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Assessing flexibility in networked multi-energy systems: A modelling and simulation-based approach

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ABSTRACT

In response to the uncertainty and volatility arising from renewable sources, there is a growing need for enhanced flexibility within the energy system to maintain a continuous balance between power generation and demand. In this context, interest is growing around the so-called Multi-Energy Systems (MES) where different energy vectors coexist and optimally interact through conversion technologies and energy networks, creating additional flexibility opportunities. Nevertheless, there exists a gap in research regarding the impact of the network on flexibility availability. Typically, these complex systems are treated as power nodes or energy hubs without comprehensive network considerations. For this reason, the paper aims to propose a methodology and a tool to evaluate flexibility in a Multi-Energy System, considering not only the individual devices in place and the users' demands but also their interactions with the physical energy network. In detail, a simulation-based methodology is developed and described, and finally tested on a Case Study. As a result, both the physical and operational flexibilities (UP-flex and DOWN-flex) of the system regarding the electrical vector were obtained analytically and graphically. Particular attention was given to the evolution of key temperatures within the district heating network and the thermal power produced by the central unit in various flexibility scenarios. The outcomes demonstrate the utility of this tool for defining flexibility boundaries and profiles, as well as for assessing whether the flexibility demanded by grid operators aligns with the physical constraints of the network.

Nomenclature

c_p Water specific heat [kJ/kgK].
d device.
DH District heating.
F_{ph} Physical flexibility.
$F_{op,UP}/F_{op,DOWN}$ Upward/Downward flexibility.
ϕ_A *and* ϕ_B Energy flowrates [kW].
GB Gas boiler.
GHG Greenhouse gases.
k_{HX} Pressure loss coefficient for heat exchangers.
$\dot{m}_A$ *and* $\dot{m}_B$ Water mass flowrates [kg/s].
MES Multi-energy system.
P_A *and* P_B Pressures [Pa].
P_{base} Baseline operating point [kW].
$P_{\min}/P_{\max}$ Minimum/maximum power modulation [kW].
Q_U Thermal power [kW].
RES Renewable energy sources.
T_A *and* T_B Temperatures [K].
$T_{in,U5}$ Temperature of water entering the U5 substation.
$T_{out,PS}$ Temperature of water exiting the power station.
$U_{i\text{-}th}$ Generic i-th final user.

1. Introduction

The energy sector is experiencing a deep transition towards a post-carbon society that is changing the energy paradigm. The phaseout of fossil fuels and the increasing use of renewable energy sources (RES) are driving the progressive shift toward electrification of final uses (Long et al., 2019) (e.g., in transportation (Yuan et al., 2021) and buildings (Neirotti et al., 2020)). This shift is impacting energy generation and conversion, as well as the operation and management of transmission and distribution networks. Consequently, in response to the uncertainty and volatility arising from the increasing share of renewable sources, the

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energy system requires greater flexibility to continuously ensure the power balance between generation and demand (Neirotti et al., 2020; La Bella et al., 2021; Turk et al., 2020; Kondziella and Bruckner, 2016). In this context, the concept of Multi-Energy System (MES) is gaining interest. MES represents an effective way to satisfy users' needs, thanks to the exploitation of the synergies between different energy vectors (e.g., thermal, electrical, gas), conversion technologies (e.g., fuel cells, heat pumps, co-generation) and energy networks (e.g., district heating systems, electricity grids, gas networks) (Mancarella, 2014; Bartolucci et al., 2022). It also unlocks new forms of flexibility (Chicco et al., 2020). In general, managing different energy carriers as a whole and exploiting their combined effects is more convenient than running traditional separate energy systems. For instance, from an environmental perspective, MES can optimally leverage the reduction of greenhouse gas (GHG) and pollutant emissions through its ability to exploit the suitable conversion efficiencies of technologies and harness local RES (Balakrishnan et al., 2016).Furthermore, MES configuration can reduce operational costs, as demonstrated in (Turk et al., 2020). Concerning flexibility in the energy sector, it refers to the ability of an energy system (e.g., power plant, a building, or an industrial process) to adjust its electrical power consumption or generation profile in response to changing conditions, demands, or market signals. Flexibility denotes the system's capability in reliably and efficiently mitigating the fluctuations and uncertainties associated with both demand and supply across various timescales. In other words, flexibility is necessary to the power grid to ensure uninterrupted supply during transient and substantial imbalances (Babatunde et al., 2020; Lechl et al., 2023; Ulbig and Andersson, 2015). Therefore, in the ongoing energy transition toward a decarbonised society driven by renewable sources, being most of them inherently intermittent and non-deterministic, the concept of flexibility assumes fundamental importance in creating more resilient, efficient, and sustainable energy systems. While the term flexibility often refers to the adaptability of the electrical vector, it has been demonstrated that MESs offer new opportunities beyond single technologies and energy carriers, and they can create new business and market opportunities (Mancarella, 2014 ;Mavromatidis et al., 2019). It is worth noting that power flexibility plays a crucial role in supporting the power grid to compensate unexpected power imbalances, and it is actively traded in the market for electrical ancillary services. The Transmission System Operator (TSO) can in fact exploit the flexibility offered to electrical system to ensure the reliable and efficient operation of the power grid, maintaining grid stability and continuously balancing supply and demand. As suggested in (Chicco et al., 2020; Corsetti et al., 2021), a MES can enhance several flexibility sources, among which: (i) the capability to switch between different energy vectors; (ii) the ability to use the same input carrier to produce different outputs, according to the installed conversion technologies; and (iii) the use of storages (e.g., electric, thermal or gas ones) to decouple in time demand and supply as well as the access to energy markets. In this context, Kleinschmidt et al., 2020 have classified flexibility resources into three main categories: Conversion, Storage and Demand-Side Management, being those encompassing the majority of the MES flexibility potential. Furthermore, in (Lund et al., 2015) the concept of flexibility is extended from a pure techno-energy issue to regulation and market considerations. Regarding conversion technologies well suited for the MES application, (Guelpa et al., 2019) have produced a comprehensive review of the main features, costs, and efficiencies of devices. Authors focus on their classification according to the involved energy carries (i.e., power-to-gas, power-to-heat, gas-to-heat, gas-to-power and power-to-commodities). In (Witkowski et al., 2020), a similar categorisation is proposed, enlarging the discussion to include flexibility valuation, presenting power ramps and responsiveness of each solution. In this regard, (Makarov et al., 2009) have defined the flexibility of a conversion system not only in terms of available power but through a triplet of necessary physical variables: power provision capacity (MW), power ramp-rate (MW/min) and energy provision capacity (MWh). Moving to the demand side, for example in the building sector, the concept of flexible buildings and the necessity to assess the flexibility of building clusters or communities has become a trending topic in the last few years, since the awareness of final users in the energy matter increased a lot (Amadeh et al., 2022; Tina et al., 2022; Vigna et al., 2018; Wang et al., 2022; Vigna et al., 2021; Arteconi et al., 2019). In (Hurtado et al., 2017), Hurtado et al. have extended the flexibility triplet proposed by Makarov to make it suitable for evaluating flexibility actions in buildings, taking into account also the thermal comfort of the occupants. Considering that the flexibility evaluation is affected by external factors, e.g., the power demand, robust methods considering uncertainty are also investigated in the literature, as in (Martínez Ceseña et al., 2016; Zhao et al., 2021; Vignali et al., 2022).

The synergetic operation of different energy domains, as outlined in references (Arteconi, 2018; La Bella et al., 2021; Mancarella et al., 2016), brings increased complexity from the modelling, simulation and control perspectives. It also introduces additional physical and regulatory constraints. However, there is a lack of studies in literature regarding the impact of energy networks on the availability of flexibility in a complex system. Accounting for networks can unlock new forms of flexibility, as some of them inherently act as storages (i.e., thermal and gas networks), but at the same time, it introduces further limitations due to their physical and structural constraints (e.g., temperature and pressure limits) (Chicco et al., 2020). Therefore, finding a method and a tool is essential not only to determine how much flexibility can be delivered but also to understand the implications it has on the analysed system.

Various approaches have been proposed in the literature to calculate the aggregated flexibility of multiple energy systems. Good and Mancarella (Good and Mancarella, 2019) present a stochastic smart district optimisation model for demand response resources in a multi-energy community, mainly focusing on power flexibility. (Chicco et al., 2020) extend MES framework to distributed MES (DMES) and provide a comprehensive overview of DMES modelling and main features concerning flexibility. In detail, the authors enlarge the concept of power node (commonly used in the electricity field) to multi-energy nodes for MES application. Starting from the energy hub model, authors represent the MES as input-output matrices, considering constraints on conversion devices and storage, and highlighting implications on power network constraints. A novel multi-energy lattice framework for modelling MES flexibility is developed in (Corsetti et al., 2021), with the final aim to optimise the participation of the MES in the control frequency ancillary services. In detail, the MES is represented as a lattice of energy layers connected through conversion nodes. Despite the similarities with the multi-energy nodes used in (Chicco et al., 2020), the multi-energy lattice methodology aims to support and assess the multi-market participation of the system, rather than analysing the physical operation of the system. From the analysed literature on flexibility from multi-energy systems, it becomes evident that most works focus only on the installed conversion, generation, and load technologies without considering the presence of multi-energy networks and their physical limits. However, since energy networks of different carriers can exhibit different dynamics that affect the overall flexibility, MES cannot be modelled solely in terms of generation and load nodes, as is common in the energy hub concept.

For these reasons, the scope of the paper is to propose a simulation-based methodology for evaluating flexibility in a multi-energy system, taking into account not only the individual devices installed but also the effect of the network. To achieve this, the paper proposes a tool for the simulation of complex energy systems, which allows to consider the dynamics of energy networks. With this developed tool, it becomes possible to analyse the actual physical limits of the systems under examination, allowing to obtain profiles and margins of flexibility. A lightweight solution for simulating MES in a unique simulation environment is developed, enabling the coexistence of multiple energy sources, technologies and networks. Then, through the application on a Case Study, evaluations on the flexibility of the system are conducted, demonstrating the ability of the simulator to be used as a tool to identify flexibility boundaries and profiles. In detail, the proposed Case Study is a third-generation district heating network (DH), which aligns with the definition of a multi-energy system, presenting a thermal demand, a distribution thermal network and a central power plant made of a cogeneration plant (i.e., gas-to-heat&power) and a gas boiler (gas-to-heat).

The paper is structured as follows: in Section 2, starting from a global perspective on the calculation of flexibility in MES, an overall methodological approach is proposed. The steps are then retraced through the application on a Case Study in Section 3, describing in detail the proposed tool, while the outputs of the simulation and the flexibility assessment are exposed in Section 4. Finally, the conclusions (Section 5) summarise the main outcomes of the research, highlighting the potentialities and limitations of the proposed methodological approach and suggesting future developments for the work.

2. Materials and methods

This section presents the methodological framework for estimating the potential flexibility that a MES can offer, with a focus on the modelling and simulation phase.

The overall methodological approach can be divided into the following five pillars:

1. Set the objective(s) of the study and identify involved stakeholders, considering their specific scopes and interests concerning flexibility (e.g., define flexibility profiles for participation in the market).
2. Model and simulate the selected MES, in line with the defined objective(s).
3. Quantify and compute flexibility, according to the objectives and outcomes from the previous steps. As outlined in Section 1, there are different ways to quantify and evaluate MESs flexibility, as well as different kinds of flexibilities.
4. Explore multi-domain flexibility implications, in line with stakeholders' needs. This step is intended to explore the possibility of assessing flexibility not only in energy terms but accounting for its implications in other fields (e.g., performing financial or environmental evaluations). This step is not part of the current paper.
5. Analyse the outcomes of the research concerning simulation and flexibility calculation, and critically discuss the results. If requested by the stakeholder, this phase may also involve providing graphical tools or other user-friendly representation of results to make the outcomes of the analysis clear also for a non-expert audience (e.g., final users).

Each step of the general methodology requires a separate in-depth examination. Specifically, in this paper, Steps 2 and 3 will be discussed in detail, considering the need for a proper model and simulation tool capable of simulating and capturing the system dynamics to compute flexibility.

Starting from Step 2, the focus is on modelling and simulating multi-energy systems and it is further divided into several methodological sub-steps, as highlighted in Fig. 1.

Step 2 can be used both for assessing the flexibility of the system and as a stand-alone procedure to investigate and evaluate MESs operations and dynamics. All these steps will be recalled in Section 3, where an example of application is presented, but a brief review of the simulation tool available is necessary at this point. As previously mentioned, the selection of a proper simulator, according to the objective of the analysis, is fundamental to obtain consistent results. There are several tools for the simulation of energy systems, including those that support the Modelica language, namely OpenModelica, DYMOLA and SimulationX can be mentioned. Tools that allow simplified simulation of energy networks are TRNSYS or TERMIS, as well as MATPOWER, NEPLAN or PowerWorld for the electricity and renewable sources field (Mavromatidis et al., 2019). In this case, to perform a quick simulation capable of catching the dynamics of the system, there is the need to use a simulator that allows the co-simulation of different energy vectors in the same environment. Therefore, the software selected, among the other possible simulation environments, was Simscape® (Abbà and La Bella, 2022), a MATLAB® tool, developed in the Simulink® environment (Simscape web page, 2022), enabling construction of object-oriented models based on physical links between components. It was chosen because, with its numerous libraries, it can cover all the physical domains involved in the analysis of a MES (i.e., electrical, thermal fluid and gas). This tool fits with the requirements for simulating the third-generation district heating network used as the Case Study in this research. However, it is worth noting that the proposed simulation-based methodology can be developed also using other simulation environments (e.g., Modelica).

For flexibility calculation in the current paper, some points of the methodology proposed by (Corsetti et al., 2021). are used to compute flexibility of the MES based on the simulation results.

In detail, as depicted in Fig. 2, both physical and operational flexibility are computed. Physical flexibility represents the maximum allowed modulation for an energy vector according to the devices used in the system, and it is calculated according to Eq. (1),

$$F_{ph,d} = P_{\max,d} - P_{\min,d} \tag{1}$$

where the subscript d refers to each power device, the variable $F_{ph,d}$ expresses the maximum physical flexibility, whereas $P_{\max,d}$ and $P_{\min,d}$ are the maximum and minimum allowed power production, respectively.

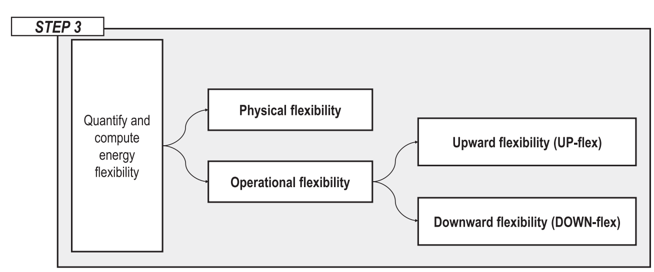

Fig. 2. Workflow of Step 3.

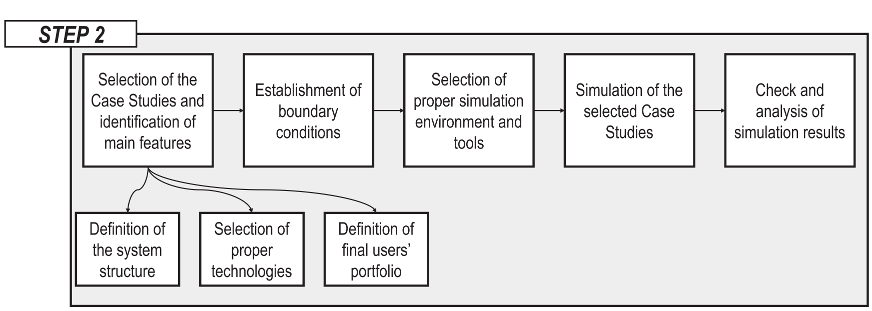

Fig. 1. Workflow of step 2.

On the other hand, the operational flexibility of an energy carrier in the MES refers to its capability to modulate its capacity in relation to a given baseline operating point. This deviation can be either positive or negative with respect to the baseline, leading to two types of flexibility profiles: upward (UP-flex) and downward (DOWN-flex), defined in Eqs. (2) and (3), respectively,

$$F_{op\_UP} = P_{\max,d} - P_{base,d} \tag{2}$$

$$F_{op\_DOWN} = P_{base,d} - P_{\min,d} \tag{3}$$

where F_{op_UP} and F_{op_DOWN} are the UP-flex and DOWN-flex power flexibility, respectively, whereas $P_{base,d}$ is the baseline operating point. In depth, UP-flex relates to the device's ability to increase its power output with respect to a base operating point, vice versa for DOWN-flex.

3. Application

This section outlines the proposal for a new simulator suitable for the efficient simulation of MESs, while also considering network dynamics. The main goal of the presented tool is to allow the assessment of the upper and lower bounds of power flexibility compliant with local network constraints. To achieve this result is necessary to provide a rapid response regarding the performance of a MES, which is a key feature when dealing with energy optimisation and control algorithms (Abbà and La Bella, 2022). For this reason, the simulator is designed as a lightweight tool, capable of conducting both quick and accurate simulations, despite its simplified modelling of certain components compared to their actual operations. This is because the scope of this research extends beyond the functioning of individual components and encompasses the entire energy system, including generation, the network, and end-users. As elaborated upon in Section 3, the simulator was developed using the simulation software Simscape®, which is a MATLAB® tool compatible with the integration of Simulink® for system management and control. Furthermore, flexibility calculations have been implemented in MATLAB®, directly exploiting the outputs derived from the dynamic simulation in Simscape®, all within the same simulation environment.

In line with the definition of Step 2, this section explores its application in a Case Study, following the steps graphically summarised in Fig. 1 and the main assumptions for flexibility calculation are listed.

3.1. Selection of the case study and identification of main features

Since the MES concept involves the coexistence and synergy of different energy vectors, a local district heating network was chosen as the reference system for the application. This network has the ability to mix several heating sources and technologies to serve diverse typology of users' needs, as well as to interface with the electrical system, e.g., through cogeneration and heat pumps. In detail, the analysis started with the development of a simulator for the thermal vector, and the AROMA network was selected from literature and adapted to be the Case Study for the current analyses (Krug et al., 2021).

The DH network is made of two supply branches and presents a loop. The system has a centralised architecture, consisting of a central thermal plant that supplies the required thermal power to heat the water flow rate in the supply pipes, ensuring that the thermal demand of the final users connected to the network is met at any time of the day (scheme in Fig. 3).

In detail, the central power station is composed of (i) a cogeneration plant (CHP), which represents the technology that links thermal and electric vectors (considering the outputs of the CHP) and the gas vector (also considering the fuel used); and (ii) a gas boiler (GB), connected in series to the CHP. Given these plant features, the DH can be classified as third-generation district heating (Lund et al., 2018), (Bilardo et al., 2021).

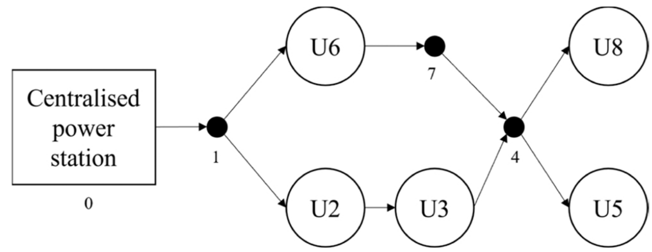

Fig. 3. Scheme of the supply network of the AROMA network. ($U_{i\text{-}th}$ = final user.)
Adapted from (Krug et al., 2021).

As illustrated in Fig. 3, considering the thermal energy demand, loads are distributed on five final users (represented by the $U_{i\text{-}th}$ in the scheme), following the weighted allocation proposed in (Krug et al., 2021). The different shapes and peak powers of the load profiles come from the elaboration of experimental data measured on a real DH in Italy. Fig. 4 displays the hourly thermal demand for each user.

Moving to the distribution network, the architecture and the geometrical features (i.e., lengths and diameters) of supply and return pipes are obtained from (Krug et al., 2021). Table 1 reports the pipe parameters for the supply network, the same are considered for the return line.

3.2. Establishment of boundary conditions

The DH is assumed to be located in the North of Italy. For this location, the ground temperature during the year is set as constant and equal to 12 °C. The heat transfer fluid of the DH network is hot water, assumed as an incompressible fluid. The other boundary conditions regard temperatures in the thermal network; indeed, it was supposed to set a 90 °C (363 K) imposed supply temperature at the exit of the central power station, and a 65 °C (338 K) return temperature is imposed downstream of the users' substation (Abbà and La Bella, 2022). Properly designed controllers track and keep the desired reference temperatures during the simulation, thus ensuring thermal needs supply.

3.3. Selection of proper simulation environment and tools

As mentioned in Section 2, Simscape® from the MATLAB® environment was chosen for the current application due to its ability to model and simulate different energy domains simultaneously. Specifically, for each domain, energy flows are associated with two (or more) variables (i.e., Through and Across variables) characterised by intensity and sign. The Through variables are the ones flowing through the simulation components (e.g., electrical currents, liquid and gas flows, etc.), while the Across ones are measured across components (e.g., voltages, pressure differences, etc.). Among the Simscape® libraries, the Thermal Liquid library was chosen to model the aforementioned AROMA district heating network. Differently from most of the other domains that are characterised by two variables, the thermal liquid domain is determined by four variables: mass flowrate [kg/s] and energy flowrate [kW] represent the Through variables, while temperature [K] and pressure [Pa] are the Across ones. In detail, in this domain, the dynamic evolution of pressure and temperature is governed by mass conservation and energy conservation principles, respectively. Considering the Through variables, the mass flowrate is determined by the principle of momentum conservation, while the energy flowrate is calculated using the thermal energy conservation equation. The equations corresponding to the above-mentioned principles are included in the blocks of the Simscape® library and should always be defined for the blocks created manually by the user. Each block has at least one inlet port/node (A) and one outlet port (B) associated with the above-mentioned variables.

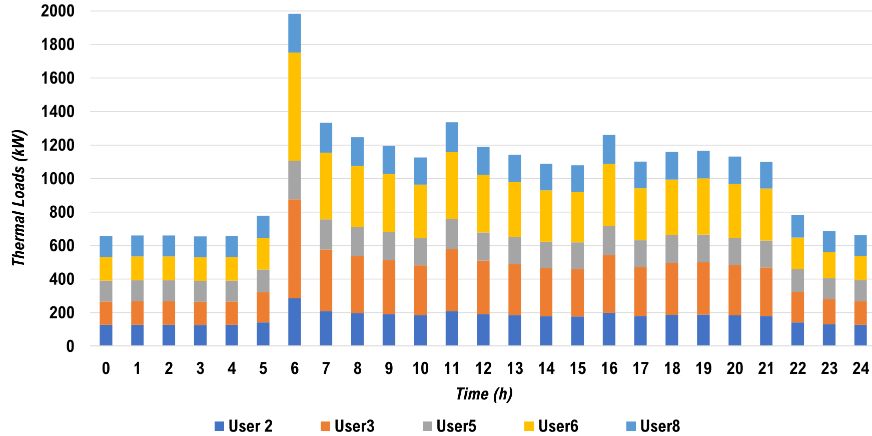

Fig. 4. Users' thermal load profiles.

Table 1
Pipe parameters, elaboration from (Krug et al., 2021).

Pipe section	Length [m]	Diameter [m]
P01	500	0.107
P12	282.8	0.107
P23	500	0.083
P34	282.8	0.083
P45	400	0.070
P47	282.8	0.083
P16	282.8	0.107
P67	500	0.083
P78	600	0.070

Fig. 5 shows the layout of the AROMA network (both supply and return networks) that has been implemented in the simulation software.

In the following, a brief description of the main components of the system will be reported, with a focus on the ad-hoc created blocks and their conservation equations. On the other hand, only the general behaviour of existing blocks is described since a detailed explanation of equations is provided by Simscape® guides (Simscape web page, 2022).

3.3.1. *Central power station*

The centralised thermal power station is a subsystem created specifically to provide the correct amount of thermal power at the desired temperature to satisfy users' needs. It is developed through the aggregation of several blocks; some of them exist in the reference libraries, while the rest are manually created. The power station consists of not only blocks closely linked to power generation but also contains blocks for managing flows, temperatures, and pressure, as can be seen in Fig. 6.

Going into detail of the station's operation, as imposed as a boundary condition, the return flowrate enters the plant at almost 65 °C after the heat exchange between the supply network and the users' substations, also taking into account thermal losses along pipes. To ensure that the correct amount of thermal power is supplied to the users, the water mass flowrate should be heated. Therefore, in the thermal station there are the cogeneration plant and the gas boiler, placed in series, which are activated and regulated independently by a dedicated control system. In detail, the CHP is controlled to track a reference power profile. A CHP with a maximum thermal capacity of 2 MW is selected, with a unitary power-to-heat ratio and with the capacity to hourly modulate its output power in a range 30–100% of the nominal power. For the flexibility evaluation, a reference thermal power profile of the CHP is defined, representing the baseline for the calculation. If the tracked CHP thermal profile is not sufficient to provide the correct amount of heat to the network, the water flowrate goes through the GB stage in which it is further heated. A proportional control system verifies that the output temperature from the boiler is as close as possible to the desired reference temperature of 90 °C and, if not, sends a power regulation signal to

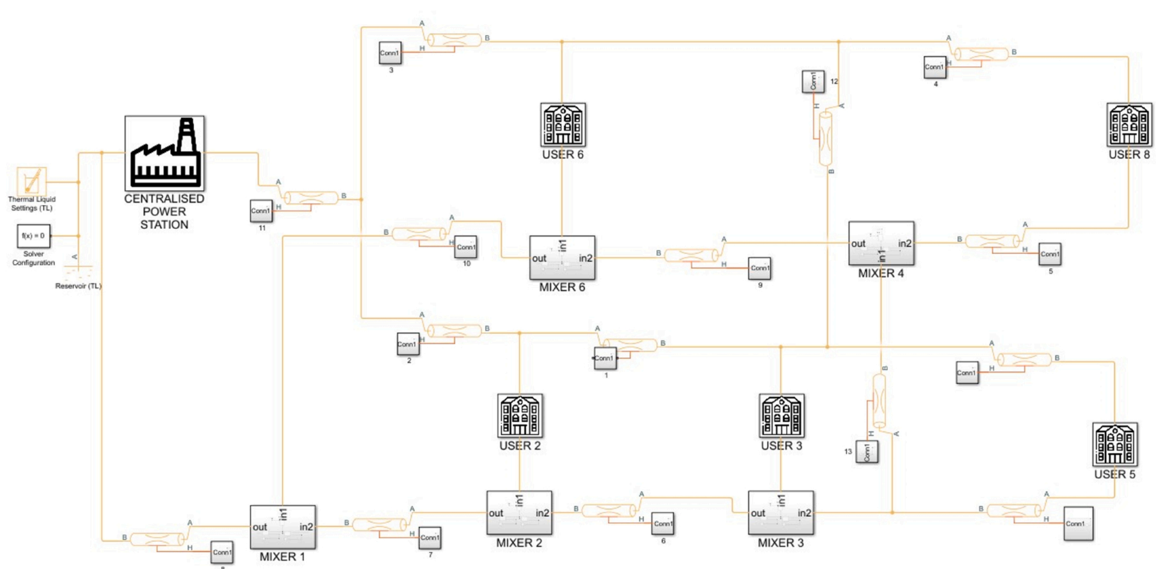

Fig. 5. Layout of the AROMA network on the simulation tool. Elaboration of (Abbà and La Bella, 2022).

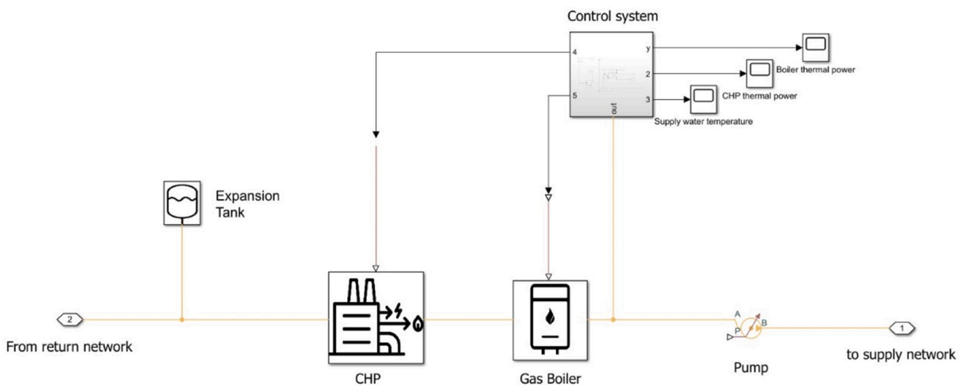

Fig. 6. Scheme of the centralised thermal power station.

the boiler to modulate its thermal power output, up to a maximum value of 1 MW. Both CHP and GB blocks have been modelled in Simscape® as simplified heat exchangers using the following equations (Eqs. 4, 5, 6 and 7), according to the desired level of detail for the simulation (Li et al., 2015).

$$Q_U = \dot{m}_A * c_p * (T_A - T_B) \tag{4}$$

$$\phi_A + \phi_B + Q_U = 0 \tag{5}$$

$$\dot{m}_A + \dot{m}_B = 0 \tag{6}$$

$$P_A + P_B = \dot{m}_A^2 k_{HX} \tag{7}$$

Where: A: inlet port; B: outlet port; Q_U: thermal power supplied to the final user [kW]; c_p: water specific heat (assumed constant and equal to 4.186 kJ/(kgK)); T: water temperatures [K]; ϕ: energy flowrates, entering the A port and exiting the B port [kW]; $\dot{m}$: water mass flowrate [kg/s]; P : water pressures [Pa]; k_{HX}: pressure loss coefficient for heat exchangers.

Finally, the central station plant is equipped with an expansion tank and a pump for the management and control of network pressure values. In detail, the expansion tank compensates for changes in pressure and volume within the district heating network due to temperature fluctuations along the pipes. The reference pressure of the expansion vessel is set equal to $5{\cdot}10^5$ Pa, and the block has been manually created to model the expansion vessel as a closed chamber capable of expanding or reducing its volume to ensure that the flow that enters the chamber comes out with the desired pressure. On the other hand, the circulation pump block is derived from Simscape® libraries and is responsible for imposing a pressure increase of $5.5{\cdot}10^5$ Pa (Krug et al., 2021) on the flowrate passing through it. This imposed pressure differential ensures the delivery of the required amount of water with the desired thermal characteristics, even to the most disadvantaged user, who is located farthest from the power plant.

3.3.2. User's substation

Similar to the central power station, the users' substations also consist of the aggregation of existing and manually created blocks. The purpose of the substations is to transfer the desired amount of thermal power from the supply network to the final user, after setting specific boundary conditions. As mentioned earlier, one of these conditions is the return temperature, which is enforced to be equal to the reference temperature of 65 °C. To cope with this requirement, each user's substation is made of a heat exchanger and a dedicated control system that, through a valve, regulates the water flowrate entering the heat exchanger. In detail, the control system takes inputs such as the reference temperature for the return network (65 °C) and the user's load profile. It then compares the reference temperature with the temperature of the water flow rates exiting the heat exchanger. If discrepancies exist between these two temperature values, the controller sends a signal to the regulating valve. This valve, by adjusting its section, increases or decreases the water flow rate. In this case, the heat exchanger is modelled in a simplified way by using Eqs. 4, 5, 6 and 7, according to (Krug et al., 2021).

3.3.3. Pipelines

Pipelines are the network dedicated to transporting the heat transfer fluid through enclosed ducts. Pipe blocks are already modelled in the Simscape® library. In the simulator, each connection between two different blocks (e.g., central station and the first user's substation, etc.) is established using a pipe block. Thanks to this component, for both the supply and return networks, it becomes possible to simulate the dynamics of water flow over time and along the pipes, considering temperature and pressure drops, as well as thermal losses occurring between the pipes and the ground. In detail, viscous frictions are modelled through the Darcy-Weisbach equation, while the heat transfer is governed by correlations that involve the calculation of the Nusselt numbers, after defining if the flow is laminar or turbulent. For a more detailed and comprehensive description of this model component, please refer to (Simscape web page, 2022).

3.4. Simulation of the selected case studies

After setting the boundary conditions, choosing blocks from the library and implementing new components through their constitutive equations, the simulator is assembled, resulting in the final AROMA network layout of Fig. 5. The simulation of the supply side and the distribution network is done directly on Simscape®, while users' load profiles are derived from the elaboration of real monitoring data and are included in the simulator as signals entering the substations' control systems. The chosen time horizon for the simulation is 24 h, aimed at evaluating the system's behaviour over one day and overcoming the initial stabilisation transient. Since the monitoring campaign reports thermal loads once per hour, it is assumed that consumptions remain constant during an hour.

3.5. Assumption for flexibility calculation

Moving to the flexibility assessment of the system, the objective, in this case, is not to propose new metrics or methods of quantification but to demonstrate how the simulator, previously described in Section 3.3, can be useful for this kind of evaluation. The focus of the application is power flexibility.

Starting with physical flexibility, in the current case study, only the CHP contributes to electricity production. However, since the CHP is not the only conversion technology in the central power station of the MES, it is not sufficient to check its power limits. Indeed, boiler production should also be considered because, at each time step, users must receive the required amount of heat within an acceptable range of supply temperatures. In line with this, to find the maximum and minimum operating limits for the CHP, the following constraints are imposed:

$$85^{\circ}C \leq T_{out,PS} < 100^{\circ}C \tag{8}$$

This means that the water exiting the power station cannot reach a temperature ($T_{out,PS}$) higher than 100 °C to guarantee the liquid phase of the fluid.

$$85^{\circ}C \leq T_{in,U5} \leq 90^{\circ}C \tag{9}$$

The most disadvantaged user (in this application User5 (U5) which is the farthest from the centralised station) should receive hot water in the substation at a temperature ($T_{in,U5}$) of at least 85 °C to ensure the delivery of the correct amount of heat.

This second constraint takes into account the thermal losses that occur along the district heating network.

The flexibility calculations have been carried out using the formulas discussed in Section 2 (Eqs. (1),(2) and (3)), which have been implemented in MATLAB to process the outputs of the Simscape simulations within the same simulation environment.

4. Results and discussion

This section is devoted to the analysis of the outcomes of the application to verify that the simulator performs as expected and to evaluate the dynamics of the reference case study. Additionally, some results in terms of flexibility are presented to highlight how the proposed simulator can be suitable to identify upper and lower flexibility bounds and evaluate the effect of these bounds on the network. Indeed, it has to be said that the strength of Step 2 lies in the fact that results can be used to evaluate the potential flexibility that complex systems can offer, as well as serving a stand-alone model to make some consideration on MESs behaviour.

From the perspective of using the study for the assessment of the flexibility that the simulated Case Study can offer outside its control volume, it can be interesting to analyse the power outputs of the centralised station. Given the technological composition, the station is where the different energy vectors interact, employing conversion technologies such as the CHP and GB. Both power plants use gas as input fuel, while their outputs differ when considering the different technologies involved. In detail, concerning the gas boiler, the output is the sole thermal power (gas-to-heat), while the CHP contributes to the production of thermal power to feed the DH network and electricity to be injected into the power grid (gas-to-power & heat). The current paper mainly focuses on the thermal and electricity vectors, but future works will deal also with the gas energy carrier.

Starting from the baseline definition, Fig. 7 shows CHP (orange) and GB (green) thermal power output profiles, while the dotted black line represents the hourly sum of thermal demand from the five users. It is assumed that the CHP is used to cover the hourly minimum load and can shift its power only twice a day. The motivation behind the choice, at least in the base case, is related to the logic of the electricity market. The power profile for the CHP in the Baseline scenario has been tailored to provide lower energy generation during nighttime, i.e., when users' demand for thermal energy is lower, while increasing power output during the day, starting in the slot 6–7 a.m., coinciding with peak users' demand. This thermal energy production profile for the CHP closely mirrors the normal operational pattern of CHP plants employed within district heating networks, as discussed in (La Bella and Del Corno, 2023). Once the operation of the CHP has been defined, the gas boiler is used to provide the integration of thermal power to ensure the fulfilment of the total required thermal power. With this base operation, all users are satisfied and the reference supply temperature (90 °C) reaching all substations is guaranteed. It has to be stated that no optimisation solver has been used for the definition of baseline powers.

As can be observed in Fig. 7, the GB is mostly used to help the CHP in presence of peaks, presenting a more variable profile. Indeed, under these hypotheses, the CHP covers the majority of total heating requests, reaching almost 84%. Regarding the pure simulation aspects, the simulation time is around two minutes, and the initial transient lasts one hour (3600 s) within the total simulation time horizon of 24 h.

By imposing these limitations in terms of temperatures it is possible, through the use of the simulator, to test different CHP power profiles and find those that respect the constraints, thus determining the maximum physical flexibility range.

To identify the upper margin of flexibility it was verified that the supply temperature does not exceed 100 ºC. This condition is achieved by allowing the CHP to cover the entire thermal demand of users, without the need for integration by the boiler.

On the contrary, to establish the lower limit of flexibility, the CHP can be switched off, as there is a need to identify the system's extent. However, it is not possible to switch off the CHP for the entire runtime because the power of the boiler alone is not sufficient to satisfy the thermal demand of the users, maintaining at least 85 °C throughout the entire supply network.

Then, once the physical maximum and minimum flexibility boundaries have been defined, it is possible to calculate the operational flexibility of the system, according to the Eqs. (1), (2) and (3), by comparing the flexibility bounds with the baseline power profile. Since operational flexibility is defined as the capability of the system to modulate its power with respect to a given baseline, the feasible physical flexibility region is divided into two areas, determining the UP-flex and DOWN-flex, as shown in Fig. 8. In detail, the UP-flex represents the positive deviation from the baseline, obtained by subtracting the baseline from the upper bound ($F_{op\_UP} = P_{\max,d} - P_{base,d}$), identified by the blue area in figure. On the other side, DOWN-flex is the negative deviation from the baseline ($F_{op\_DOWN} = P_{base,d} - P_{\min,d}$) and is depicted with the red area. The two

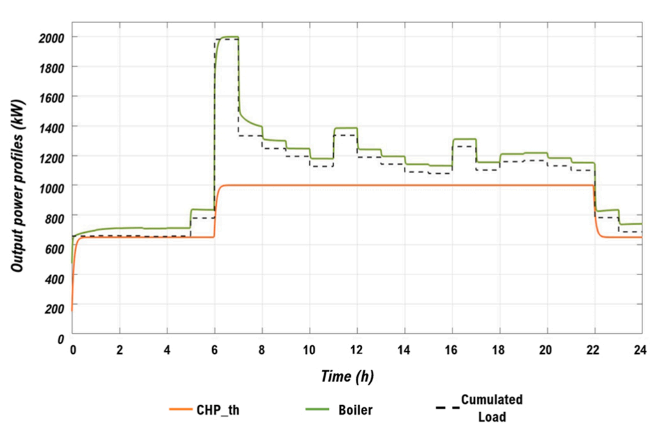

Fig. 7. Baseline thermal power hourly profiles of the central station.

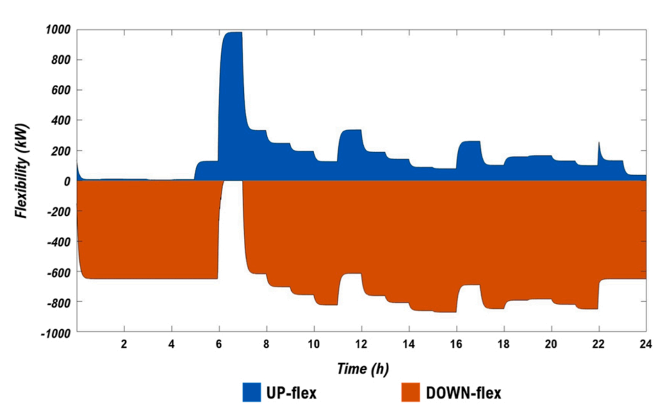

Fig. 8. UP-flex (blue) and DOWN-flex (red) power profile of the plant.

areas identify respectively the ability of the system to increase or reduce the production of electrical power compared to the basic profile, if required.

Fig. 8 shows the operational flexibility for the electricity vector for one day, for the system under investigation. The coloured regions represent all the feasible points for flexibility provision. The UP-flex is reported along the positive y-axis while the DOWN-flex presents negative y-values. With the baseline profile proposed in Fig. 7, upward and downward flexibilities result in non-symmetrical shapes and are quite unbalanced in terms of energy flexibility available in the 24 h.

Until now, the simulator has been used only to search for flexibility boundaries, but the problem can be observed also from another standpoint. Indeed, considering that the grid operator asks the plant a certain amount of flexibility in a given timespan, the simulator can be used to verify if by granting the required flexibility to the grid the network physical constraints (e.g., temperatures limitations) are respected, and the effect of the action on the network itself. For example, looking at Fig. 8, it can be noticed that during the morning peak request between 6 and 7 a.m., the system cannot provide downward flexibility; it should at least work following the baseline. Therefore, if operators ask for a reduction in electricity production from the central station in that hour, the system cannot fulfil the grid's request; otherwise, the temperature of the supply water flowrate reaching the most disadvantaged users will be lower than 85 °C, resulting in user dissatisfaction. Using the simulator, the energy manager of the plant can easily answer positively or negatively to the grid operator with a reasonable response time. To check these boundaries, one of the outputs of the simulation tool is the temperature trend at the inlet (in) and outlet (out) nodes of each component. Fig. 9 shows, on the left, the temperature evolution along the day for the two nodes mostly affected by the constraints imposed for the flexibility calculation, the inlet of the most disadvantaged user (User5) and the outlet of the central station, while on the right, the CHP thermal power output profiles in the three scenarios.

Examining the Baseline condition (Fig. 9(a)), the thermal power

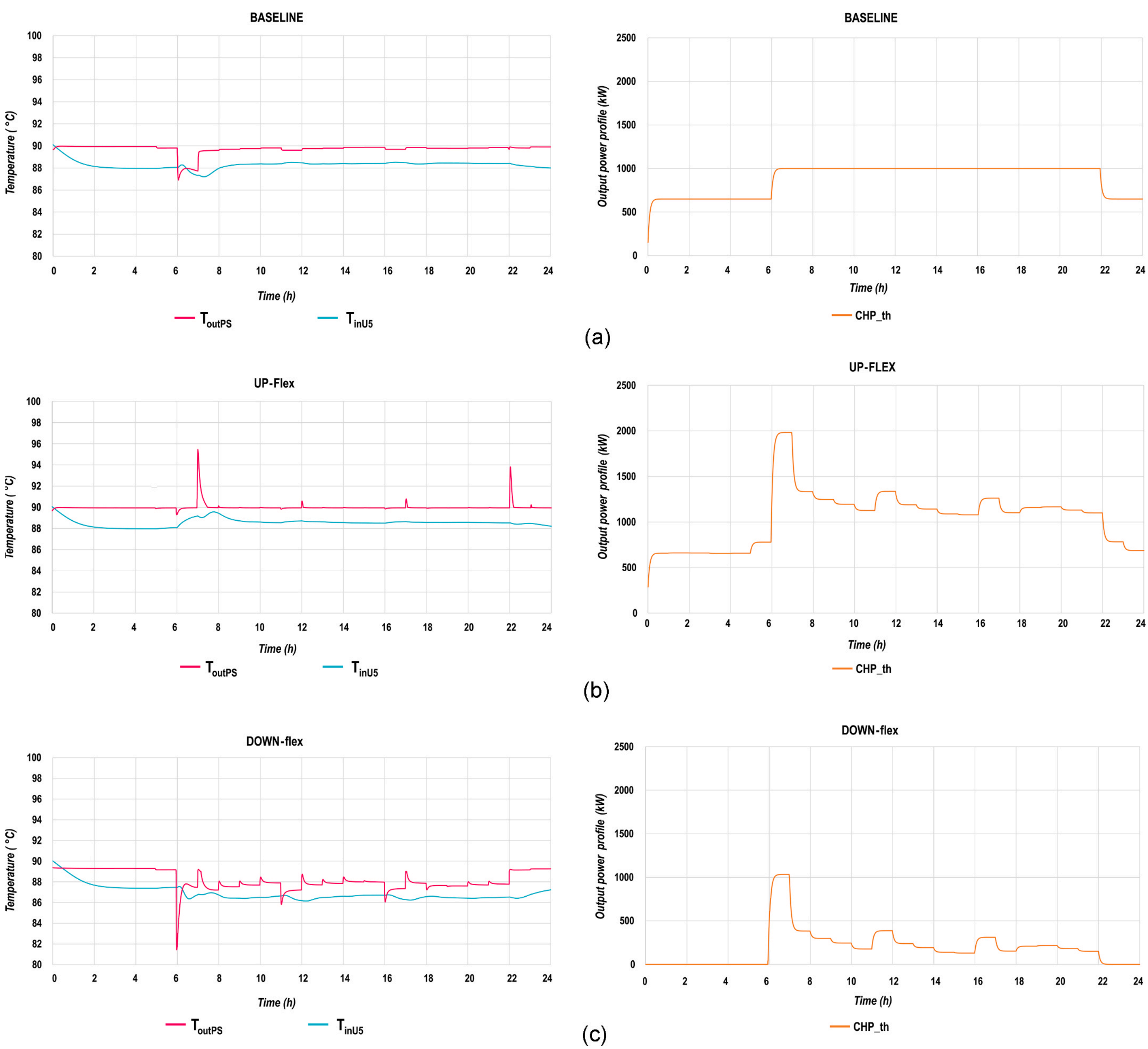

Fig. 9. Left: Trend of temperatures (inlet of User 5 and outlet of the central station); Right: CHP thermal output power profiles in the three scenarios: Baseline, (b) UP-flex, (c) DOWN-flex.

profile of the CHP (on the right) represents the normal operation of the device, and it is used as reference profile for the operational flexibility calculation. Regarding temperatures, except during peak times, the supply temperature remains almost constant, at the desired 90 °C, with water delivered at nearly 88 °C to User5, accounting for thermal losses along the thermal distribution network. It is also possible to observe the time delay between the response to the peak request on the supply temperature at central station and the propagation of the event until User5. In Fig. 9(b, left) temperature profiles are depicted when the upper flexibility limit is reached. With respect to the baseline situation more oscillations around the water set-point temperature of 90 °C exiting the central can be observe, due to the proportional controller used to manage the central station operation, but the limit temperature of 100 °C is never reached. Comparing the thermal profile of the UP-flex scenario Fig. 9(b, right) with that of the baseline Fig. 9(a, right), it is clear that the power values are higher since the CHP can heat the water to a higher temperature and is pushed to work to cover the maximum demand portion. In this case, the demand share covered by CHP is 98% while the gas boiler satisfies the remaining percentage.

On the other hand, Fig. 9(c, left) shows temperature profiles and thermal profiles when the lower flexibility margins are reached. In this case, CHP is required to provide the minimum possible power, while ensuring that the User5 is satisfied, and then the combination of CHP + GB guarantees at least a water temperature of 85 °C in input to User5′s substation. Looking at the pink curve, in this case, the $T_{out,PS}$ is already lower than the desired 90 °C. So as a result, considering the heat losses along the network the $T_{in,U5}$ will be lower than the 88 °C of the two previous scenarios, but higher than 85 °C as imposed by the boundary condition. In this scenario, CHP covers a daily share of 18% of total thermal demand.

5. Conclusions

The transition that is affecting the energy sector is asking for more and new sources of flexibility to guarantee the balance between energy demand and supply. Multi-Energy Systems (MES), designed to optimize the management of various energy vectors, appear to be a promising solution to this challenge. Intending to propose a methodological framework to evaluate the flexibility potential of a MES, the paper presents an overall methodology, while providing also a deep spotlight on MES modelling and simulation tool, as well as on flexibility assessment. In this context, a lightweight simulator is developed to simulate the operation of a MES, composed of a small district heating network fed by a central power station, with promising results in catching the dynamics of the system. In the application, the simulator is used not only to explore the system behaviour, but also to find the physical and operational flexibility of the MES, concerning the electricity vector. Indeed, it was shown how, through the use of the simulator, flexibility margins as well as upward and downward flexibility regions can be calculated, while respecting thermal network and users' constraints (e.g., temperatures and delivered heat).

The results show that, once the baseline is defined, the processing of simulation outputs allowed us to determine and graphically represent the operational flexibility of the electrical vector in the MES. In fact, two areas have been identified representing all the feasible points for available flexibility (upward and downward flexibility). Thus, it was demonstrated that the simulator can be used both to find flexibility margins to define a flexibility profile to offer for ancillary services, and also to verify if the flexibility required from grid operators is consistent with network physical restrictions.

However, it can be said that different baselines lead to different operation flexibility profiles, so the choice of the appropriate base operating points for the plant is crucial. In this regard, one of the main limitations of the work is that no optimisation has been performed to manage the combined operation of CHP and GB in the centralised power station, but it should be done to obtain a more realistic baseline for the calculation. Therefore, future works will try to solve this issue.

Moving to the strong points of the proposed methodology, the developed simulator can be used to evaluate the potential flexibility that is possible to extract from complex systems, as well as a stand-alone model to make some considerations on MESs behaviour. Indeed, thanks to the simulator, it was possible to observe the hourly evolution of two fundamental quantities within the MES, namely temperatures and CHP power, across three distinct flexibility scenarios: baseline (no flexibility), upward, and downward flexibility. Moreover, if desired, other quantities such as pressure and flow rate can also be derived at each point in the MES. To conclude, the simulator lends itself to several types of customisations, being suitable to be used with different kinds of plants, networks, and final users.

Future work will aim to address potential weaknesses in the presented research and expand upon its concepts and applications. Firstly, a future perspective involves conducting a comparison between the operation and outcomes of the simulator and a real-world case with measured data. This analysis would offer the opportunity to validate the simulator and, if necessary, calibrate the baseline using actual data. Then, concerning new case studies, with different MES architecture, one future scenario will analyse the shift from a centralised structure of the DH, with a central production station, to a decentralise layout with local heat pumps in the users' substations to reheat water. This transition is consistent with the shift toward low-temperature DH and the electrification of end-use applications. Moreover, in the current application, only power flexibility from a technical and energy perspective has been assessed. However, future research studies will expand the evaluation to include other energy vectors (i.e., gas, heat, and cooling), calculating the overall flexibility of the Multi-Energy System. This extended valuation will also incorporate financial and market perspectives. Finally, robust methods can be exploited to properly assess power flexibility, which is uncertain as it depends on external factors, e.g., the thermal demand, and these techniques can be integrated with the analysis of local network variables to evaluate if their operational constraints are respected also in presence of uncertainty.

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CRediT authorship contribution statement

Ilaria Abbà: Conceptualization, Investigation, Methodology, Software, Writing- Original draft, Visualization. **Alessio La Bella:** Conceptualization, Investigation, Methodology, Software, Visualization, Writing- Review and Editing. **Stefano Paolo Corgnati**: Conceptualization, Supervision. **Edoardo Corsetti**: Conceptualization, Supervision.

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.

Data availability

Data will be made available on request.

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