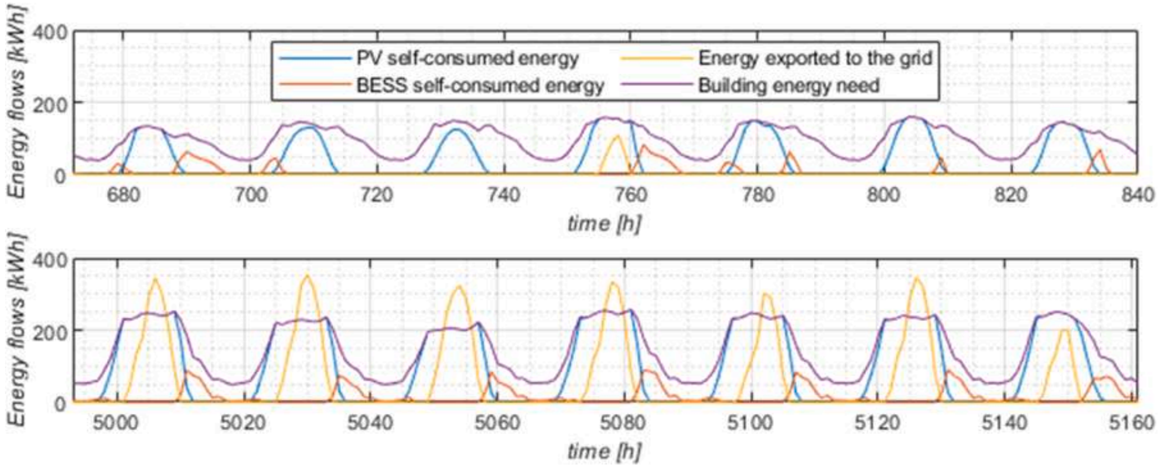

Fig. 8. Energy needs and flows in a virtual energy community during a seven-day period in winter (top) and summer (bottom).

Subsequently, the annual results are presented, identifying key indicators for energy efficiency (EE) analysis, and assessing the impact on occupants. Fig. 8 illustrates the energy flows of the virtual aggregation, offering a general overview of how the building energy community, as considered in this study, interacts with the power grid. The energy needs of the buildings are shown for two weeks: seven days in winter during the heating season (top panel of Fig. 8) and seven days in summer during the cooling season (bottom panel of Fig. 8). Additionally, the shares of energy produced by the PV system and consumed within the virtual energy aggregation (blue line), the energy exported to the power grid (yellow line), and the energy stored and later consumed when no PV production is available (orange line) are depicted. The analysed scenario refers to a configuration characterized by a 960 kW_p PV system coupled with a 1 MWh BESS, operated with a BESS power threshold of 50 kW for peak shaving. As expected, during summer, there is a high rate of energy self-consumption, substantial power injected into the grid, and significant utilization of the BESS system. Furthermore, the summer season is marked by high fluctuations in building power loads, primarily due to increased cooling demand and electrified cooling systems. This highlights that power flow management during summer may be subject to higher risks, and flexibility strategies could provide benefits. The following results will focus particularly on the summer operation of the building cluster.

Fig. 9 depicts the power demand of the building cluster considered in the EC in comparison to the actual power request from the grid for different BESS power thresholds, i.e. 150 kW, 100 kW, and 50 kW. The analysed cases, presented in the figure, refer to a DES configuration with a PV peak power of approximately 580 kW from the PV plant and a BESS capacity of 1 MWh. The reported period spans 3 days during summer, characterized by higher PV power production and increased electricity demand compared to winter.

The impact of the BESS power threshold choice, correlated with power grid requests, on the overall DES operation is evident. This choice determines the activation of the BESS for peak shaving, particularly during hours of the day with low PV power production. A lower BESS power threshold results in higher BESS utilization, leading to increased charging/discharging cycles. This dynamic relationship underscores the strategic importance of selecting an optimal BESS power threshold, influencing both peak shaving efficiency and overall DES performance, especially during periods of limited PV power generation. Fig. 9 illustrates that the EC configuration with a BESS power threshold of 150 kW ($P_{grid,BESS\ threshold\ 150\ kW}$, dark red line) does not fully exploit the 1 MWh BESS capacity, as observed during central daylight hours when exported power to the grid (negative power on the chart) is similar to the reference case ($P_{grid,ref}$, red line). The BESS capacity also influences utilization. However, low BESS power thresholds may impact the capacity to effectively "shave" peaks if the BESS lacks adequate capacity, as stored energy may be insufficient. This is observed for a BESS power threshold of 50 kW ($P_{grid,BESS\ threshold\ 50\ kW}$, yellow line).

To enhance energy flexibility potential, measures influenced by building occupants' behaviour, such as thermostat and equipment schedule adjustments, are investigated. In Fig. 10, a summary of the analysed strategies referring to a BESS power threshold of 50 kW is presented. Specifically, on the left, thermostat adjustment of 3 °C (depicted by dotted lines) during flexibility events is compared to the reference case (continuous line). The actual air zone temperature is also included to illustrate indoor temperature fluctuations resulting from these adjustments. It is worth noting that set-point adjustment is not adopted during the heating season, as the building's heating systems provide low flexibility due to their reliance on gas fuel consumption. On the right side of the figure, equipment schedules during flexibility events (small circle markers) are compared to the schedules in the reference scenario (big circle markers). As established, a 10 % increase in equipment loads occurs when electricity is exported to the grid. In contrast, when electricity demand exceeds the flexibility power threshold, equipment loads can be reduced by 20 %. These strategies may be implemented through automated control systems or manual adjustments. In this study, the method by which load reduction is achieved is not analysed for the sake of simplicity. The focus is on evaluating their impact on the overall cost-benefit balance.

Load reduction measures become particularly critical when on-site power production is limited or unavailable. This is clearly demonstrated in Fig. 11, where the impact of the described flexibility strategies is showcased. As illustrated in the figure, their implementation can lead to a substantial reduction in the building's net electricity demand.

It's noteworthy that these strategies are triggered both when the net power load, incorporating on-site PV power, surpasses the flexibility power threshold (i.e., 150 kW, 100 kW, and 50 kW in Fig. 11) and when the net power load is negative, indicating an increase in occupants' electricity demand.

It's noteworthy that these strategies are triggered both when the net power load, incorporating on-site PV power, surpasses the flexibility power threshold (i.e., 150 kW, 100 kW, and 50 kW in Fig. 11) and when the net power load is negative, indicating an increase in occupants' electricity demand. Establishing a threshold value ensures that the flexibility strategies are activated solely during peak demand periods,

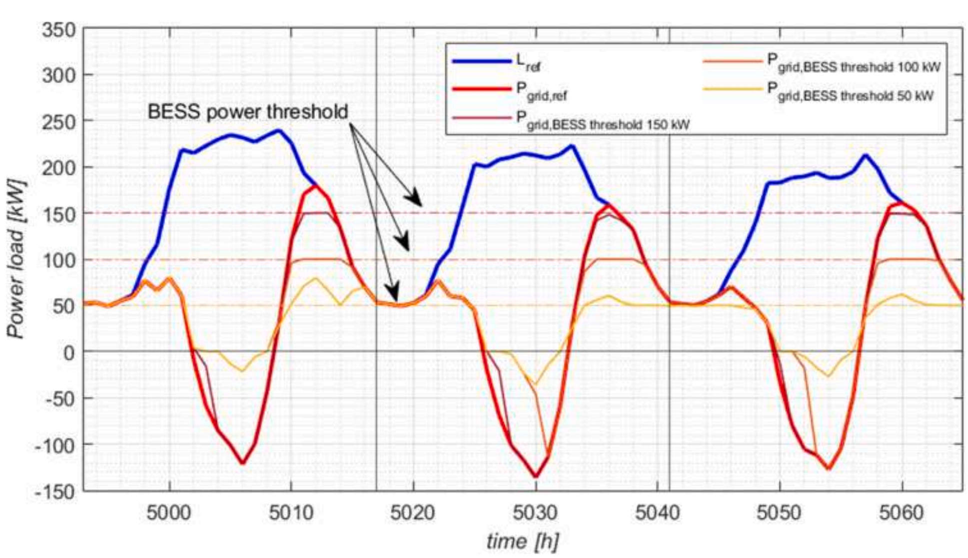

Fig. 9. Dynamic profiles of the energy community power demand and request from power grid with different BESS power thresholds.

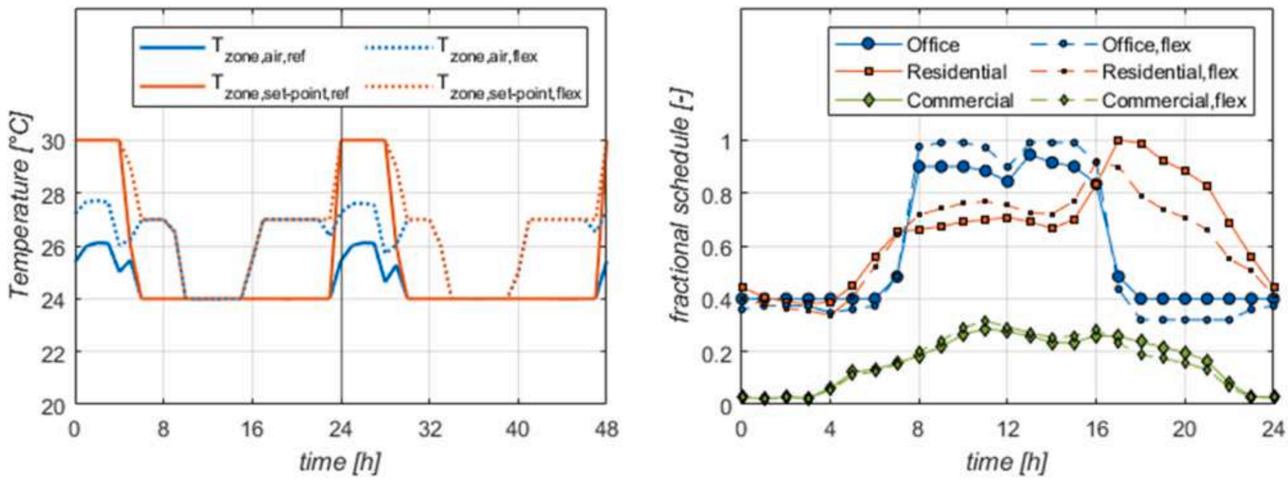

Fig. 10. Energy flexibility strategies adopted in the energy community under investigation include thermostat and equipment schedule adjustments based on BESS power threshold of 50 kW.

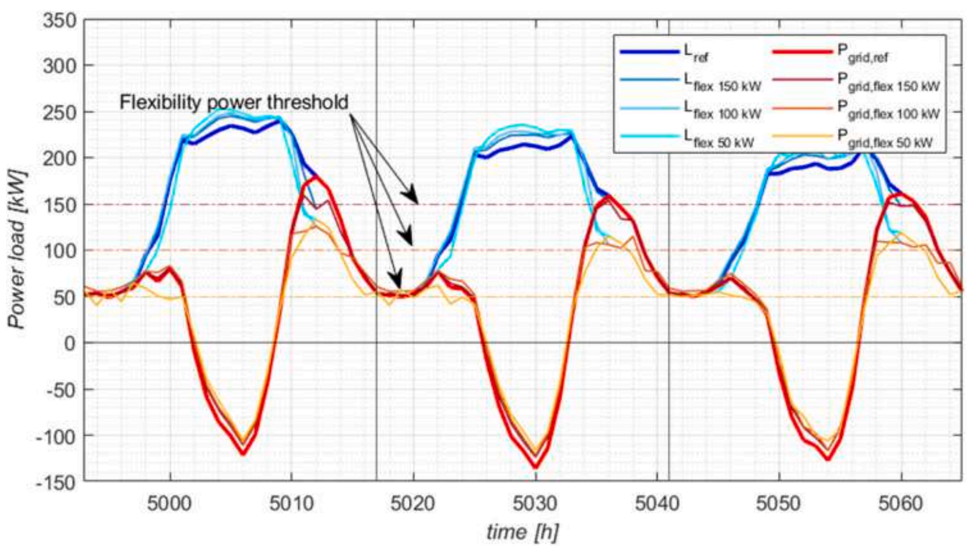

Fig. 11. Dynamic profiles of the energy community power demand and request from power grid with different flexibility power thresholds.

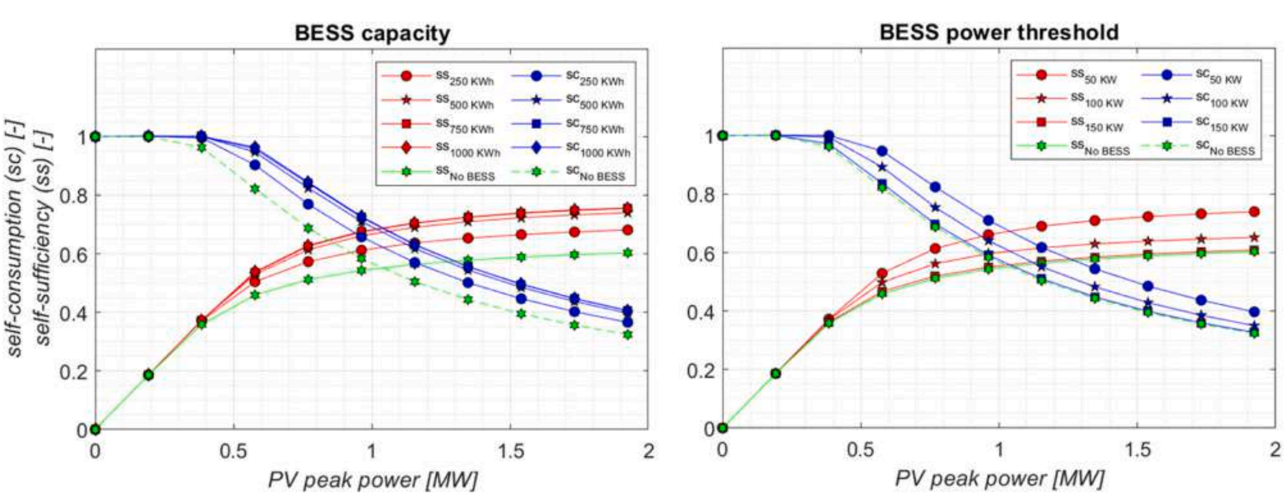

Fig. 12. Sensitivity analysis of BESS parameters on self-consumption and self-sufficiency indices.

facilitating the optimal utilization of available resources, and enhancing energy efficiency. However, as observed in the case of low flexibility power thresholds, such as 50 kW, the analysed flexibility strategies do not guarantee that the net grid power remains below the power threshold. It's important to note that the threshold simply represents the value at which the strategies to reduce the loads are activated. In this regard, the net peak power corresponding to flexibility power thresholds of 100 kW and 50 kW does not differ significantly. However, this may not hold true for the actual energy demand over time.

On an annual basis, the rate of RES-based self-consumed energy (*sc* index) and the proportion of RES covering the EC demand (*ss* index) are strongly influenced by parameters such as BESS capacity, BESS power threshold, and the buildings' capacity to respond in terms of demand.

The sensitivity analysis of these two parameters is depicted in Fig. 12 where both *sc* and *ss* indices are plotted as functions of the size of the installed PV power plant. Specifically, on the left chart, *sc* and *ss* indices are plotted for different BESS capacities with fixed BESS power thresholds at 50 kW, compared to the scenario with no BESS. Increasing BESS capacity leads to an increase in both indices, which is a positive outcome. However, it is observed that both *sc* and *ss* are less sensitive at higher BESS capacities. Transitioning from no BESS to a 1000 kWh capacity results in a 25 % increase in both indices. On the right chart, the two indices corresponding to different BESS power thresholds with a fixed BESS capacity of 500 kWh are compared to the configuration with no BESS. In this case, the configuration with the lower BESS power threshold yields higher *sc* and *ss* indices, which are up to 23 % higher than the scenario with no BESS.

A similar analysis is conducted to assess the impact of the flexibility strategies based on load adaptation investigated. The parameter under consideration is the flexibility power threshold, and the various scenarios analysed, as reported in Fig. 13, are compared to the scenario with no BESS.

As demonstrated in the figure, on an annual basis, the analysed strategies have a minor impact on the *sc* and *ss* indices compared to the use of batteries. Self-consumption may increase by up to 8 %, while self-sufficiency may be up to 15 % higher. It is worth noting that the positive effect of the increase in self-consumption is due to the improved correlation between demand and power generated on-site. Conversely, the increase in self-sufficiency is attributed to the positive effect of the analysed strategies, which leads to a reduction in the total annual building energy demand. This occurs with the specific settings assumed for these flexibility strategies analysed.

In terms of costs, ECs may offer significant benefits to their members. The analysed virtual self-consumption scheme provides income to the

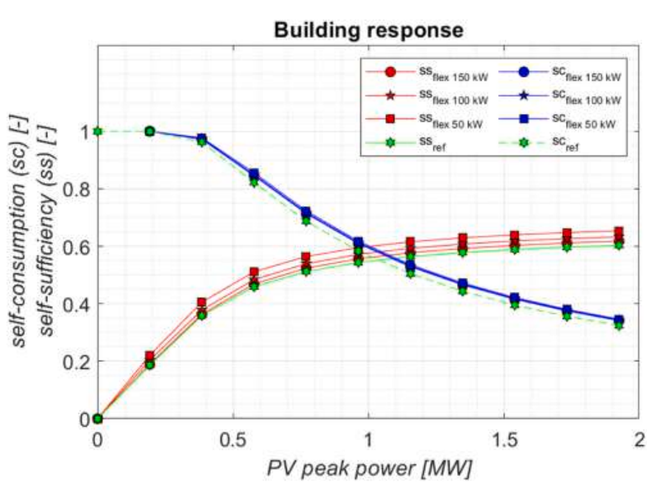

Fig. 13. Sensitivity analysis of flexibility power thresholds on self-consumption and self-sufficiency indices.

EC through both energy sales and economic incentives provided by the public energy authority. The amounts of such incomes (represented by green and purple bars) and the costs related to the purchase of energy from grid providers (depicted by purple lines) are shown in Fig. 14 (on the right axis). The charts gather the results for the scenarios of the three flexibility strategies analysed (50 kW, 100 kW, and 150 kW of flexibility power threshold), referring to a configuration with PV peak power of 960 kW and BESS capacity of 1000 kWh. The decision to opt for a 1000 kWh BESS is aimed at maximizing renewable energy self-consumption and ensuring consistent operation, particularly during peak shaving events, for extended periods. The energy price and feed-in tariff plotted in Fig. 14 are derived from actual hourly data specific to the Italian context (actual NUP data of 2023). This choice is made as the virtual self-consumption scheme analysed closely resembles the enabling framework recently adopted for renewable energy communities in Italy.

The power production from the PV plant and the utilization of BESS primarily generate income during hours when PV power is higher. However, BESS used for peak shaving ensures income from incentives and energy sales to the grid in the early morning and late evening. The chart illustrates three summer days. Regarding costs for members, the actual energy costs are depicted on the left axis (represented by blue, orange, and yellow lines). These reflect the actual unit energy costs for the three analysed flexibility strategies.

As seen in the dynamic cost data in the figure, the costs that members face are significantly offset by the incomes of the EC. At certain points during the day, the costs are negative, indicating positive incomes for each EC member. Notably, the total EC incomes exceed the EC outcome in the middle of the day. It is observed that EC members experience higher net energy costs during flexibility events when adopting lower flexibility power thresholds compared to higher thresholds. This is because of the lower energy consumed by users, as energy costs are normalized to the energy consumed by the community (Eq. (10)). Conversely, during demand response events aimed at reducing community loads, the EC experiences lower net hourly economic flows in the case of lower flexibility power thresholds (as indicated by the purple lines).

As anticipated, the flexible operation of building loads, which doesn't incorporate advanced control based on occupants' thermal comfort and using flexibility strategies aimed at increasing self-consumption and self-sufficiency, thereby generating economic benefits, may also impose certain non-economic costs on occupants. Estimating these costs accurately proves challenging. Fig. 15 assesses this impact by analyzing the variation in the Predicted Mean Vote (ΔPMV) compared to the thermal comfort index calculated in the baseline scenario (where no adjustments are made to building loads). ΔPMV is calculated using Eq. (11), indicating an increase in *PMV* when positive and a decrease when negative. This relative index offers valuable insights into the cost of flexibility in terms of its impact on occupant thermal sensation, providing more comprehensive information than considering *PMV* alone. Specifically, Fig. 15 displays the distribution of this index for each hour of the day recorded over the year. The analysis encompasses the three flexibility thresholds across three building typologies featured in the investigated EC.

As expected, relative thermal comfort decreases as the flexibility power threshold decreases across all building typologies. Notably, the magnitude of this variation varies. The most critical scenario, characterized by a flexibility power threshold of 50 kW, results in ΔPMV values not exceeding 1, indicating a tolerable increase in thermal sensation for occupants within this range. Note that the median of the ΔPMV distribution remains consistently below 1. Residential buildings exhibit the highest variations in thermal comfort votes, reflecting their less controlled environment. In general, this variation may still maintain an acceptable environment for occupants if the baseline scenario features lower limits of acceptable ranges (e.g., PMV = −0.5, between neutral and slightly cool). Conversely, when the baseline scenario is closer to the upper limit of acceptable thermal sensation (e.g., PMV = +0.5, between

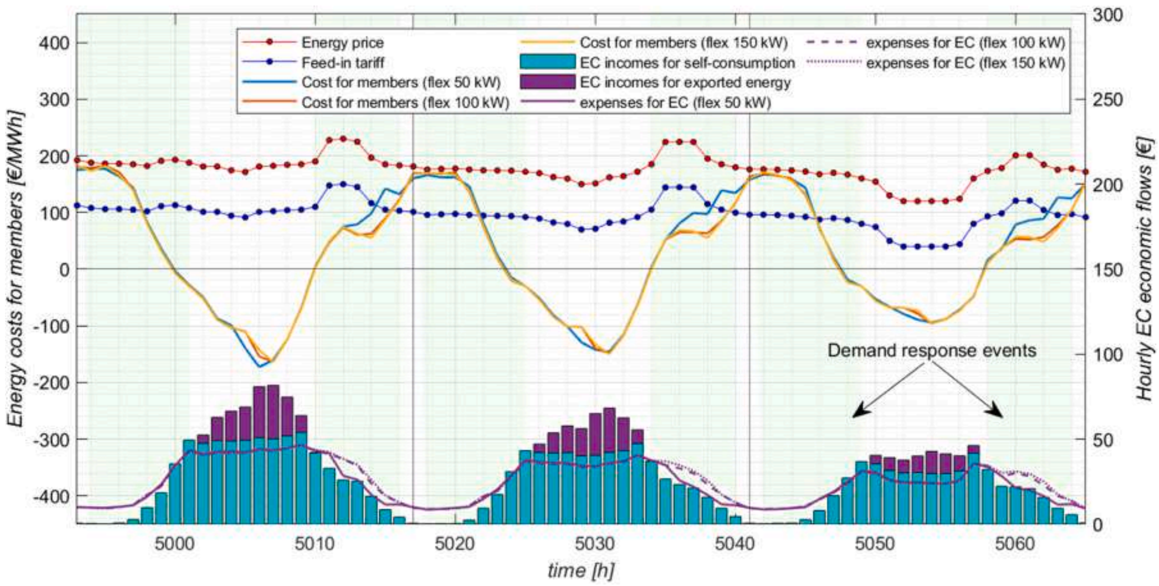

Fig. 14. Hourly net energy costs for energy community members and incomes for the aggregated users.

neutral and slightly warm), such variations can lead to significantly unacceptable thermal discomfort for occupants.

Flexibility power thresholds of 150 kW and 100 kW result in lower variations, typically within the range of 0.5, with occasional outliers observed in the distribution charts.

4. Discussion

The findings presented in this study underline the intricate dynamics involved in the design and operation of energy communities (ECs), particularly regarding the implementation of flexibility strategies. By examining the impact of various parameters and strategies on both economic and thermal comfort aspects, several key insights have emerged.

One of the central findings of this study is the significant influence of flexibility strategies on the overall energy performance and economic viability of ECs. The analysis demonstrates that the adoption of energy storage systems and demand-side management techniques can effectively enhance self-consumption and self-sufficiency rates, leading to economic benefits for EC members. However, it is crucial to strike a balance between maximizing economic gains and maintaining thermal comfort levels for occupants. While flexibility strategies can improve economic outcomes, they may also introduce certain costs in terms of thermal comfort, particularly in scenarios with lower flexibility power thresholds.

Furthermore, the study highlights the importance of carefully selecting and optimizing key parameters such as BESS capacity and power threshold to maximize the effectiveness of flexibility strategies. Results indicate that the choice of these parameters significantly impacts the utilization of BESS and the overall energy performance of ECs. Additionally, the sensitivity analysis conducted in this study provides valuable insights into the relationship between these parameters and key performance indicators such as self-consumption and self-sufficiency rates.

The analysis of thermal comfort variations offers insights into the potential trade-offs between economic benefits and occupant comfort. By quantifying the impact of flexibility strategies on thermal sensation, the study underscores the need for holistic approaches that consider both economic and comfort-related factors in the design and operation of ECs.

As highlighted, the adoption of different strategies to adapt building loads leads to varying degrees of impact on the thermal comfort of occupants. Therefore, it is crucial to mitigate this aspect and find synergies among different flexibility strategies, such as the use of BESS and building load adaptations. This raises questions regarding the design of strategies aimed at maximizing the overall benefits of ECs, which this paper seeks to address. However, further studies are needed to delve deeper into this topic:

- *Might occupants potentially sacrifice certain thermal comfort standards?*
- *What is the extent of the impact on overall well-being?*
- *Can the increased benefits derived from ECs effectively offset this aspect?*

Overall, this study contributes to advancing our understanding of the complex interplay between flexibility strategies, economic considerations, and thermal comfort in the context of energy communities. However, it should be underlined that this study contains some assumptions related to the strategies of load adaptations by the building occupants. Percentage load reductions/increases have been considered during flexibility events, which may not reflect the actual behaviour of users. This behaviour is stochastic and depends on the actual availability of users to engage in flexibility events. The end-user behaviour may be difficult to simulate for the purpose of assessing the actual reduction or increase in power demand. Despite these assumptions, the developed model is considered adequate for assessing the potential impacts of the flexibility strategies analysed in this study.

5. Conclusions

In conclusion, this study underscores the significance of implementing effective flexibility strategies within energy communities to optimize their operation. By evaluating various parameters such as battery energy storage system capacity, power thresholds, and building load adjustments, the study analyses the complex dynamics influencing energy flexibility and its implications on thermal comfort and economic outcomes. Furthermore, in this study, a detailed energy model is developed which is used to conduct a multi-domain analysis. The simulation tool developed is based on whole building energy modelling (BEM) coupled with a district energy management model in co-simulation mode.

The key findings of the study can be summarized as follow:

- BESS capacity and BESS power thresholds significantly influence energy self-consumption and self-sufficiency rates. If well-designed

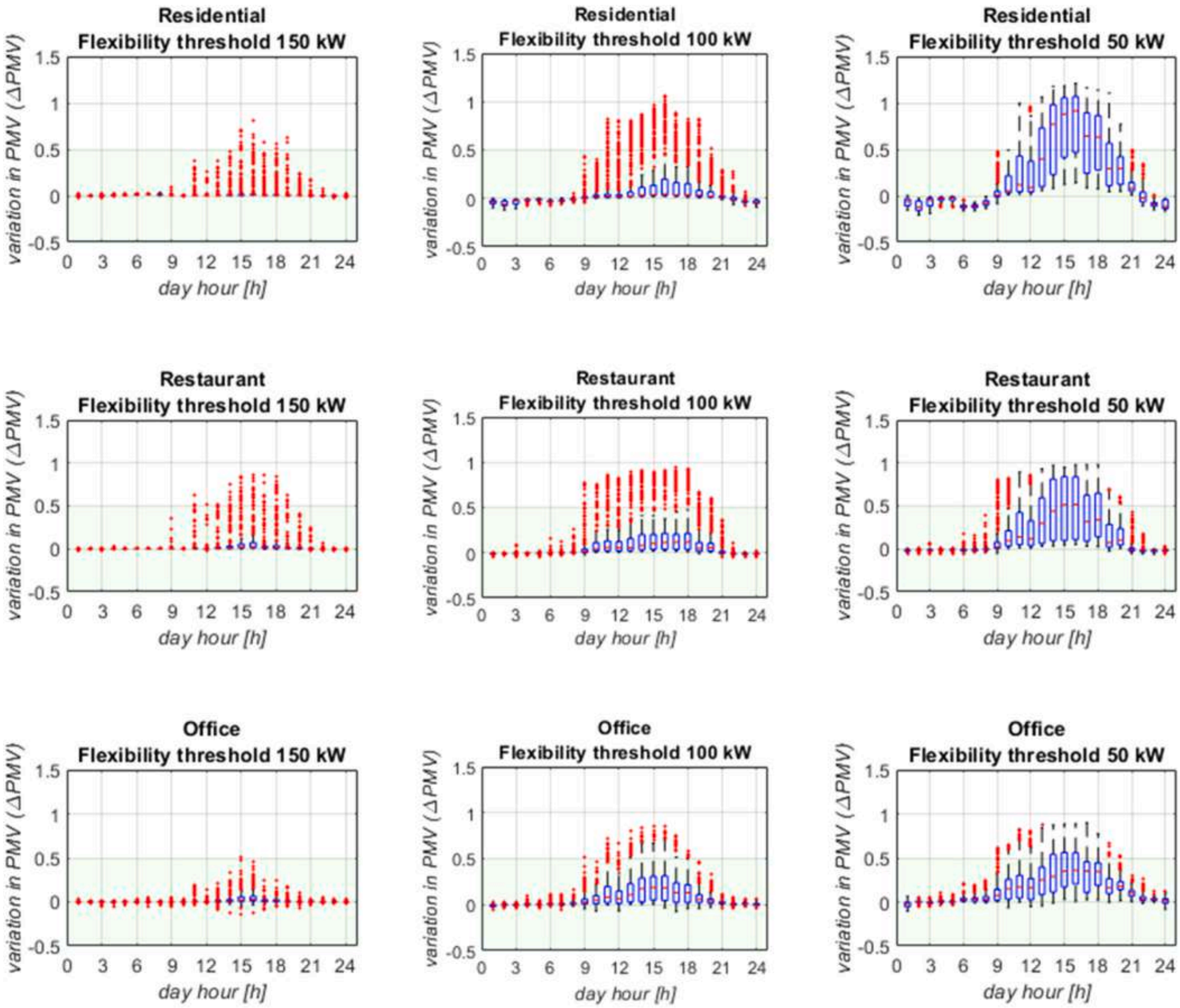

Fig. 15. Assessment of the impact that flexibility strategies have on energy community members.

BESS are adopted in the energy community as a strategy to enhance flexibility potential and reduce net power peak, self-consumption of renewable energy, as well as the dependency from grid may increase up to 25 %.

- Occupant behaviour adaptation, such as equipment load re-scheduling and thermostat control oriented to load reduction, are effective strategies. Depending on flexibility power threshold, such strategies allow significant flexibility potential in terms of net power peak reduction. On annual basis this also allow reduce net energy from the grid, and improve power generation and demand correlation. Self-consumption of renewable energy, as well as the dependency from grid may increase up to 8 % and 15 %, respectively.
- Economic benefits derived from energy community participation can offset costs associated with energy purchasing. The actual costs that each member sees depends on energy self-consumed on hourly-basis. With higher energy production, the unit cost becomes negative (meaning positive incomes for community members). Quantifying this unit cost drive the design of flexibility for EC.
- Lower flexibility power thresholds lead to increased BESS utilization but may impact occupants' thermal comfort significantly. The index adopted in this work, namely *ΔPMV*, which represents variation in thermal sensation for occupants (which is a costs for community members), reach the value of 1. Depending on baseline design this may impact significantly or not to overall thermal comfort. Less controlled environments suffer major thermal comfort variations.

The study highlights the importance of considering local energy generation and demand profiles in the design of district energy systems, as well as the potential of demand flexibility strategies in reducing energy costs and carbon emissions. The adoption of detailed building modelling approaches and digital twins can provide a valuable tool for energy planners and designers to optimize the performance of district energy systems and enable effective demand response programs.

Ultimately, by addressing these complexities, energy communities can achieve enhanced sustainability and resilience in urban energy systems.

CRediT authorship contribution statement

Giovanni Francesco Giuzio: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Giuseppe Russo:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Cesare Forzano:** Investigation, Formal analysis, Data curation, Conceptualization. **Gianluca Del Papa:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Annamaria Buonomano:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: As Annamaria Buonomano, a co-author on this paper, is an Editor of Energy Reports, she was blinded to this paper during review, and the paper was independently handled by Editor-in-Chief Nelson Fumo.

Data availability

Data will be made available on request.

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