Energy Conversion and Management 367 (2026) 121913

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Unlocking the grid flexibility potential of fifth-generation district heating and cooling systems through user-level demand-side strategies

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A R T I C L E I N F O

Keywords:
Fifth-generation district heating and cooling
heat pumps and thermal energy storage
energy flexibility
flexibility-oriented control strategies
urban multi-energy systems

A B S T R A C T

The increasing penetration of renewable energy sources is intensifying the need for energy flexibility solutions capable of supporting power grid stability. In this context, fifth-generation district heating and cooling (5GDHC) systems represent a promising yet still underexplored interface between urban thermal demand and electricity grids. This work investigates the potential of 5GDHC systems to provide energy flexibility services through demand-side management strategies implemented at building-user level. A physics-based dynamic modelling framework is developed, integrating building thermal demand calculation, heat pump performance modelling, and the representation of thermal energy storage and electrical batteries. Flexibility-oriented control strategies, including indoor temperature setpoint modulation, battery-assisted heat pump operation, and thermal energy storage integration, are simulated and assessed using dedicated flexibility indices for downward and upward load modulation and load shifting. The methodology is applied to a multi-user 5GDHC case study considering three alternative thermal balancing configurations: ground-coupled, groundwater-based, and solar-assisted solutions. The results of the simulative case study show that setpoint modulation enables short-term flexibility, achieving electricity load reductions of up to 37% and load increases of up to 26%. Battery integration enhances flexibility further, enabling load variations of 51–60%, while thermal energy storage achieves the highest performance, with load modulation exceeding 99% and load shifting fractions up to 54%. Flexibility provision is accompanied by primary energy savings of up to 11% and operating cost reductions of up to 14%, with groundwater-based configurations yielding the best overall performance. The proposed framework provides a robust tool to support the design and operation of flexible, low-carbon district energy systems.

1. Introduction

Power grid systems are becoming increasingly efficient, and renewable energy sources are projected to become the largest contributor to global electricity generation by early 2026, with their share of the power mix rising from 30% in 2023 to 36% in 2026 [1]. Power grids with high shares of renewable generation are characterised by more frequent and pronounced imbalances, due to the mismatch between electricity demand and generation, which exacerbates the effects of so-called duck curves in demand profiles [2]. Consequently, it is essential to understand the capabilities and limitations of these power systems in being integrated into future flexible power grids [3].

Energy flexibility is defined as the ability of an energy system, device, or consumer to adjust its generation or consumption behaviour in response to external signals from the power grid, with the aim of enhancing grid stability [4]. Energy flexibility actions are primarily implemented through demand-side management strategies [5], which modify energy-use behaviours to shift consumption to periods of high electricity generation [6], and through the adoption of storage technologies, which enable the proper management of renewable electricity production without compromising grid stability [7]. The provision of energy flexibility can occur implicitly, when achieved through energy management strategies such as time-of-use pricing [8], or explicitly, when flexibility services are remunerated by the grid [9].

Modifying energy-use behaviour can be challenging due to the high unpredictability and stochastic nature of energy consumption [10]. For this reason, energy flexibility strategies based on the thermal demands of buildings – specifically space heating and cooling – represent a promising solution to provide flexibility to the power grid with minimal

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https://doi.org/10.1016/j.enconman.2026.121913

Available online 21 July 2026

Nomenclature

Acronyms

5GDHC	fifth-generation district heating and cooling
BEPS	building energy performance simulation tool
COPE	heat pump coefficient of performance
CS	cost saving ratio
DMI	downward modulation index
DSM	demand side management
HVAC	heating, ventilation and air conditioning
LF	heat pump load fraction
MPC	model predictive control
PCM	phase change material
PES	primary energy saving ratio
PV	photovoltaic system
PV-T	hybrid photovoltaic thermal system
SEF	shifted energy fraction index
SOC_b	state of charge of electrical battery
SOC_{TES}	state of charge of thermal energy storage
TES	thermal energy storage
UMI	upward modulation index

Symbols

A_{TES}	TES heat transfer surface area [m^2]
C_b	battery capacity [J, Wh]
C_{bldg}	building thermal capacity [J/K]
c_{el}	unit cost of electricity [€/kWh]
C_{TES}	TES maximum thermal capacity [J, Wh]
c_w	specific heat capacitance of water [J/kg/K]
$\dot{m}_v$	building ventilation air flowrate [kg/s]
$P_{b,in}$	stored electricity in battery [W]
$P_{b,out}$	discharged electricity from battery [W]
P_f	electricity consumption in flexible operation [W]
P_{HP}	heat pump electricity consumption [W]
P_r	electricity consumption in reference operation [W]
$Q_{c,max,HP}$	maximum cooling capacity of heat pump [W]
Q_f	thermal demand in flexible operation [W]
Q_g	buildings heat gains due to occupant, lights, and equipment [W]
$Q_{h,max,HP}$	maximum heating capacity of heat pump [W]
Q_{HVAC}	building thermal demand [W]
Q_r	thermal demand in reference operation [W]
Q_s	building heat gain due to solar irradiance [W]
$Q_{TES,in}$	TES stored thermal flux [W]
$Q_{TES,out}$	TES discharging thermal flux [W]
R_{wl}	thermal resistance of building internal wall [K/W]
t	time [s]
T_{5GDHC}	5GDHC water pipe network temperature [°C, K]
T_a	ambient temperature [°C, K]
T_{bldg}	indoor building temperature [°C, K]
T_r	return temperature from the building heating and cooling terminals [°C, K]
T_s	supply temperature to the building heating and cooling terminals [°C, K]
T_{set}	indoor setpoint [°C, K]
$T_{set,f}$	indoor setpoint in flexible operation [°C, K]
$T_{set,r}$	indoor setpoint in reference operation [°C, K]
T_{TES}	thermal energy storage temperature [°C, K]
T_{wl}	building internal wall surface temperature [°C, K]
U_{TES}	TES heat transfer coefficient [$W/m^2/K$]
V_{TES}	TES volume [m^3]

Greek

Δ	variation
η_g	power grid efficiency [-]
λ	time interval [h]
ρ_w	water density [m^3]

impact on occupants' energy needs and behaviours [11]. Such strategies exploit the thermal inertia of buildings to regulate energy loads while maintaining the required levels of thermal comfort [12]. Electrification of heating and cooling needs through heat pumps further enables energy flexibility for the power grid [13], and their potential can be enhanced when combined with solar-assisted systems [14], thermal energy storage [15], electrical batteries [16], or electric vehicles [17].

To address the challenges associated with the electrification of building thermal demands, low-temperature fifth-generation district heating and cooling systems (5GDHC) represent a key solution [18]. 5GDHC systems are inherently equipped with components that enable energy flexibility, including heat pumps, thermal energy storage, electrical batteries, and solar-assisted technologies [19]. Their capability to integrate these key technologies positions 5GDHC systems as an essential interface for enhancing the energy flexibility of large urban districts, enabling effective interaction between thermal demands and the electricity grid [20].

The following Section 1.1 presents a state-of-the-art review, examining recent advances in energy flexibility strategies and identifying the research gap in the use of 5GDHC systems as enablers of energy flexibility at the scale of large districts and cities.

1.1. State of the art and research gap

Recent research has focused on determining optimal technologies and operational strategies to implement demand-side management (DSM) strategies that support power grids in achieving energy flexibility and enhancing system stability.

Song et al. [21] demonstrated that building energy efficiency – considering enhanced thermal performance of the building envelope and efficient HVAC systems and energy-use equipment – represents a primary source to increase the flexibility potential of buildings. Their findings showed that during downward load modulation events requested by the grid, energy-efficient buildings can reduce electricity loads by up to 63% more than standard, non-efficient buildings. Lu et al. [22] investigated the potential of buildings' thermal mass for short-term flexibility events, reporting an average reduction of 8.0 Wh/m^2 (per unit of floor area) during downward load modulation events and an average increase of 23 Wh/m^2 during upward load modulation events. Similarly, Qureshi et al. [23] demonstrated that peak load shifting can be significantly enhanced when building envelopes are equipped with phase-change materials (PCM).

Supply-side strategies have also been explored. Behzadi et al. [24] proposed a combined solar-assisted heating system with PV modules, an electric boiler, and biomass-driven heaters. This configuration allowed proper supply-side flexibility: excess PV electricity could be injected into the grid when required, while the biomass-driven heater acted as a demand-side flexibility enabler, reducing grid reliance by 65%. Pan et al. [25] showed that combined solar heat, cooling, and power solutions, when integrated with demand-response strategies, can reduce costs by 16% and CO_2 emissions by 58% compared to designs without demand-response measures. However, these studies did not consider energy storage technologies, which play a key role in enhancing energy flexibility.

Cirocco et al [26] demonstrated that integrating latent heat storage with on-site PV systems and grid connections can improve electricity management by storing excess PV generation as thermal energy and purchasing electricity when prices are lower, facilitating flexibility provision and cost reductions for users. Li et al. [27] investigated the feasibility of integrating electrical batteries with PV systems to implement supply-side management strategies, showing that while batteries can reduce PV energy injections into the grid, high investment costs often make curtailment more economically viable unless PV generation exceeds 51% of total electricity consumption. Maturo et al. [28] studied hybrid photovoltaic-thermal (PV-T) modules coupled with PCM storage, showing that excess electricity and waste heat from PV-T during peak hours can significantly reduce building electricity loads, particularly during morning hours. Gradwohl et al. [29] highlighted the key role of heat pumps in energy flexibility, demonstrating that their size should be optimised to integrate efficiently with thermal energy storage and renewable sources, accounting for operational strategies driven by grid flexibility needs.

Algorithmic and control strategy development is another pivotal aspect. Turner et al. [30] developed a data-driven approach for replacing gas boilers with air-source heat pumps, demonstrating an average peak-demand reduction of 88% when proper load modulation strategies were planned in advance. Salgado-Bravo et al. [31] proposed a day-ahead demand-response scheme, showing that extended planning improves flexibility response accuracy. Chong et al. [32] optimised dynamic operational strategies to coordinate thermal, electrical, and hydrogen availability with building electricity demand to achieve optimal flexibility. Zhou et al. [33] developed a non-linear optimisation problem to maximise flexibility of PV systems coupled with electric vehicles. Cui et al. [34] developed demand-response strategies based on active and passive building thermal storage, showing that setpoint modulation exploiting building thermal mass and heat pump shutdown can provide effective flexibility. Chen et al. [35] demonstrated the importance of optimising DSM while considering constraints such as occupant comfort and economic feasibility. Doma et al. [36] proposed occupant-based control strategies, predicting occupancy profiles and behaviour on a day-ahead basis to implement model predictive control (MPC) for optimising HVAC operation and maximising flexibility potential.

DSM strategies show significant benefits when applied at the district or community scale. Jafarinejad et al. [37] demonstrated that indoor setpoint-based demand-response strategies can achieve 88% load-shifting and 69% peak-shaving efficiency across a cluster of 480 buildings, substantially impacting the local power grid. Luzzati et al. [38] compared flexibility performance of individual prosumers versus an energy community of 192 prosumers, showing that peer-to-peer energy sharing and a sense of community membership can enhance flexibility. Srithapon et al. [39] developed a home energy management system using MPC to coordinate electric vehicle charging/discharging with heat pumps and thermal energy storage, demonstrating significant energy flexibility potential through user cooperation.

In the context of district heating and cooling systems, research has primarily focused on centralised solutions, often overlooking the flexibility of thermal demand at the building level. For example, Du et al. [40] integrated a central PCM thermal storage to provide flexibility to a district heating network, optimising the strategy through linear programming and achieving an 11% peak demand reduction and a 0.3% decrease in price-responsive heating costs.

The literature indicates that DSM strategies at the single-building level have high potential for providing flexibility to the grid. Heat pumps are critical for enabling interaction between thermal and electrical energy vectors. Expanding DSM strategies to large districts, cities, and energy community frameworks can significantly enhance flexibility impacts. However, a key research gap remains while some studies examine the flexibility potential of district heating and cooling systems, they are generally limited to thermal flexibility and cannot provide direct electrical flexibility to the grid. 5GDHC systems, with their ability to interface building thermal demands to the electricity grid via heat pumps, represent a promising solution, but studies investigating DSM strategies specifically within 5GDHC systems remain scarce.

1.2. Objectives and contributions of the study

Unlike existing literature that predominantly evaluates low-temperature networks as isolated thermal entities, this work explicitly addresses the under-examined multi-energy interface between district assets and macroscopic power grid stability constraints. Building on the identified research gaps, this study aims to evaluate the potential of 5GDHC systems in providing energy flexibility to the power grid. The main objectives of the study are as follows:

- Assessment of demand-side management strategies, evaluating the impact of different flexibility strategies on both individual 5GDHC building users and the overall system. The strategies include indoor setpoint modulation, integration of thermal energy storage (TES) with heat pumps to manage building thermal loads, and integration of electrical batteries with heat pumps to manage electricity consumption. These strategies are designed to support downward and upward load modulation as well as load shifting, contributing to the provision of energy flexibility.
- Assessment of 5GDHC system configurations, investigating the influence of various 5GDHC network configurations on flexibility performance. The configurations analysed include: (1) thermal balancing of the water pipe network via vertical probes exchanging heat with the ground; (2) thermal balancing through a groundwater source; (3) thermal balancing using a solar-assisted system characterised by a central reversible air-to-water heat pump powered by PV modules.
- Assessment of energy and economic performance, quantifying the impact of demand-side management strategies on the energy and economic performance of the 5GDHC system. This includes evaluating primary energy consumption and operating cost variations for individual buildings and the overall system, compared to reference operations without flexibility strategies.

To achieve these objectives, the study develops a physics-based modelling framework that integrates: the dynamic thermal demand calculation of building users, heat pump performance modelling, and the energy modelling of TES tank and electrical battery systems. Rule-based control algorithms for implementing the proposed flexibility strategies at the user level are also developed. The study further introduces flexibility indices to quantitatively assess system performance and conducts a correlation-based analysis to evaluate the influence of flexibility strategies and 5GDHC configurations on both energy and economic outcomes.

The structure of this work is organised as follows. Section 2 presents the methodology, including the case study description, the modelling framework of the 5GDHC system, the implemented demand-side management strategies, the simulation setup and analysed scenarios. Section 3 presents the results, including the dynamic performance of the flexibility strategies, the yearly energy flexibility assessment, and the energy and operating cost analysis. Finally, Section 4 discusses the key findings, highlights the implications for 5GDHC systems in providing energy flexibility, and draws conclusions on the potential of these systems to support future flexible power grids.

2. Methods

This study defines a methodology to assess the potential of 5GDHC systems to provide energy flexibility to the power grid. The 5GDHC architecture promotes the electrification of building thermal demands in urban areas through water-to-water heat pumps installed at building thermal substations. These heat pumps are interfaced, on the source side, with the 5GDHC water pipe network and, on the load side, with the building heating and cooling terminals. This configuration enables a multi-energy interaction between the thermal and electrical domains, allowing 5GDHC systems to actively participate in demand-side flexibility provision.

Within this framework, this study investigates how 5GDHC systems can provide demand-side energy flexibility to the power grid. Flexibility may be required for downward modulation of electricity demand during periods of low renewable generation, in order to limit the activation of fossil fuel-based power plants. Conversely, upward modulation of electricity demand may be required when renewable electricity production exceeds demand, in order to avoid electricity curtailment or dissipation. The combined application of downward and upward demand-side management strategies enables load shifting, with the shifted energy defined as the minimum between the total energy reduced during downward modulation and the total energy increased during upward modulation over a defined time horizon, such as a one-day period.

A schematic representation of the methodology developed in this study is shown in Fig. 1. The figure summarises the overall framework, highlighting the adopted system modelling approach, the analysed 5GDHC system configurations, the proposed demand-side flexibility strategies, and the performance assessment methodology. The latter includes the definition of flexibility metrics and the evaluation of the impact of flexibility strategies on the energy and operating cost performance of the 5GDHC system.

A physics-based model of the buildings connected to the 5GDHC system is implemented to enable a detailed prediction of thermal energy demands for both heating and cooling. The performance of the building heat pumps is evaluated as a function of the operating temperatures at the source and sink sides, as well as of the partial load operation ratio. Thermal energy storage (TES) systems and electrical batteries are modelled using energy balance-based approaches.

To assess the energy flexibility potential of 5GDHC systems, three different system configurations are analysed, depending on the thermal balancing strategy adopted for the water pipe network. These configurations include thermal balancing through underground soil (denoted as 5GDHC configuration #1), through a groundwater source (denoted as 5GDHC configuration #2), and through a solar-assisted central heat pump powered by PV modules (denoted as 5GDHC configuration #3).

The demand-side management strategies analysed for energy flexibility provision include four different building user configurations and associated flexibility strategies. These consist of indoor temperature setpoint modulation of ±1 °C for space heating and cooling reduction or increase (denoted as flexibility strategy #1), indoor temperature setpoint modulation of ±2 °C (denoted as flexibility strategy #2), the integration of a TES tank within the building substations to store thermal energy when the building heat pump is operated for upward regulation of electricity demand or to supply thermal energy to the heating and cooling terminals during downward regulation (denoted as flexibility strategy #3), and the integration of an electrical battery system within the building substations to enable charging or discharging during periods requiring upward or downward electricity demand modulation (denoted as flexibility strategy #4).

The analysis is aimed at identifying demand-side algorithms and operational strategies that enable 5GDHC systems to provide energy flexibility across different building user configurations and network layouts. Performance assessment is conducted through the introduction of flexibility indicators, namely the downward modulation index (DMI), the upward modulation index (UMI), and the shifted energy fraction (SEF). In addition, the impact of the proposed flexibility strategies on the primary energy performance of the overall 5GDHC system and on the resulting operating costs for building users is evaluated.

2.1. System modelling and main assumptions

This section presents the modelling of the key components of the 5GDHC system. The configuration of 5GDHC users is characterised by the building, defined by its space heating and cooling demand, and by a thermal substation. The thermal substation consists of a water-to-water heat pump that supplies heating or cooling to the building terminals to meet the thermal demand, while rejecting excess process heat during cooling mode or excess cooling during heating mode to the 5GDHC water pipe network. For the purpose of investigating the energy flexibility potential of 5GDHC systems, the integration of TES tank and electrical battery systems at the building level is also considered.

Space heating and cooling demands are predicted using the experimentally-validated building energy performance simulation (BEPS) tool DETECt [41]. The tool is based on a finite-difference numerical scheme and adopts a one-dimensional formulation of heat transfer, modelling the building envelope and indoor space through a distributed high-order resistive-capacitive (RC) thermal network. The RC network is governed by the following differential equation, in which the thermal capacity of the indoor air node of the building (C_{bldg}) interacts with the main thermal power fluxes influencing the indoor air temperature (T_{bldg}):

$$C_{\mathrm{bldg}}\frac{dT_{\mathrm{bldg}}}{dt}=\sum_{i=1}^{N_{\mathrm{wl}}}\frac{T_{\mathrm{wl,i}}-T_{\mathrm{bldg}}}{R_{\mathrm{wl,i}}}+\dot{Q}_{\mathrm{s}}+\dot{Q}_{\mathrm{g}}+\dot{m}_{\mathrm{v}}c_{\mathrm{p,a}}\left(T_{\mathrm{a}}-T_{\mathrm{bldg}}\right)\pm\dot{Q}_{\mathrm{HVAC}} \quad (1)$$

where the ratio between the temperature difference of the i-th internal wall surface ($T_{\mathrm{wl,i}}$) and T_{bldg}, and the thermal resistance of the corresponding wall element ($R_{\mathrm{wl,i}}$), accounts for heat transfer through the building envelope [42]. The heat gains due to transmitted solar irradiance (Q_{s}) and internal sources, including occupants, lighting, and equipment (Q_{g}), are also included. The ventilation-related thermal load depends on the mass flow rate of incoming outdoor air ($\dot{m}_{\mathrm{v}}$) and the outdoor ambient temperature (T_{a}). The thermal power required for space heating or cooling (Q_{HVAC}) compensates for the combined thermal fluxes acting on the indoor zone and restores T_{bldg} to the desired setpoint temperature.

To perform the energy simulations, the BEPS tool requires climate data for the selected location, building geometry and orientation, thermo-physical properties of construction materials, internal heat gain schedules, air change rates, and temperature and humidity setpoint profiles.

The calculation of building space heating and cooling demands is required to determine the electricity consumption of the heat pumps serving the 5GDHC users under both the reference scenario and the scenarios governed by the proposed flexibility strategies. The performance of the water-to-water heat pumps is modelled through a polynomial fit of the coefficient of performance (COP), derived from experimental data collected during tests conducted on a small-scale 5GDHC system in our previous study [43]. The heat pumps integrated in the users' thermal substations are Aermec WRL041 units, tested under different operating conditions.

For heating mode operation, the experimental dataset is interpolated at a fixed sink-side temperature of 45 °C, required to satisfy space heating demand, while varying the source-side temperature corresponding to the 5GDHC network temperature (T_{5GDHC}) and the load fraction (LF). The load fraction is defined as the ratio between the required building heating demand (Q_{HVAC}) and the maximum heating capacity of the heat pump ($Q_{\mathrm{h,max,HP}}$). For cooling mode operation, the dataset is interpolated at a fixed source-side temperature of 7 °C to meet space cooling demand, while varying the sink-side temperature equal to T_{5GDHC} and the load fraction, defined as the ratio between the required cooling demand and the maximum cooling capacity of the heat pump ($Q_{\mathrm{c,max,HP}}$). The resulting COP is expressed as:

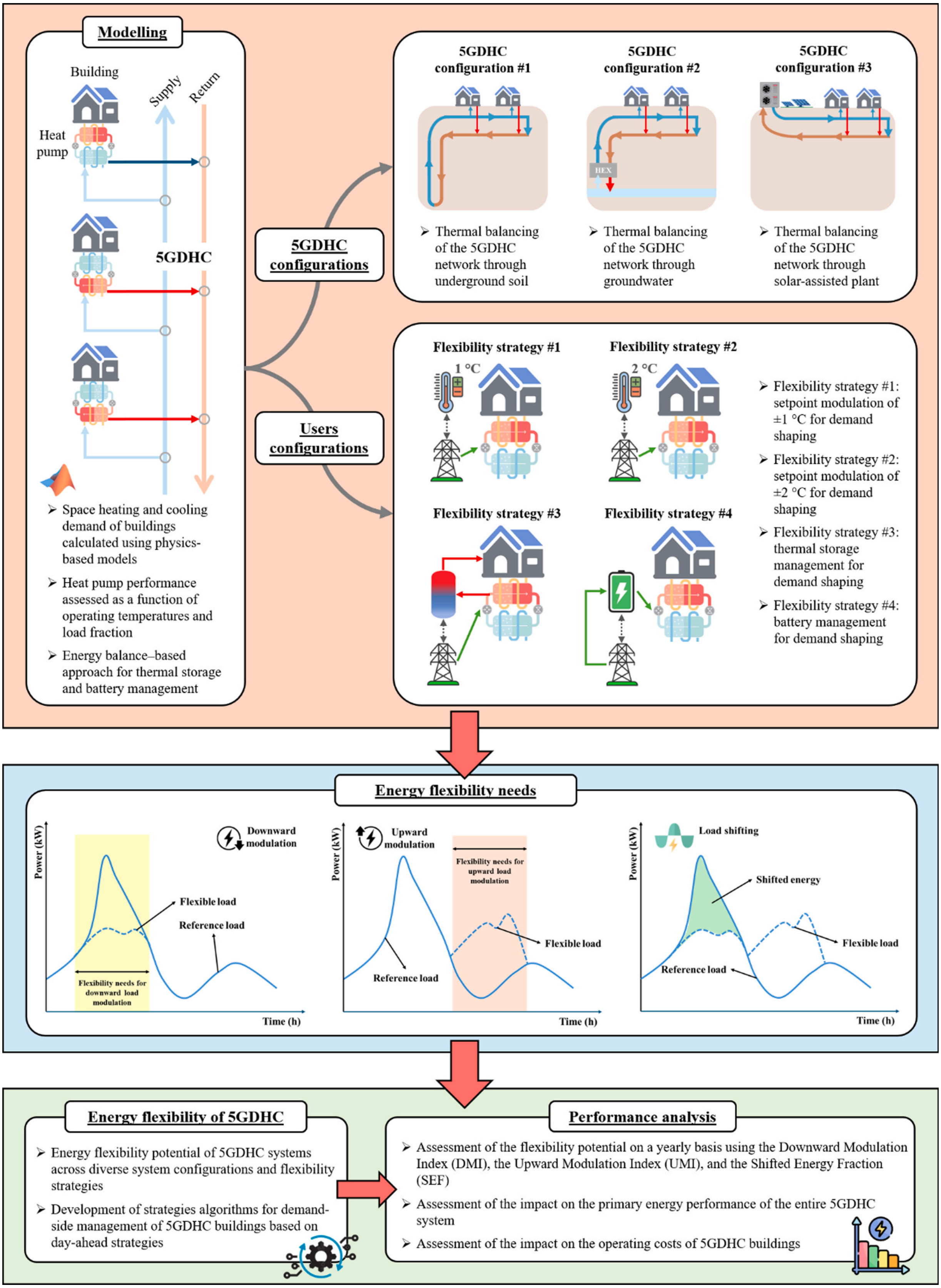

Fig. 1. Methodology schematisation. Demand-side flexibility strategies: indoor temperature setpoint modulation, thermal energy storage and electrical battery management. These strategies are analysed across different 5GDHC configurations, characterised by thermal balancing of the network through underground soil, groundwater, or a solar-assisted heat pump.

$$\mathrm{COP} = \begin{cases} f\left(T_{5GDHC}, \mathrm{LF} = \dfrac{\dot{Q}_{HVAC}}{\dot{Q}_{h,max,HP}}\right) \rightarrow \text{heating mode} \\ f\left(T_{5GDHC}, \mathrm{LF} = \dfrac{\dot{Q}_{HVAC}}{\dot{Q}_{c,max,HP}}\right) \rightarrow \text{cooling mode} \end{cases} \quad (2)$$

The corresponding electricity consumption of the heat pump (P_{HP}) is calculated as:

$$P_{HP} = \dot{Q}_{HVAC}/\mathrm{COP} \quad (3)$$

The thermal energy storage system is modelled using the following energy balance equation solved in the transient regime to evaluate the temporal evolution of the TES tank temperature (T_{TES}) [44]:

$$\rho_w c_w V_{TES} \frac{dT_{TES}}{dt} = \dot{Q}_{TES,in} - \dot{Q}_{TES,out} - U_{TES} A_{TES} (T_{TES} - T_a) \quad (4)$$

where ρ_w and c_w represent the density and specific heat capacity of the water stored in the TES volume, while V_{TES} denotes the storage volume. The temperature evolution of the TES tank is governed by the convective thermal fluxes associated with charging ($Q_{TES,in}$) and discharging ($Q_{TES,out}$) processes, as well as by heat losses to the surrounding environment. The latter are modelled through the heat transfer coefficient of the TES shell (U_{TES}), the heat transfer surface area of the storage (A_{TES}), and the temperature difference between T_{TES} and T_a.

The state of charge of the thermal energy storage (SOC_{TES}) is introduced to quantify the residual thermal capacity available for energy delivery or storage and is defined as:

$$SOC_{TES}(t) = \rho_w c_w V_{TES} T_{TES}(t)/C_{TES} \quad (5)$$

where SOC_{TES} at time t is given by the ratio between the thermal energy stored at the same time instant and the maximum thermal capacity of the TES tank (C_{TES}). The TES tank thermal capacity is calculated as:

$$C_{TES} = \rho_w c_w V_{TES} |T_s - T_r| \quad (6)$$

where C_{TES} is proportional to the absolute temperature difference between the supply temperature (T_s), equal to 45 °C for heating and 7 °C for cooling, and the return temperature (T_r) from the building terminals, equal to 25 °C for heating and 12 °C for cooling.

The modelling of the electrical battery system is based on an electricity balance that accounts for both stored and withdrawn electrical energy. The state of charge of the battery (SOC_b) is dynamically evaluated as:

$$SOC_b(t) = SOC_b(t-1) + P_{b,in}\Delta t/C_b - P_{b,out}\Delta t/C_b \quad (7)$$

where SOC_b at time t represents the fraction of energy stored relative to the nominal battery capacity (C_b) and depends on the SOC_b at the previous time step ($t-1$), the electrical energy charged into the battery ($P_{b,in} \bullet \Delta t$), and the electrical energy discharged to meet user demands ($P_{b,out} \bullet \Delta t$).

The modelling of the network pipes is based on a set of energy balance equations applied to each pipe section. These equations are solved to determine the transient temperature evolution of the water flowing through the network while accounting for heat exchange with the surrounding ground. The thermal behaviour of the pipes is represented using a lumped-parameter model operating under transient conditions, as expressed below:

$$\begin{cases} \rho_w c_{p,w} V_j \dfrac{dT_{w,j}}{dt} = \dot{m}_{w,j}(T_{w,j-1} - T_{w,j}) + \dot{Q}_{H,j} \\ \dot{Q}_{H,j} = \left[\left(\dfrac{1}{R_{k,w,j}} + \dfrac{1}{R_{c,w,j}}\right)^{-1} + R_{k,pip}\right]^{-1} (T_{soil} - T_{w,j}) \end{cases} \quad (8)$$

where ρ_w and $c_{p,w}$ denote the density and specific heat capacity of water respectively. T_w represents the temperature of the water volume of the j-th pipe portion (V_j). $T_{w,j-1}$ is the temperature of the back segment, and Q_H represents the heat dissipation due to conduction and convection of the water volume (where $R_{k,w}$, $R_{c,w}$ are the thermal resistances) and conduction with the wall of the pipe (where $R_{k,pip}$ is the thermal resistance), assuming the external surface temperature of the pipe wall to be equal to the soil temperature (T_{soil}).

The hydraulic behaviour of the network is not explicitly modelled. Therefore, pressure drops, flow distribution, bidirectional flow constraints, and the associated circulation pumping energy are neglected, as these effects are expected to have a limited influence on the comparative assessment of the investigated flexibility strategies.

As described in Section 2, three different 5GDHC configurations are analysed. In the first configuration, in which the network temperature is balanced through a heat exchanger coupled to a vertical ground probe, the supply temperature of the water pipe network is influenced by the ground soil temperature measured at the same depth as the vertical probe. In the second configuration, where the network is thermally balanced through a heat exchanger interfaced with a groundwater source, T_{5GDHC} follows the constant trend of the groundwater temperature. In the third configuration, which includes a solar-assisted thermal balancing unit based on a photovoltaic-driven central heat pump, it is assumed that the central heat pump operates during periods of electricity generation to control T_{5GDHC} at a reference value of 20 °C, identified as a compromise between heating and cooling operation of the users' heat pumps [45]. During periods without electricity generation, the network temperature is assumed to follow the ground soil temperature at the depth at which the water pipe network is installed.

These 5GDHC configurations can be framed as a comparison of alternative boundary temperature scenarios, where the dynamic temperature fluctuations along the network are explicitly considered through the thermal model of Equation (8). This approach enables a systematic evaluation of how distinct primary-side infrastructure choices influence the electrical load-shaping capacity of user-level demand-side management.

2.2. Demand-side management strategies

The flexibility strategies associated with the 5GDHC users' configurations introduced in Section 2 are based on the system modelling framework described in Section 2.1. These strategies focus on demand-side management approaches aimed at providing energy flexibility to the power grid through both upward and downward electricity load modulation. The flexibility strategies are implemented through a rule-based control framework, as this approach is highly robust and widely applied within complex district networks like 5GDHC. This avoids the reliance on optimised control strategies that could adopt simplified predictive models, which can affect the accurate representation of physical system constraints.

The proposed demand-side management strategies are grouped into two main categories. Flexibility strategies #1 and #2 are based on indoor temperature setpoint modulation of 1 °C and 2 °C, respectively, while flexibility strategies #3 and #4 rely on the management of energy storage systems, namely TES tank and electrical batteries.

A schematic representation of the algorithm developed to simulate flexibility strategies #1 and #2 is shown in Fig. 2. The main inputs of this algorithm are the reference indoor temperature setpoint under standard operating conditions ($T_{set,r}$), the setpoint variation adopted for load modulation (ΔT_{set}), which are fixed parameters, and T_{5GDHC}, which varies over time as a function of the analysed 5GDHC configuration. The time-dependent outputs of the algorithm include the resulting indoor temperature setpoint under flexible conditions ($T_{set,f}$), the corresponding building thermal demand resulting from the activation of the flexibility strategy (Q_f), LF, defined as the ratio between Q_f and the maximum heating or cooling capacity of the heat pump, the coefficient of performance of the heat pump under flexible operation (COP_f), and the resulting electricity consumption (P_f) shaped by the adopted flexibility

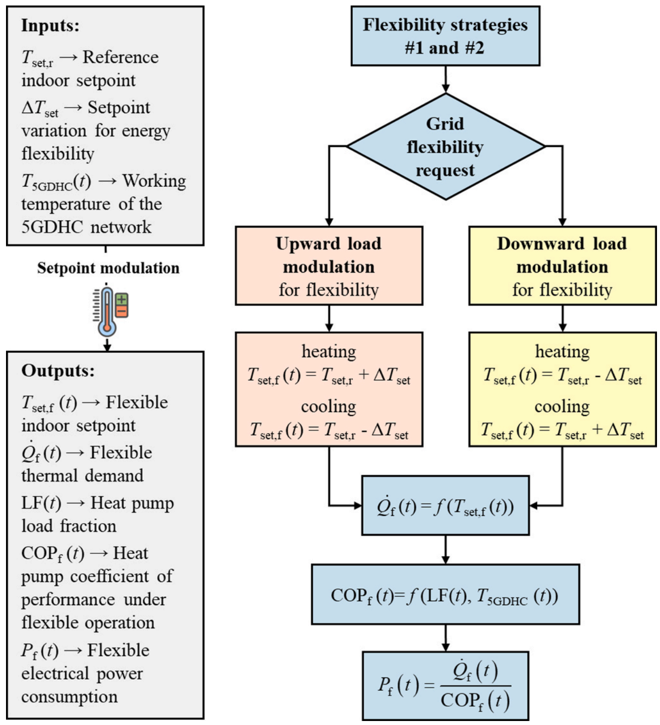

Fig. 2. Schematic representation of the algorithm implemented for flexibility strategies #1 and #2, based on indoor temperature setpoint modulation of ±1 °C and ±2 °C, respectively, for shaping the electricity demand of 5GDHC buildings in response to power grid flexibility requirements.

strategy.

As illustrated in Fig. 2, the algorithm first identifies the flexibility request from the power grid. When upward load modulation is required, an increase of the indoor temperature setpoint is applied during heating operation by 1 °C for flexibility strategy #1 and by 2 °C for flexibility strategy #2. Conversely, during cooling operation, a decrease of the indoor setpoint by the same ΔT_{set} values is applied. When downward load modulation is required, the opposite logic is adopted, with a decrease of the indoor setpoint during heating operation and an increase during cooling operation. Once the flexible indoor setpoint $T_{set,f}$ is defined, the resulting thermal demand Q_f at each time step is calculated using the building energy performance simulation tool described in Section 2.1. The corresponding COP_f is then evaluated using Equation (2) as a function of the updated load fraction and the value of T_{5GDHC} for the specific time step and 5GDHC configuration. Finally, the resulting electricity consumption P_f is determined according to Equation (3).

The algorithm adopted for the management of energy storage systems associated with flexibility strategies #3 and #4 is schematically presented in Fig. 3.

The main inputs of this algorithm include C_{TES} and C_b, SOC_{TES} – evaluated according to Equation (5) – and SOC_b – evaluated according to Equation (7) – T_{5GDHC}, the number of consecutive hours over which upward ($Flex_{up}$) or downward ($Flex_{down}$) load modulation is required, and the building thermal demand (Q_r) and associated heat pump electricity consumption (P_r) under reference operating conditions. The main outputs include $Q_{TES,in}$ and $P_{b,in}$ stored during upward load modulation, as well as $Q_{TES,out}$ and $P_{b,out}$ delivered during downward load modulation. For flexibility strategy #3 only, the resulting Q_f, LF, and COP_f are also evaluated, together with P_f.

As shown in Fig. 3, when upward load modulation is requested by the power grid, the algorithm first evaluates the availability of residual storage capacity, either thermal for flexibility strategy #3 or electrical for flexibility strategy #4. If residual capacity is available, the maximum amount of thermal energy $Q_{TES,in}$ or electrical energy $P_{b,in}$ that can be stored at the given time step is calculated. The charging fluxes are determined as the ratio between the residual storage capacity and the number of consecutive hours over which upward load modulation is required, starting from the specific time step. For flexibility strategy #3, Q_f is obtained as the sum of the reference thermal demand Q_r and $Q_{TES,in}$, and the corresponding electricity consumption P_f is evaluated accordingly. For flexibility strategy #4, the electricity consumption P_f providing upward flexibility is calculated as the sum of the reference electricity consumption P_r and the electricity stored in the battery $P_{b,in}$.

An analogous approach is adopted when downward load modulation is required. In this case, the availability of stored thermal energy or electrical energy is first assessed. The discharge fluxes of the TES tank and the electrical battery are defined as the ratio between the available storage capacity and the number of consecutive hours over which downward load modulation is required. For flexibility strategy #3, the resulting thermal demand Q_f is obtained as the difference between Q_r and $Q_{TES,out}$, and the corresponding electricity consumption P_f is calculated accordingly. For flexibility strategy #4, the electricity consumption P_f providing downward flexibility is determined as the difference between the reference electricity consumption P_r and the electricity discharged from the battery $P_{b,out}$.

The proposed demand-side management strategies are compared to evaluate the capability of 5GDHC systems to provide energy flexibility to the power grid. In Section 2.3, specific performance indices are introduced to quantify the flexibility potential in terms of downward load modulation, upward load modulation, and energy shifting.

2.3. Energy, flexibility, and operating cost performance indicators

The analysis carried out in this study aims to assess the energy flexibility potential of 5GDHC systems under different network layouts, thermal balancing configurations, and demand-side management strategies applied at the building level. Three distinct flexibility capabilities are evaluated, and three corresponding performance indices are introduced. These include load modulation for downward regulation, quantified through DMI; load modulation for upward regulation, quantified through UMI; and the capability of shifting electrical energy in response to power grid requirements, quantified through SEF.

The index used to assess downward load modulation, DMI, is defined as:

$$\mathrm{DMI} = 100 \times \left[1 - \left(\int_{\lambda} P_f(t)\mathrm{d}t \Big/ \int_{\lambda} P_r(t)\mathrm{d}t\right)_{\mathrm{down}}\right] \tag{9}$$

where DMI expresses the fraction of reduction in electricity consumption under flexible operation with respect to the reference operation, integrated over a given time interval λ, which may correspond to one hour or one day. The index is evaluated only during periods in which the power grid requires downward load modulation and varies between 0 and 100%.

The index used to assess upward load modulation, UMI, is defined as:

$$\mathrm{UMI} = 100 \times \left[\left(\int_{\lambda} P_f(t)\mathrm{d}t \Big/ \int_{\lambda} P_r(t)\mathrm{d}t\right)_{\mathrm{up}} - 1\right] \tag{10}$$

where UMI expresses the fraction of increase in electricity consumption under flexible operation with respect to the reference operation, integrated over the same time interval λ, during periods in which the power grid requires upward load modulation. Unlike DMI, UMI may exceed 100%, depending on the magnitude of the load increase enabled by the flexibility strategy.

The shifted energy fraction, SEF, is defined as:

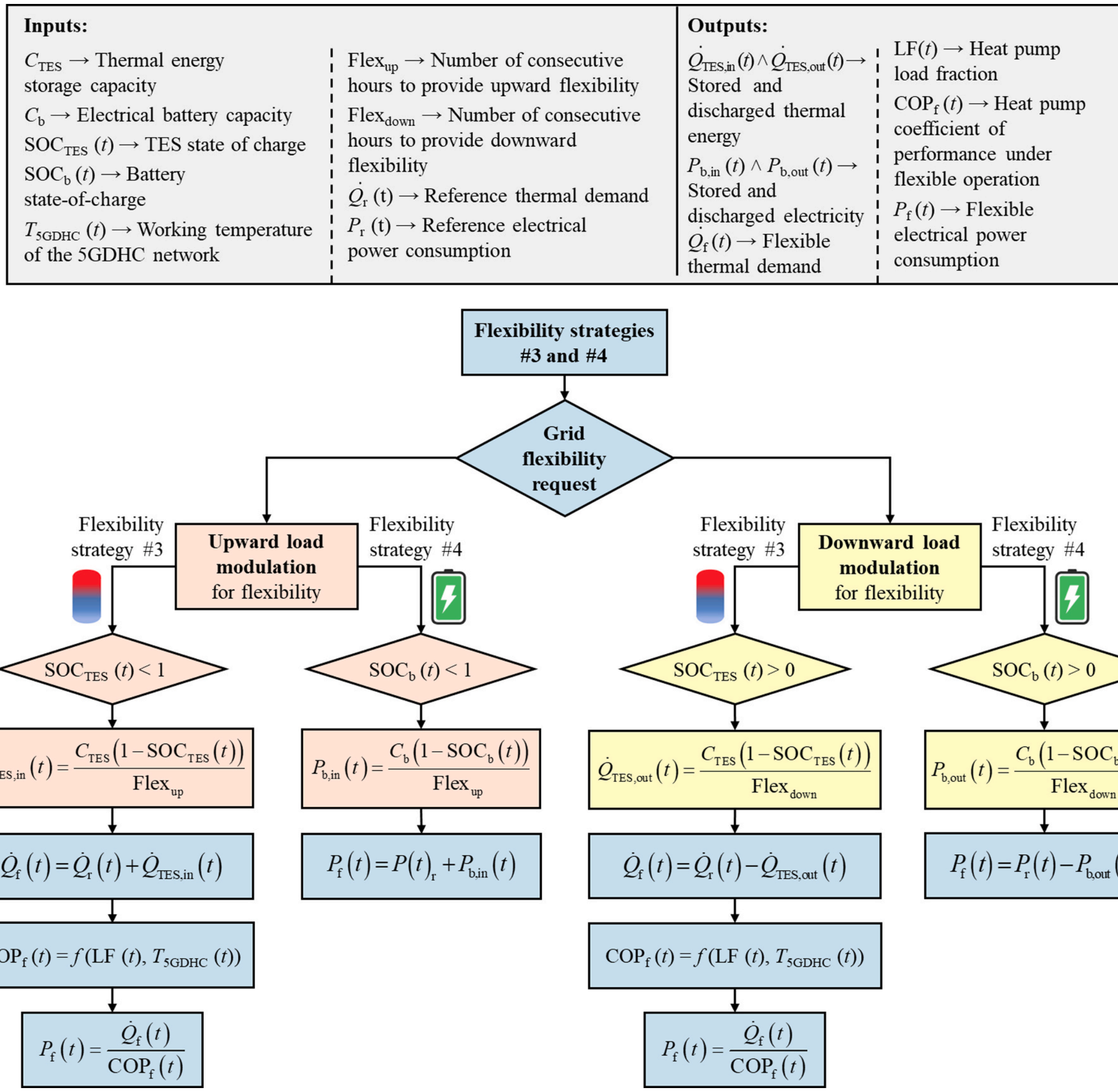

Fig. 3. Schematic representation of the algorithm implemented for flexibility strategies #3 and #4, based on TES tank and electrical battery management, respectively, for shaping the electricity demand of 5GDHC buildings in response to power grid flexibility requirements.

$$SEF = 100 \times \left[\frac{\min\left(\left(\int_\lambda P_f(t) - P_r(t)dt \right)_{up}; \left(\int_\lambda P_r(t) - P_f(t)dt \right)_{down} \right)}{\int_\lambda P_r(t)dt} \right] \tag{11}$$

where SEF represents the fraction of electrical energy shifted with respect to the electricity consumption under reference operation, integrated over the time interval λ. The index varies between 0 and 100%. The amount of shifted energy is determined as the minimum between the energy increased during upward load modulation events and the energy reduced during downward load modulation events, both evaluated over the same time interval λ.

In addition to flexibility performance, the analysis also evaluates the impact of the proposed strategies on the energy and operating cost performance of the 5GDHC system. From an energy perspective, the primary energy saving (PES) ratio is adopted and calculated as:

$$PES = 100 \times \left[1 - \left(\int_\lambda P_f(t)dt / \int_\lambda P_r(t)dt \right) / \eta_g(t) \right] \tag{12}$$

where η_g represents the conversion efficiency of the power grid, defined as the amount of primary energy required to produce one kilowatt-hour of electricity. The value of η_g is evaluated dynamically to account for variations in the electricity generation mix. The PES ratio quantifies the relative reduction or increases in primary energy consumption associated with flexible operation compared to reference operation, integrated over the time interval λ.

From an economic perspective, the operating cost saving ratio (CS) is used and defined as:

$$CS = 100 \times \left[1 - c_{el}(t) \left(\int_\lambda P_f(t)dt / \int_\lambda P_r(t)dt \right) \right] \tag{13}$$

where c_{el} denotes the dynamic unit cost of electricity per kilowatt-hour. The CS index quantifies the relative reduction or increases in the operating costs incurred by each 5GDHC building for electricity purchased from the grid under flexible operation compared to reference operation, integrated over the same time interval λ.

The economic analysis is limited to operational electricity costs under dynamic tariff conditions and does not account for investment costs, maintenance requirements, component degradation, replacement costs, or potential revenues from flexibility services. Consequently, the reported results should be interpreted as an assessment of short-term operational economic performance rather than a comprehensive life-cycle techno-economic evaluation of the investigated solutions.

2.4. Simulation framework

A simulation-based analysis is conducted to assess the potential of 5GDHC systems to provide energy flexibility services to the power grid. The analysis is based on a small-scale 5GDHC configuration inspired by the system implemented at the ENEA research centre located in Portici (Naples, Italy), previously presented in [43]. Although the reference system is derived from an existing infrastructure, the present study is entirely simulation-based and aims to explore alternative configurations and operational strategies to support the future implementation of flexibility-oriented control solutions.

The simulated 5GDHC network serves eight buildings within the research centre, as schematically illustrated in Fig. 4.

The main parameters adopted for the calculation of the buildings' thermal demand include geometric characteristics, thermophysical properties of the building envelope, internal heat gains from lighting, equipment and occupants, ventilation rates, and indoor temperature setpoints. These parameters are reported in Table 1.

The weather data required for the simulations are generated using Meteonorm 8, based on statistical climatic data derived from the previous 20 years for the location of Portici (Naples, Italy) [46].

The nominal capacities of the water-to-water heat pumps installed in the buildings' thermal substations are reported in Table 2. The same table also reports the sizes of the thermal energy storage systems and electrical batteries considered for the flexibility analysis. The sizing of both storage technologies follows a conservative criterion. Specifically, the TES volume is defined to accommodate the maximum daily thermal energy demand simulated over a one-year period, while the battery capacity is set equal to the maximum daily electricity demand simulated over the same period. This conservative sizing approach is intentionally adopted as a methodological baseline to establish an unconstrained thermodynamic scenario. By ensuring that the TES tank and battery capacities do not act as a physical capacity bottleneck during peak demand-side management events, the framework can effectively isolate and evaluate the maximum theoretical flexibility potential inherent to each control strategy. Consequently, the primary analytical focus is placed on assessing the comparative impacts of the operational logic and network configurations, rather than executing a component dimension optimisation.

In order to define the boundary conditions for the energy flexibility analysis, a criterion is introduced to identify time periods in which the power grid requires upward or downward load modulation. The proposed approach is based on a day-ahead assessment of the expected electricity production and electricity demand to be balanced by the power grid, with particular attention to the presence of excess electricity generation from renewable energy sources.

Periods characterised by excess renewable electricity production may require upward load modulation to avoid curtailment and energy dissipation. Conversely, periods without excess renewable production correspond to conditions in which downward load modulation may be beneficial to reduce reliance on fossil fuel-based generation technologies. Data on monitored and forecasted electricity production by source, electricity demand, and surplus generation are provided by the Italian transmission system operator (TERNA) [47]. On the basis of these data, time intervals requiring upward or downward flexibility are identified for the purposes of the proposed simulation. It should be noted that the adopted criterion does not represent the actual activation logic of ancillary service markets or system operator requests. Rather, it provides a simplified physical proxy based on grid surplus conditions, enabling a consistent assessment of the flexibility potential offered by the investigated 5GDHC configurations.

The hourly surplus electricity production of the Italian power grid for the year 2025 ($P_{sur,g}$) is shown in Fig. 5. Time intervals in which $P_{sur,g}$ is greater than zero correspond to conditions requiring upward load modulation, whereas intervals in which $P_{sur,g}$ is equal to zero correspond to conditions requiring downward load modulation. The corresponding hourly values of the power grid conversion efficiency (η_g), which are used for the assessment of primary energy consumption, are also reported in Fig. 5.

The dynamic electricity prices adopted for the operating cost analysis of the simulated 5GDHC building users are sourced from the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) [48].

It should be noted that due to the intrinsic case-specificity of district networks, adding further case studies cannot ensure universal representativeness. Consequently, the primary contribution of the conducted analysis lies in highlighting the scalability of the proposed methodological framework to assess the impact of diverse user-level flexibility strategies.

3. Results and discussion

This section presents the main results of the simulation-based analysis conducted on the 5GDHC system described in Section 2.4. The key findings focus on evaluating the performance of the proposed demand-side management strategies and their capability to dynamically shape the electricity load profile in response to power grid flexibility requirements. The effects of the different flexibility strategies on load modulation and energy shifting are discussed in Section 3.1. A yearly assessment of energy flexibility indicators and energy and operating cost

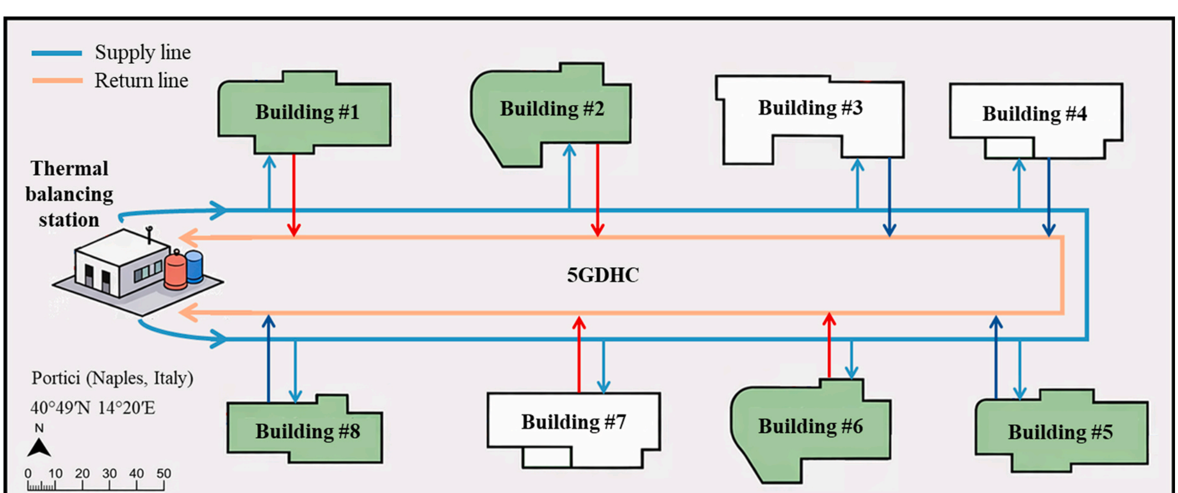

Fig. 4. Simulation framework: small-scale 5GDHC system serving the buildings of the ENEA research centre located in Portici (Naples, Italy).

Table 1
Main properties of the eight buildings considered in the simulation framework.

Building feature	Property	Unit	Building #1	#2	#3	#4	#5	#6	#7	#8
Geometry	Floor area	[m^2]	110	120	115	115	110	120	115	95
	Height	[m]	3.1							
	Windows-walls ratio	[%]	30	35	30	30	30	35	30	25
Thermal properties	Walls heat transfer coefficient	[W/m^{2}K]	0.33							
	Windows heat transfer coefficient	[W/m^{2}K]	1.3							
Heat gains	Lights	[W/m^2]	40	35	40	40	40	35	40	45
	Equipment	[W/m^2]	20	30	15	30	15	20	20	15
	Ventilation rate	[Vol/h]	0.60							
	Occupants' number	[-]	6	6	5	4	4	6	5	4
Setpoints	Heating	[°C]	20							
	Cooling	[°C]	26							

Table 2
Thermal substation components of the simulated buildings: heat pumps, thermal energy storage, and electrical batteries.

Component	Property	Unit	Building #1	#2	#3	#4	#5	#6	#7	#8
Heat pump	Heating capacity	[kW]	6.5	7.5	7.0	7.0	6.5	7.5	7.0	6.0
	Cooling capacity	[kW]	5.5	6.5	6.0	6.0	5.5	6.5	6.0	5.0
Thermal energy storage (TES)	Volume (V_{TES})	[m^3]	1.8	2.3	2.0	2.0	1.8	2.3	2.0	1.5
Battery	Electrical capacity (C_b)	[kWh]	6.0	7.0	6.5	6.5	6.0	7.0	6.5	6.0

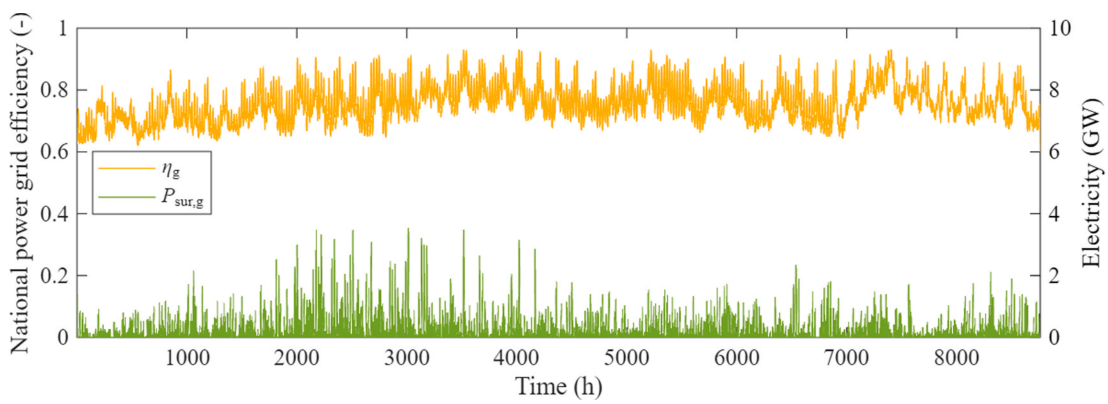

Fig. 5. Hourly energy data of the Italian power grid for the year 2025: power grid conversion efficiency (η_g) and excess electricity production ($P_{sur,g}$), used to identify periods requiring upward or downward load modulation.

performance is then carried out by comparing the proposed flexibility scenarios with the reference operation across the 5GDHC building users considered in the analysis. These results are presented and discussed in Section 3.2 and Section 3.3. Finally, Section 3.4 provides a critical discussion of the overall flexibility potential of 5GDHC systems and examines the implications of the proposed strategies on both energy performance and operating costs.

3.1. *Dynamic performance of demand-side management strategies*

This section presents the dynamic performance of the four proposed flexibility strategies. The analysis focuses on highlighting how the proposed strategies dynamically shape the reference electricity consumption of 5GDHC building users to meet power grid flexibility requirements through upward and downward load modulation, and on assessing the resulting flexibility performance over time.

Reference operating conditions correspond to the operation of the 5GDHC building users' thermal substations in the absence of indoor setpoint modulation and without the integration of energy storage systems. The dynamic results presented in this section refer to one representative building among the eight considered in the case study and to one 5GDHC configuration, namely 5GDHC configuration #1, in which thermal balancing of the water pipe network is achieved through underground soil vertical probes.

The dynamic behaviour is analysed for two representative operating days: a winter day with heat pump operation in heating mode (14 January) and a summer day with heat pump operation in cooling mode (14 July). These periods are selected to illustrate the flexibility performance under typical seasonal operating conditions.

The results associated with flexibility strategies #1 and #2, based on indoor setpoint modulation, are presented in Section 3.1.1. The results of flexibility strategy #3, characterised by the integration of TES tank, are discussed in Section 3.1.2, while the results of flexibility strategy #4, based on electrical battery integration, are presented in Section 3.1.3.

3.1.1. *Setpoint modulation*

The demand-side management strategies denoted as flexibility strategies #1 and #2, described in Section 2.2, shape the electricity consumption of 5GDHC building users through indoor setpoint modulation.

The dynamic performance of flexibility strategy #1 for one representative building of the eight analysed in the case study is illustrated in Fig. 6. These results highlight the impact of the strategy on the building thermal demand and electricity consumption during heating and cooling operations. Fig. 6(a) presents the dynamic thermal demand modification

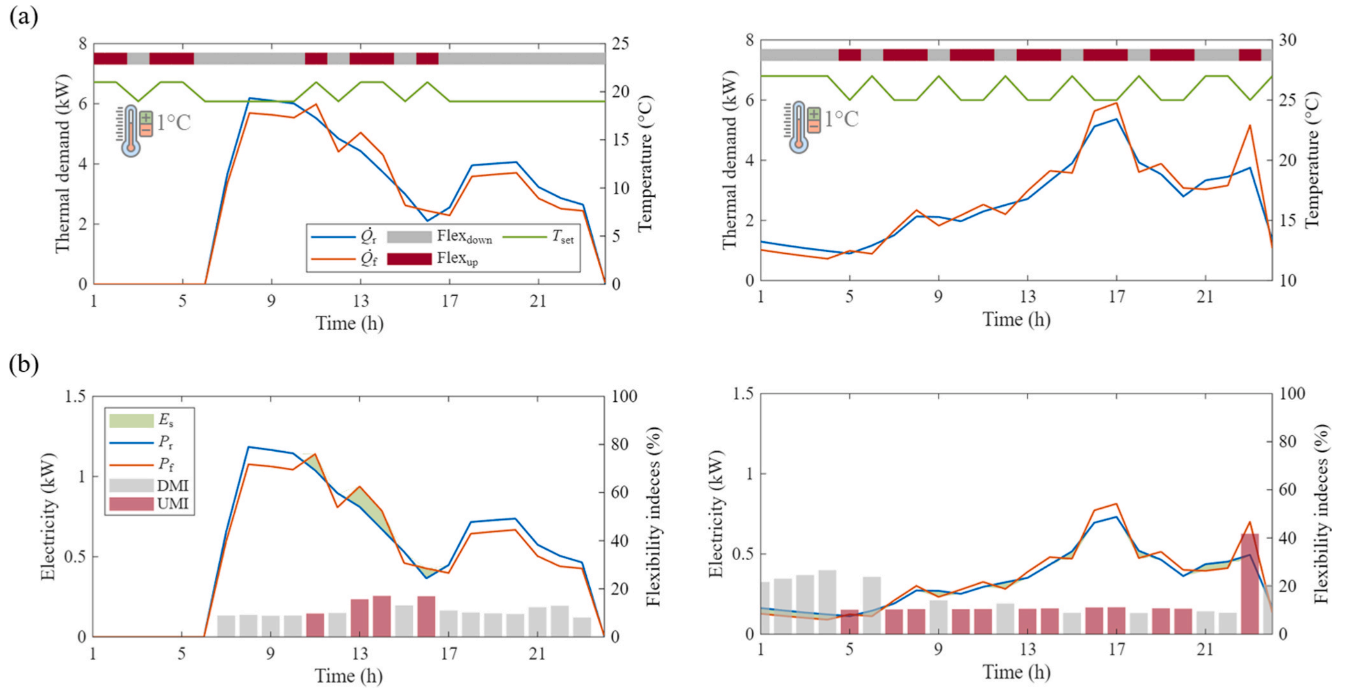

Fig. 6. Dynamic performance of flexibility strategy #1 (setpoint modulation of ±1 °C): (a) Thermal demand under reference scenario (Q_r), T_{set} modulated according to upward (red) and downward (grey) load modulation needs and resulting thermal demand under flexible operation (Q_f), for a winter day (left, 14 January) and a summer day (right, 14 July). (b) Reference and flexible electricity demand (P_r and P_f) with hourly DMI and UMI, and daily shifted energy (E_s) for a winter day (left) and a summer day (right).

resulting from a setpoint modulation of ±1 °C, with heating operation shown on the left and cooling operation on the right. When upward load modulation is required by the power grid (red bars in Fig. 6), the indoor setpoint (T_{set}) increases by 1 °C during heating and decreases by 1 °C during cooling. Consequently, the building thermal demand under flexible operation (Q_f) increases relative to the reference demand (Q_r) during these intervals. Conversely, during downward load modulation (grey bars), T_{set} decreases by 1 °C for heating and increases by 1 °C for cooling, resulting in Q_f being lower than Q_r.

The effect of flexibility strategy #1 on electricity consumption is

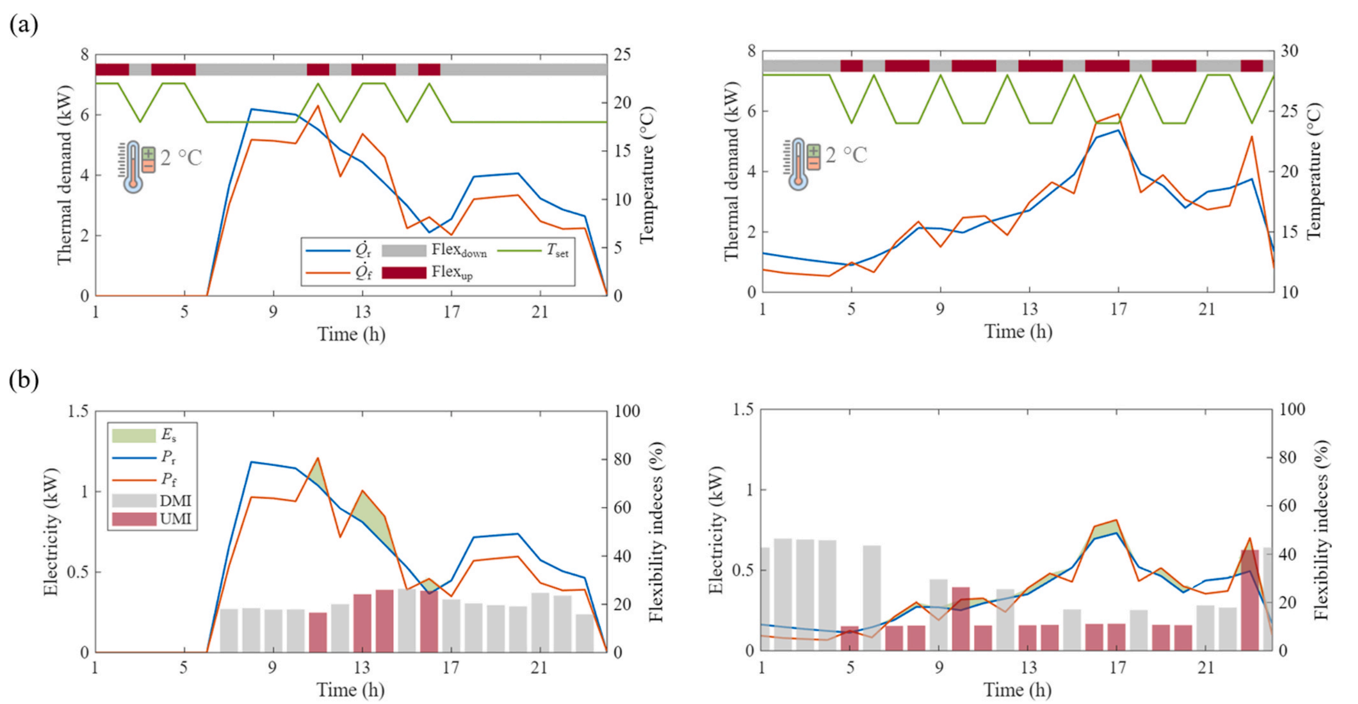

Fig. 7. Dynamic performance of flexibility strategy #2 (setpoint modulation of ±2 °C): (a) Thermal demand under reference scenario (Q_r), T_{set} modulated according to upward (red) and downward (grey) load modulation needs and resulting thermal demand under flexible operation (Q_f), for a winter day (left, 14 January) and a summer day (right, 14 July). (b) Reference and flexible electricity demand (P_r and P_f) with hourly DMI and UMI, and daily shifted energy (E_s) for a winter day (left) and a summer day (right).

shown in Fig. 6(b), with heating operation on the left and cooling on the right. The electricity consumption profiles under flexible (P_f) and reference (P_r) conditions are determined by the heat pump operation required to meet Q_f and Q_r, respectively. Hourly flexibility indices DMI and UMI, calculated from P_f and P_r, are also shown. For the winter day analysed (heating operation), hourly DMI ranges from 8% to 13% with a daily average of 10%, UMI ranges from 10% to 17% with a daily average of 12%, and the daily shifted energy (E_s) is 4% of the reference load. For the summer day (cooling operation), hourly DMI ranges from 9% to 26% with a daily average of 13%, UMI ranges from 10% to 39% with a daily average of 12%, and E_s equals 6% of the reference load. These results indicate a limited potential for load shifting when setpoint modulation is restricted to ±1 °C.

The same analysis was conducted for flexibility strategy #2, in which the indoor setpoint is modulated by ±2 °C. The differences between Q_f and Q_r under upward and downward load modulation is reported in Fig. 7(a), while the corresponding electricity consumption profiles are presented in Fig. 7(b). The larger setpoint modulation improves load-shaping performance, with greater increases and decreases of P_f compared to P_r during upward and downward modulation, respectively. For the winter day, hourly DMI ranges from 16% to 26% (daily average 20%), UMI ranges from 17% to 26% (daily average 18%), and E_s equals 5% of the reference load. For the summer day, hourly DMI ranges from 17% to 46% (daily average 26%), UMI ranges from 10% to 41% (daily average 13%), and E_s equals 9% of the reference load.

While flexibility strategy #2 achieves higher load-shaping potential compared to strategy #1, it also results in larger deviations from comfort setpoints (20 °C for heating and 26 °C for cooling), which may reduce occupant thermal comfort.

To quantify the effect of setpoint modulation on occupants' thermal comfort, a steady-state comfort boundary analysis was conducted based on ISO 7730 baselines (assuming 50% relative humidity, 0.1 m/s air velocity, and 1.2 met). While the ±1 °C modulation (strategy #1) maintains the predicted mean vote (PMV) within acceptable standard

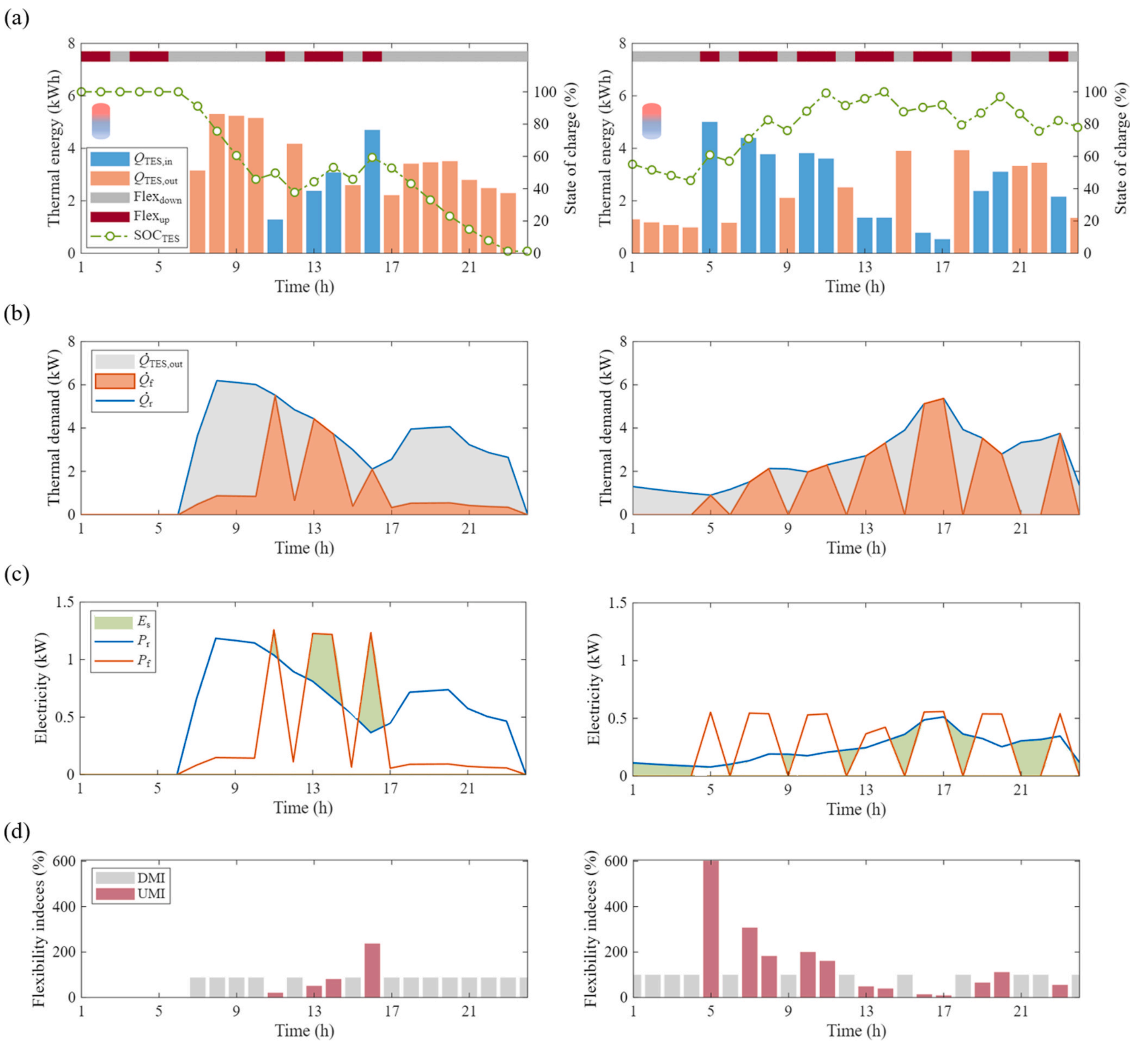

Fig. 8. Dynamic performance for a winter day (left, 14 January) and a summer day (right, 14 July) of flexibility strategy #3 with TES tank: (a) TES tank management with stored ($Q_{TES,in}$) and supplied thermal fluxes ($Q_{TES,out}$) according to upward (red) and downward (grey) load modulation needs;(b) reference and flexible thermal demand (Q_r and Q_f); (c) reference and flexible electricity demand (P_r and P_f) and daily shifted energy (E_s); (d) hourly flexibility indices DMI and UMI.

thresholds (PPD < 15%), the ±2 °C relaxation (strategy #2) transiently pushes the PMV to -1.0 in winter and +0.8 in summer during peak modulation events. This results in a short-term increase in the predicted percentage of dissatisfied (PPD) to approximately 22–27%, clearly defining the physical trade-off between grid flexibility and occupant thermal comfort thresholds.

3.1.2. Thermal energy storage

This section presents the dynamic performance of flexibility strategy #3, which integrates a TES tank in the building user thermal substation alongside the water-to-water heat pump. As described in Section 2.2, this strategy manages the TES tank such that, during upward load modulation needs of the power grid, the heat pump operates both to meet the building thermal demand and to store thermal energy, increasing electricity consumption relative to reference conditions. Conversely, during downward load modulation needs, the TES tank discharges to satisfy the building's thermal demand, reducing the heat pump operation and, consequently, electricity consumption compared to the reference scenario. The strategy dynamic performance is presented in Fig. 8.

The TES tank dynamic management is illustrated in Fig. 8(a), showing the hourly thermal fluxes stored ($Q_{TES,in}$) and delivered to the building ($Q_{TES,out}$), along with SOC_{TES}, for heating operation (left) and cooling operation (right). The results demonstrate how thermal energy stored during upward load modulation intervals is subsequently utilised to supply the building during periods of downward load modulation.

The resulting thermal demand under flexible operation is shown in Fig. 8(b). Unlike the previously analysed setpoint modulation strategies, the building's experienced thermal demand remains unchanged relative to reference conditions; however, the thermal demand seen by the heat pump varies. During downward load modulation, the heat pump meets a reduced thermal demand ($Q_f < Q_r$) because the TES tank provides part of the required heating or cooling ($Q_{TES,out}$). Conversely, during upward load modulation, the heat pump meets an increased thermal demand, given by the sum of Q_r and the thermal energy stored in the TES tank ($Q_{TES,in}$), thereby enabling electricity load increase.

These dynamics are reflected in the building heat pump electricity consumption (P_f), as shown in Fig. 8(c). Electricity consumption decreases during downward load modulation intervals and increases during upward load modulation compared to the reference profile (P_r).

The flexibility performance achieved with TES tank integration significantly surpasses that of setpoint modulation alone, as reported in Fig. 8(d). For the winter day with heating operation, hourly DMI remains constant at 88%, indicating high capability to reduce electricity consumption when required; UMI varies between 21% and 238%, with a daily performance of 71%; and the daily shifted energy (E_s) reaches 16% of the reference load. For the summer day with cooling operation, DMI achieves full flexibility at 100%, UMI ranges from 17% to 600%, with a daily performance of 92%, and E_s reaches 42% of the reference load.

The higher flexibility potential provided by TES tank integration is further supported by the ability to modulate electricity consumption without altering occupant comfort, unlike the setpoint modulation strategies (flexibility strategies #1 and #2). With this strategy the indoor air temperature remains strictly at the optimal reference values (20 °C in winter and 26 °C in summer). Consequently, the occupant PMV remains at its optimal baseline (*i.e.*, 0.5 in winter and +0.3 in summer),

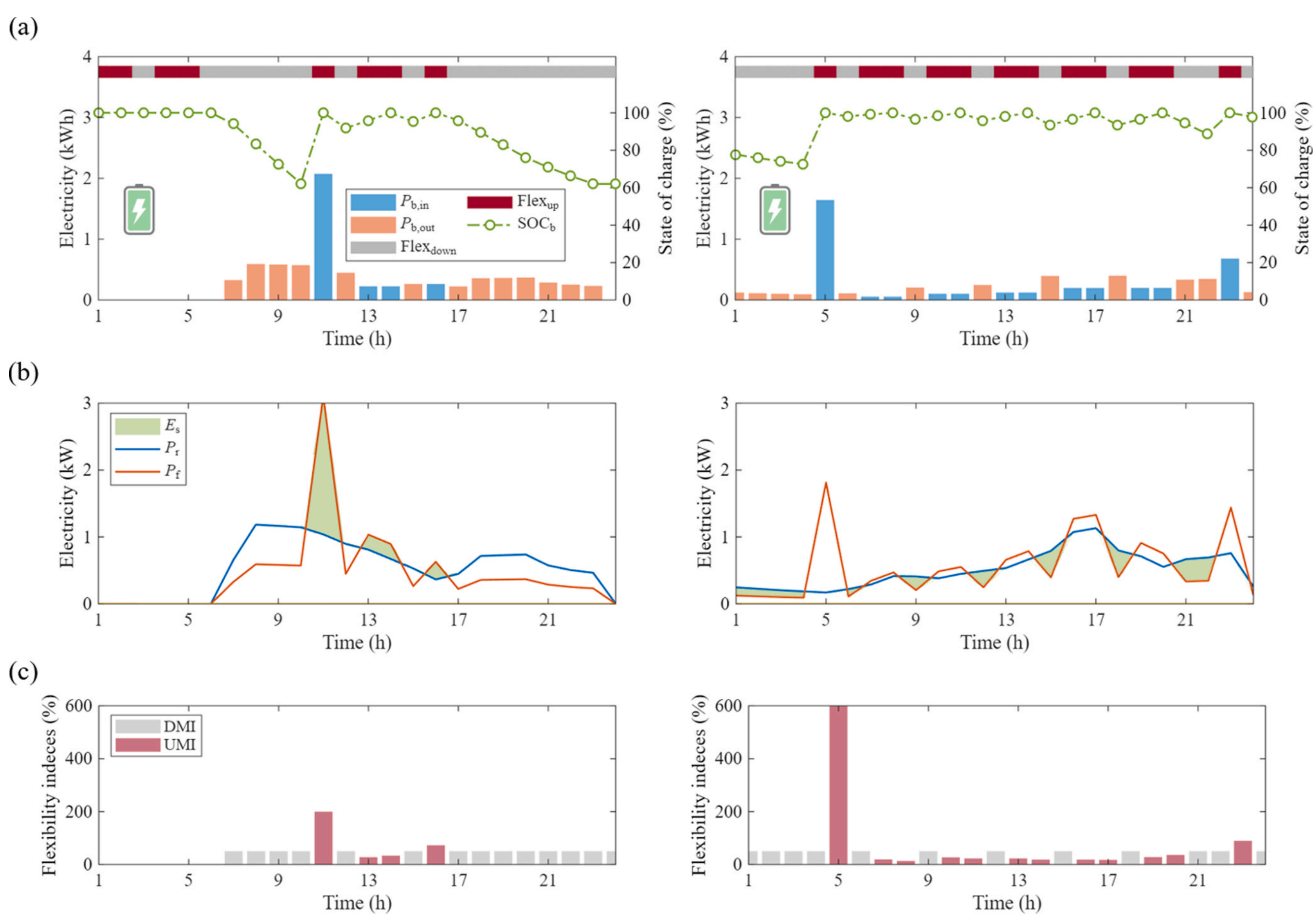

Fig. 9. Dynamic performance for a winter day (left, 14 January) and a summer day (right, 14 July) of flexibility strategy #4 with electrical battery: (a) battery management with stored ($P_{b,in}$) and supplied electricity ($P_{b,out}$) according to upward (red) and downward (grey) load modulation needs; (b) reference and flexible electricity demand (P_r and P_f) and daily shifted energy (E_s); (d) hourly flexibility indices DMI and UMI.

always keeping the PPD securely below 10%.

3.1.3. Electrical battery

The final demand-side management strategy, flexibility strategy #4, integrates an electrical battery into the 5GDHC building user's thermal substation alongside the heat pump of the reference configuration. The dynamic performance of this strategy is illustrated for the same building, 5GDHC configuration, and time periods as in Sections 3.1.1 and 3.1.2, as shown in Fig. 9.

The electrical battery operates to store electricity during upward load modulation requirements and to supply electricity during downward load modulation, thereby reducing the electricity consumption of the heat pump. This strategy follows the same principle as flexibility strategy #3, but without converting electricity into thermal energy.

The dynamic management of stored ($P_{b,in}$) and delivered electricity ($P_{b,out}$), alongside SOC_b, for heating operation (left) and cooling operation (right) are illustrated in Fig. 9(a). The resulting P_f compared to P_r is shown in Fig. 9(b).

The flexibility performance achieved with the electrical battery, reported in Fig. 9(d), surpasses that of setpoint modulation strategies presented in Section 3.1.1. For the winter day under heating operation, hourly DMI is constant at 53%, indicating a strong capability to reduce electricity consumption when required; UMI varies between 28% and 213%, with a daily performance of 96%; and the daily shifted energy (E_s) reaches 22% of the reference load. For the summer day under cooling operation, DMI achieves 50%; UMI ranges from 16% to 600%, with a daily performance of 51%; and E_s reaches 21% of the reference load.

Comparing flexibility strategies #3 and #4, the configuration with an electrical battery outperforms the TES configuration for the UMI and daily shifted energy fraction, particularly for the winter day under heating operation

3.2. Energy flexibility performance

A comparative analysis based on a one-year simulation of the case study presented in Section 2.4 was conducted to evaluate the overall energy flexibility performance of the 5GDHC system. This analysis accounts for all building users and combines the three 5GDHC configurations with the four demand-side management strategies described in Section 2.

The 5GDHC configurations are: (1) 5GDHC configuration #1 – thermal balancing of the water pipe network via heat exchange with ground soil through vertical probes; (2) 5GDHC configuration #2 – thermal balancing through heat exchange with a groundwater source at a fixed temperature; (3) 5GDHC configuration #3 – a solar-assisted heat pump system driven by PV modules to regulate the water flow temperature within the 5GDHC pipe network.

The four demand-side management strategies implemented to satisfy power grid flexibility requirements are: (1) flexibility strategy #1 – indoor setpoint modulation of ±1°C; (2) flexibility strategy #2 – indoor setpoint modulation of ±2°C; (3) flexibility strategy #3 – integration of TES tank in the building thermal substation, combined with the water-to-water heat pump; (4) flexibility strategy #4 – integration of an electrical battery with the building heat pump.

The heatmaps in Fig. 10 summarise the flexibility potential of the combinations of 5GDHC configurations and building flexibility strategies. The flexibility indices – DMI, UMI, and SEF – are calculated as described in Section 2.3 and provide the following information: DMI represents the fraction of yearly electricity consumption reduction during downward load modulation; UMI represents the fraction of yearly electricity consumption increase during upward load modulation; and SEF represents the fraction of shifted electricity consumption over the one-year simulation.

The setpoint modulation strategies (#1 and #2) achieved DMI values of 20% and 37%, UMI values of 18–19% and 25–26% across the three 5GDHC configurations, and SEF values of 9–10% and 15–16%, respectively. These results demonstrate that a moderate relaxation of thermal comfort constraints can improve the flexibility capability of 5GDHC building users, as reflected in the higher scores of flexibility strategy #2. The type of 5GDHC configuration has a negligible effect on these strategies, as indicated by the minimal variation in scores across configurations.

Flexibility strategy #4, integrating an electrical battery, outperforms the setpoint modulation strategies. DMI scores range from 48% to 51%, UMI scores from 57% to 60%, and SEF scores from 27% to 28%. For this strategy, the capability to reduce electricity consumption is intrinsically linked to the ability to increase it: the electricity reduction during downward load modulation relies on the electricity stored during upward load modulation, and the storage capacity therefore determines both aspects. Minor differences among the 5GDHC configurations are observed for this strategy.

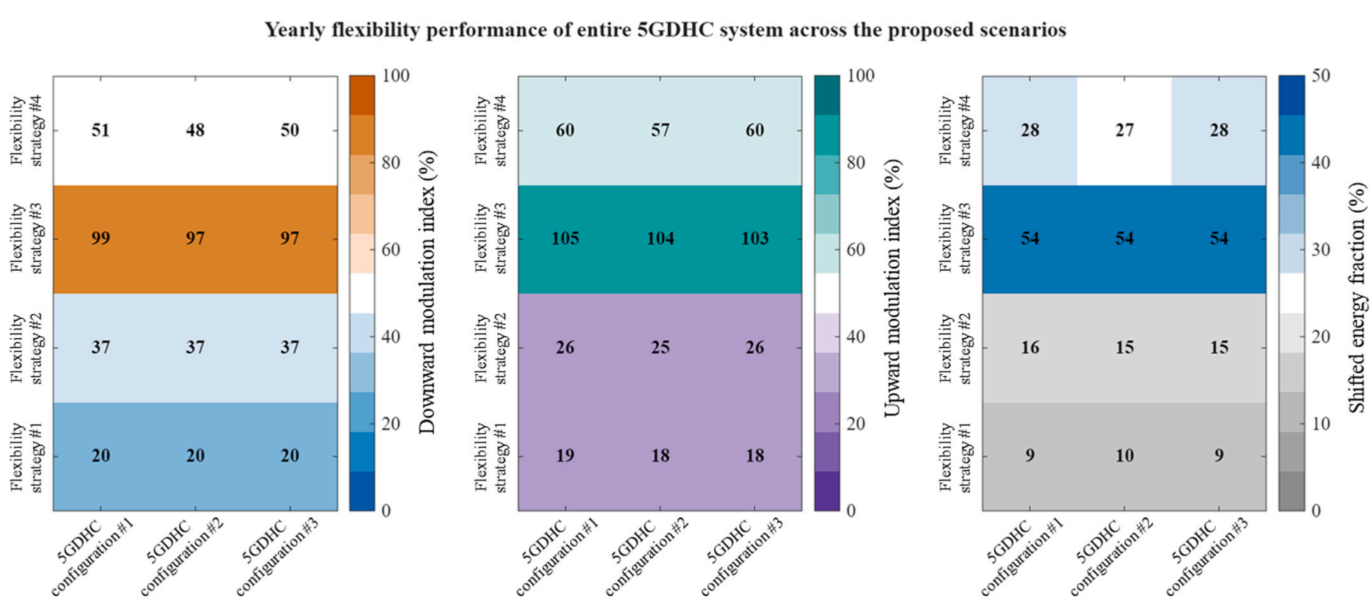

Fig. 10. Yearly flexibility performance of the 5GDHC system across three configurations and four demand-side management strategies, illustrating DMI, UMI, and SEF indices.

Flexibility strategy #3, employing a TES tank, achieves the highest performance among all scenarios, with DMI scores of 97–99%, UMI scores of 103–105%, and a SEF score of 54%. Similar to the battery strategy, the ability to reduce and shift electricity consumption is determined by the thermal energy stored during upward load modulation events. These results demonstrate that 5GDHC building users equipped with TES tank combined with heat pumps can almost completely modulate their electricity consumption during downward and upward load modulation events, while shifting approximately half of the yearly electricity demand of the entire 5GDHC system. This highlights the substantial energy flexibility potential of such integrated systems.

€Flexibility strategies #3 and #4 rely on energy storage systems, and both TES tank and batteries for the 5GDHC building users are sized according to the same criteria. However, the superior performance of flexibility strategy #3 compared to #4 can be explained by the conversion of the stored electricity into thermal energy through the building user heat pump. During downward load modulation events, a portion of the building's thermal demand can be supplied by the stored thermal energy, reducing the thermal demand seen by the heat pump under flexible operation. This partial load operation enhances heat pump efficiency by improving the COP, resulting in a further reduction in electricity consumption. Conversely, in flexibility strategy #4 with batteries, the thermal demand to be met by the heat pump remains unchanged from the reference scenario. The stored electricity is used solely to offset part of the heat pump's electricity consumption, and thus the same COP benefit observed with TES tank is not achieved.

Similarly, during upward load modulation, flexibility strategy #3 with TES tank increases electricity consumption to store excess thermal energy. The heat pump must balance both the building's thermal demand and the additional energy to be stored, which increases the load fraction and reduces operating efficiency, leading to a higher electricity consumption. By contrast, flexibility strategy #4 directly stores electricity to increase the electricity consumption profile while the heat

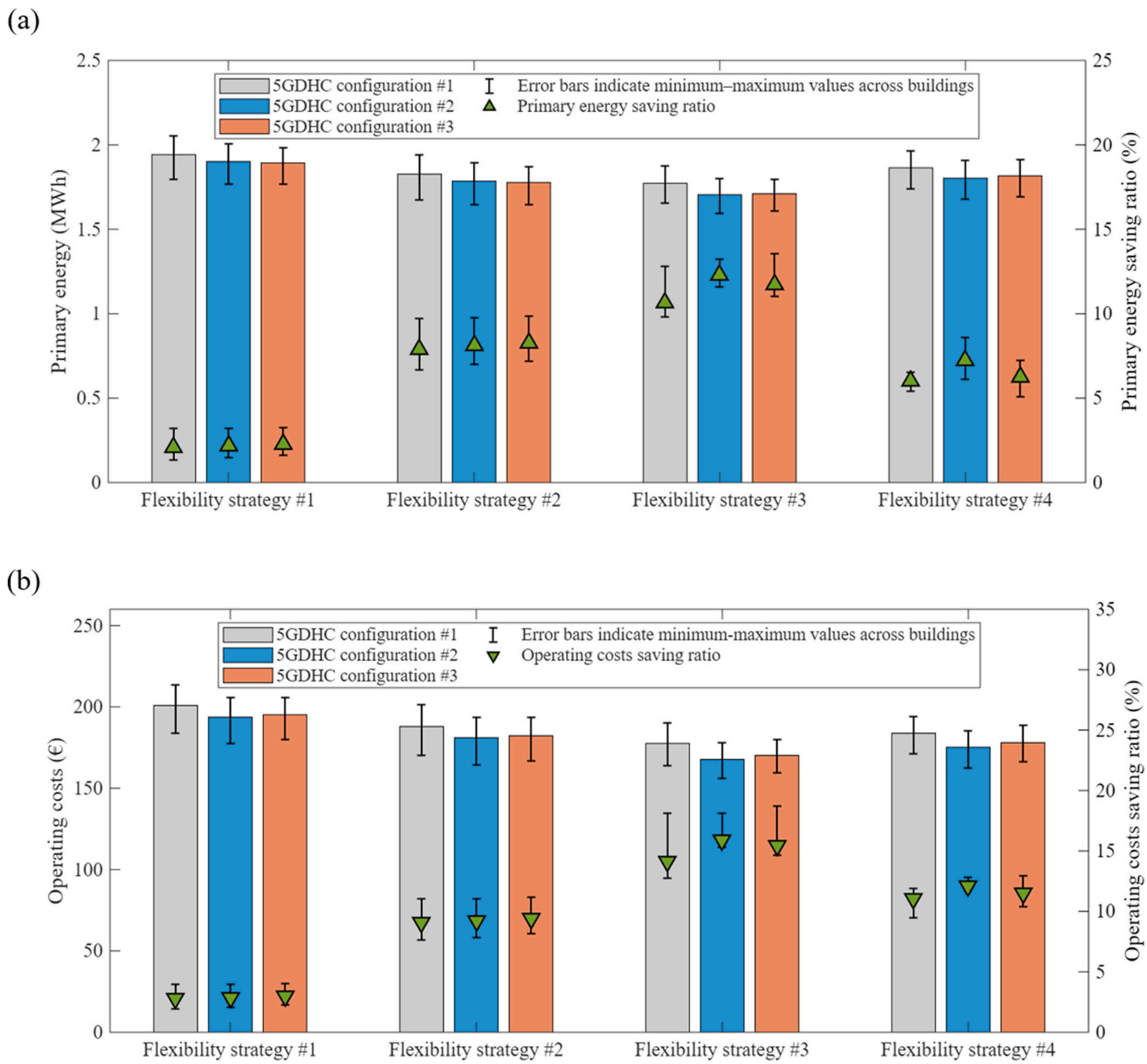

Fig. 11. Yearly energy and operating cost performance of 5GDHC building users across three configurations and four flexibility strategies: (a) average primary energy consumption and saving ratio with error bars indicating minimum–maximum values across buildings; (b) average operating costs and saving ratio with error bars indicating minimum–maximum values across buildings.

pump continues to operate under reference conditions, missing the additional effect of increased load on heat pump operation observed with TES.

3.3. Energy and operating cost performance

The flexibility performance analysis is complemented by an energy and operating cost assessment to evaluate the impact of the proposed strategies on primary energy consumption and operating costs across the combinations of 5GDHC configurations and flexibility strategies. The results are presented in Fig. 11, showing primary energy consumption in Fig. 11(a) and operating costs in Fig. 11(b).

Under 5GDHC configuration #1, the average primary energy consumption of the building users is: 2.0 MWh (deviation of +0.11 MWh and -0.14 MWh across the buildings) for the flexibility strategy #1; 1.8 MWh (deviation of +0.11 MWh and -0.15 MWh across the buildings) for the flexibility strategy #2; 1.7 MWh (deviation of +0.10 MWh and -0.11 MWh across the buildings) for the flexibility strategy #3; and 1.9 MWh (deviation of +0.10 MWh and -0.11 MWh across the buildings) for the flexibility strategy #4. The lowest primary energy consumption occurs with strategies #2 and #3. For strategy #2, this reduction is primarily due to thermal demand remodulation via setpoint regulation, whereas for strategy #3, TES tank management shifts energy consumption to periods of higher grid efficiency, coinciding with upward load modulation events. These results are corroborated by the associated primary energy saving ratios relative to reference operation: 2.1% (deviation of +1.1% and -0.8% across the buildings) for the flexibility strategy #1; 7.9% (deviation of +1.8% and -1.2% across the buildings) for the flexibility strategy #2; 11% (deviation of +2.1% and -0.80% across the buildings) for the flexibility strategy #3; 6.0% (deviation of +0.50% and -0.60% across the buildings) for the flexibility strategy #4.

Comparing the 5GDHC configurations, configuration #2 achieves reductions in primary energy consumption of 2.0%, 2.0%, 4.0%, and 3.5% for strategies #1, #2, #3, and #4, respectively, relative to configuration #1. Configuration #3 achieves reductions of 2.5%, 2.5%, 3.5%, and 3.0% for the same strategies. Moreover, for strategies #3 and #4, configurations #2 and #3 also provide higher primary energy saving ratios compared to configuration #1: strategy #3 reaches 13% and 12% for configurations #2 and #3, respectively, compared to 11% for configuration #1; strategy #4 reaches 7.5% and 6.5%, compared to 6.0% for configuration #1. These findings indicate that the type of 5GDHC configuration can contribute to additional relative improvements in primary energy reduction for some flexibility strategies, not only absolute savings.

Regarding operating costs, under configuration #1, the average annual costs of the building users are: 200 € (deviation of +12 € and -17 € across the buildings) for the flexibility strategy #1; 188 € (deviation of +13 € and -17 € across the buildings) for the flexibility strategy #2; 177 € (deviation of +12 € and -13 € across the buildings) for the flexibility strategy #3; and 183 € (deviation of +10 € and -12 € across the buildings) for the flexibility strategy #4. The lowest costs occur with strategies #3 and #4, reflecting the advantage of energy storage strategies in shifting electricity purchases to periods of lower unit cost. The associated operating cost saving ratios relative to reference operation are: 2.8% (deviation of +1.1% and -0.80% across the buildings) for the flexibility strategy #1; 9.0% (deviation of +1.9% and -1.4% across the buildings) for the flexibility strategy #2; 14% (deviation of +4.0% and -1.3% across the buildings) for the flexibility strategy #3; 11% (deviation of +0.80% and -1.6% across the buildings) for the flexibility strategy #4.

Comparing 5GDHC configurations, configuration #2 reduces operating costs by 3.5%, 3.7%, 5.6%, and 4.4% for strategies #1, #2, #3, and #4, respectively, relative to configuration #1. Configuration #3 achieves reductions of 3.0%, 3.5%, 5.0%, and 4.0% for the same strategies. These results highlight that both flexibility strategy selection and 5GDHC configuration can significantly influence the energy and operating cost performance of building users.

3.4. Discussion

This study aimed to demonstrate the potential of 5GDHC systems to provide energy flexibility to power grids. While previous research has explored flexibility strategies based on setpoint regulation and energy storage management (both thermal and electrical), the integration of these strategies into 5GDHC systems remains largely unexplored.

5GDHC systems represent a promising resource to enhance demand-side management for urban space heating and cooling. By promoting the electrification of thermal demands through heat pumps, 5GDHC systems enable the provision of energy flexibility to power grid infrastructures. Additionally, these systems improve the willingness of citizens to adopt electrified heating and cooling solutions by delivering higher energy efficiency and lower operating costs compared to traditional systems. Beyond individual benefits, 5GDHC systems support thermal energy community initiatives, facilitating energy sharing, providing incentives, and reducing costs, which can accelerate the transition towards the electrification of urban thermal demands. This work highlights the role 5GDHC systems can play in enhancing the flexibility of power grid operations.

Furthermore, in practical district-scale applications, rule-based control architectures remain the industry standard due to their computational robustness and reliable real-time execution. By contrast, more advanced predictive control approaches often rely on reduced-order representations of highly non-linear, transient thermodynamic systems with bidirectional flows, which may introduce model-mismatch errors and yield optimal solutions that are not fully representative of actual system behaviour. In this context, demonstrating that significant flexibility can be achieved through standard rule-based frameworks represents a particularly practical and scalable outcome for district operators.

Final remarks from the conducted analysis are summarised in Fig. 12, which relates the achieved energy flexibility to the total primary energy consumption of the 5GDHC system and to the operating costs of the building users across the investigated 5GDHC configurations and flexibility strategies. As illustrated in Fig. 12(a), increases in electricity shifting performance – moving from setpoint regulation strategies to strategies integrating electrical batteries or thermal energy storage – are accompanied by reductions in global primary energy consumption. Regression lines, correlating the results of each flexibility strategy for each 5GDHC configuration, further illustrate that configuration #2 (thermal balancing via a groundwater source) achieves the greatest primary energy savings for a given increase in energy flexibility. This is evidenced by the steeper slope and lower intercept of its regression line compared to configuration #1 (thermal balancing with ground soil) and configuration #3 (solar-assisted central heat pump).

A similar trend is observed in Fig. 12(b), where flexibility performance is correlated with average operating costs of the building users. Increasing the energy flexibility potential through the proposed strategies also results in reduced operating costs. Differences among the 5GDHC configurations are highlighted by the intercepts of the regression lines, with configuration #2 outperforming configurations #1 and #3. No differences are observed in the slopes, indicating that the reduction in operating costs with increasing flexibility is consistent across all configurations.

These results demonstrate that the proposed flexibility strategies not only improve the capacity of 5GDHC systems to provide energy flexibility to the power grid but also enhance the overall energy and economic performance of the buildings they serve. This underscores the significant role 5GDHC systems can play in supporting urban energy flexibility, promoting cost-effective and sustainable energy solutions for cities.

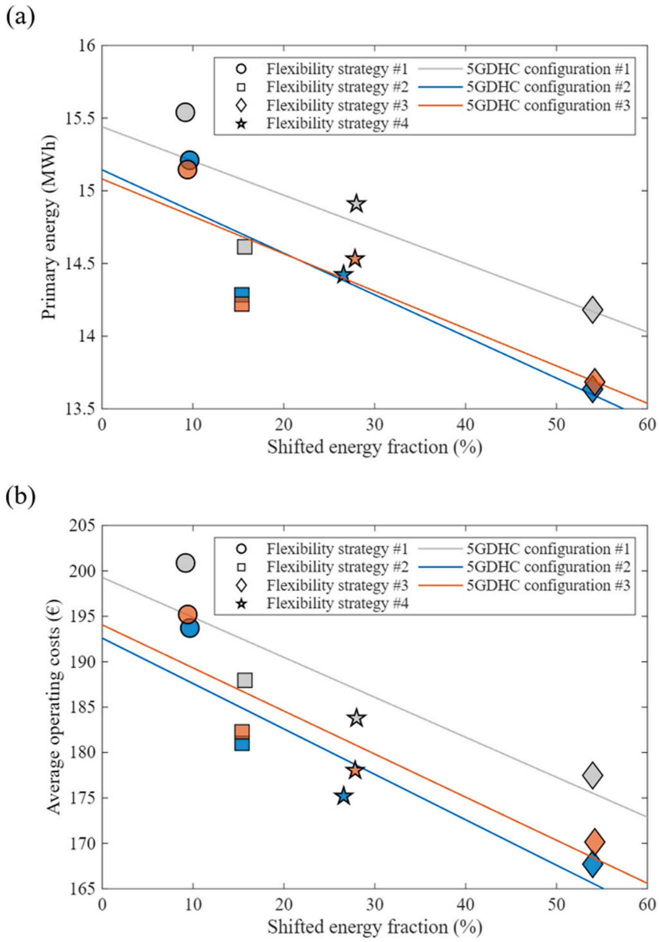

Fig. 12. Yearly energy-economic performance of 5GDHC building users across three configurations and four flexibility strategies: (a) correlation between shifted energy fraction (SEF) and total primary energy consumption of the 5GDHC system; (b) correlation between SEF and average operating costs of 5GDHC building users.

4. Conclusions

This study investigated the potential of 5GDHC systems to provide energy flexibility services to power grids with an increasing penetration of renewable energy sources. The primary objective was to evaluate how demand-side management strategies and alternative 5GDHC configurations can enhance flexibility provision while maintaining acceptable energy and economic performance at district scale. To achieve this objective, a physics-based dynamic modelling framework was developed, integrating building thermal demand calculation, heat pump performance modelling, and the representation of thermal energy storage and electrical batteries. The framework enables the simulation of user-level, flexibility-oriented control strategies and their interaction with the district network. Flexibility indices were introduced to quantify downward and upward load modulation (DMI and UMI indices) and load shifting capabilities (SEF index). In addition, a correlation-based analysis was conducted to assess the impact of flexibility strategies on primary energy consumption and operating costs.

The methodology was applied to a representative 5GDHC simulative case study located in Portici (Naples, Italy), comprising a small-scale district of multiple building users and three alternative thermal balancing configurations: ground-coupled, groundwater-based, and solar-assisted heat pump solutions. Although the analysis refers to a specific district configuration, the adopted modelling approach, control strategies, and performance indicators are general and can be extended to other urban and district-scale energy systems.

The results demonstrate that 5GDHC systems can provide a substantial contribution to power grid flexibility. Indoor temperature setpoint modulation enabled short-term flexibility provision, achieving electricity load reductions of 20% (±1 °C setpoint regulation) and 37% (±2 °C) during downward modulation events, and load increases of 19% (±1 °C) and 26% (±2 °C) during upward modulation periods. The integration of electrical batteries with heat pumps further enhanced flexibility, achieving load reductions of 51% during downward events and load increases of 60% during upward events. The highest flexibility performance was obtained through the integration of thermal energy storage with heat pumps, enabling load reductions of 99% during downward events and load increases of 105% during upward events. This superior performance is primarily attributed to the impact of thermal storage on heat pump operation, which allows reduced electricity consumption during downward events and increased electricity consumption during upward events, thereby amplifying the flexibility response.

The capability of shifting electricity consumption loads is confirmed by the SEF index values, which reached 10% and 16% for the ±1 °C and ±2 °C setpoint modulation strategies, respectively, 28% for the battery-based strategy, and 54% for the thermal energy storage strategy. The analysis further shows that the different 5GDHC configurations have a limited influence on the absolute flexibility potential of the proposed strategies, indicating that flexibility provision is mainly driven by control strategies and storage integration rather than by the thermal balancing solution itself.

The proposed flexibility strategies also impacted primary energy consumption and operating costs. Setpoint temperature modulation led to average primary energy saving ratios of 2.1% and 7.9% for ±1 °C and ±2 °C modulation, respectively, although these strategies introduce a potential reduction in occupants' thermal comfort. Conversely, the battery- and thermal-storage-based strategies do not affect comfort conditions and, by managing thermal and electrical energy flows according to grid requirements, achieved average primary energy savings of 6.0% and 11%, respectively. These trends are reflected in operating cost reductions, which reached 2.8% and 9% for ±1 °C and ±2 °C setpoint modulation, respectively, and 11% and 14% for the electrical battery and thermal energy storage strategies.

A regression-based analysis further clarifies the relationship between energy flexibility and system performance. The results show that the groundwater-based configuration achieves the highest primary energy savings for a given increase in flexibility, as indicated by steeper regression slopes and lower intercepts compared to the ground-coupled and solar-assisted configurations. Increasing flexibility is also consistently associated with reduced operating costs across all configurations, with similar regression slopes and differences mainly reflected in the intercepts. This indicates that while cost reductions scale similarly with flexibility, the absolute performance level depends on the selected 5GDHC configuration.

This simulative study, conducted on a specific small-scale district topology, indicates the significant potential of 5GDHC networks to act as localised flexibility enablers by linking user-level thermal demand with power grid needs. By combining demand-side management strategies, storage technologies, and renewable-based configurations, 5GDHC networks can support grid stability while simultaneously improving energy efficiency and reducing operating costs. The proposed modelling framework provides a robust tool to support the design and operation of flexible district energy systems and can inform planners and policymakers in the deployment of future low-carbon urban energy infrastructures.

CRediT authorship contribution statement

Giovanni Barone: Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation.

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

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.

Acknowledgement

The research has been co-founded by the Italian Ministry of Research through the HERA (Prot. 2022P7HAJF, CUP. E53D23003580006) "Holistic Energy Recovery Agent tool for sustainable urban clusters" project, within the PRIN 2022 program, Partenariato NEST "Network 4 Energy Sustainable Transition" - Spoke 6 Energy Storage, funded by EU - NextGenerationEU, MUR – M4C2 PNRR (ID PE0000021, CUP E13C22001890001) and the Italian National Project "Ricerca di Sistema Elettrico – PTR 25-27 – Progetto 1.5 Edifici ad alta efficienza per la transizione energetica". The authors want to thank the project colleagues for the constructive feedback and collaboration.

Data availability

Data will be made available on request.

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