Optimising low-temperature district heating networks: A simulation-based approach with experimental verification

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ABSTRACT

Fifth generation district heating and cooling systems are becoming increasingly popular due to their ability for working with low temperature of heat transfer fluids. Among the other benefits, this characteristic allows for a better exploitation of renewable energy sources. On the other hand, these networks require a fine design and precise management to exploit their full potential. Both these requirements can be met by using advanced simulation and optimisation tools. This research proposes a simulation tool purposely conceived for the design and the optimisation of fifth-generation district heating and cooling systems. This tool is capable of assessing the effects of each building-plant system on the whole district heating and cooling water loop, and to evaluate the effectiveness of diverse network morphology. These capabilities are due to the level of detail of the mathematical modelling which takes into account the thermohydraulic characteristics of the network, each building thermo-physics properties, and the heat pump/chiller detailed operation. The described tool has been adopted to simulate an existing experimental network prototype (consisting of a central heat pump, behaving as thermal energy balancing station, and eight users), and the achieved results were compared to those experimentally obtained for validation aims. The capabilities of the validated tool have been demonstrated by investigating an innovative control logic (representing a further novelty of this research) for a "proof-of-concept" fifth-generation district heating and cooling network. In particular, by adopting a predictive control logic, the water loop temperature is dynamically optimised to minimise the entire network energy demand. The adopted control strategy has yielded significant primary energy savings, amounting to 10.3 MWh/year, with a rate of 6.5 % compared to the reference case characterised by a fixed network temperature. These results underscore the potential of the proposed method and demonstrate the effectiveness of the developed tool.

1. Introduction

Low temperature district heating and cooling networks are considered an essential technology to reduce buildings energy consumption, traditionally acknowledged as one of the primary contributors to greenhouse gas emissions [1]. In this field, fifth-generation district heating and cooling network (5GDHC), characterised by a very low thermal level of the heat transfer fluid, are increasing in popularity among research activities and centralised heating and cooling applications.

The concept of 5GDHC network derives from ground source heat pump (GSHP) systems as well as water loop heat pump systems. The first is commonly used only for single buildings whereas the second is mainly widespread in commercial buildings when heating and cooling loads simultaneously occur [2]. The 5GDHC system is distinguished from the other generations by its decentralised thermal production, where each user is connected to the network via a heat pump, allowing for bidirectional thermal exchange [3]. Therefore, the piping network is often characterised by a two-pipes distribution, while three- or four-pipes designs are also employed in case of direct heat exchange with the user [4]. The temperature levels ease the integration of waste heat sources or renewable energy technologies. However, the resultant higher complexity of the network layout demands for an optimal management of these sources to simultaneously meet the users' comfort demands [47] and energy efficiency potential [5]. Hence, distinct design approaches are needed for 5GDHC systems since their features change particularly from those of previous generation systems [6].

Nomenclature

Acronymous

A	surface area [m^2]
C	heat capacity rate [W/K]
D	diameter [m]
f	Darcy friction factor [−]
h	convective heat transfer coefficient [W/m^2·K]
H	heat exchanger height [m]
HEX	heat exchanger
k	thermal conductivity coefficient [W/(m•K)]
L	length [m]
$\dot{m}$	mass flow rate [kg/s]
NTU	number of transfer units [−]
P	electrical power [W]
p	pressure [Pa]
$\dot{Q}$	thermal power [W]
Re	Reynolds number [−]
T	temperature [K]
t	time [s]
u	internal energy [J/kg]
UA	heat transfer coefficient [W/K]
V	volume [m^3]
v	specific volume [m^3/kg]
w	velocity [m/s]

Greek letters

Δ	variation
ε	heat exchanger effectiveness [−]
η	energy efficiency [−]
ρ	density [kg/m^3]

Subscripts

co	condenser
cons	consumers
DHC	district heating and cooling
ev	evaporator
liq	liquid
pros	prosumers
rec	heat recovery unit
sh	superheated
sc	subcooled
v	vapour
w	water
2P	two phase

1.1. Fifth-generation district heating network modelling

As specified, 5GDHC systems require a fine design and a precise management to exploit their full potential. Consequently, modelling tools are essential for describing their configuration, choosing design parameters, and enhancing their management and performance [7] while favouring energy conservation, and putting control strategies into practise [8]. It is worth noting that existing simulation tools, designed for older generations, are not capable of accurately performing and investigating 5GDHC networks peculiarities. Specifically, the differences between 5GDHC systems and those of previous generations in layout, thermal levels, and bidirectional thermal fluxes between users and networks necessitate the development of new modelling tools. These tools should account for the heat transfer fluid thermal inertia (which cannot be neglected because of the low temperatures and the absence of insulation on pipes [9]), should be able to determine the network thermal loads to assess the potential for bidirectional exchange between a user and the network (eventually, by precisely estimating buildings thermal loads [10]), and should accurately simulate the reversible heat pumps behaviours (by taking into account the type of heat pump, the thermodynamic properties of the refrigerant fluid, and its part-load behaviour [11]). In addition, accurate models for the central thermal station, or for the decentralised renewable energy sources are also required [12].

In the literature, there is a variety of works proposing novel simulation tools for 5GDHC system simulations, with some of them listed in Table 1. The analysed works of Table 1 are categorised also based on their modelling approach (i.e., white-box, black-box, and grey-box). In this regard, the simulations of network design and flexibility/peak-shaving are appropriate for white-box modelling. Furthermore, from the classification of Table 1 and it is possible to highlight the objectives and shortcomings of the investigated works, with a focus on the following crucial aspects for the modelling of 5GDHC networks.

- Hydraulic behaviour for thermal network sizing and design
- Thermal interaction of the network with the surrounding area, individual substations, and central stations
- Thermal inertia of the network
- Impact of buildings thermal inertia on network users' thermal demands and overall energy performance
- Modelling of heat pumps with a focus on their operational transients and their influence on network flexibility.

By comparing all the investigated modelling approaches, it has been found that white-box modelling offers a transparent insight into the interactions among various components, providing a detailed understanding of system behaviour. This comprehension is essential for optimising and fine-tuning system performance, serving as a robust tool for designing 5GDHC systems. The potential of employing this modelling type lies in its ability to meticulously examine the effect of various operating configuration parameters , such as network temperature, and their impact on the actual energy performance of the entire system.

Table 1
5GDHC network modelling approach.

Reference	Modelling approach	Hydraulic behaviour	Thermal interaction	Network thermal inertia	Heat pumps transient operation	Buildings thermal inertia
Hirsch, H. and A. Nicolai [13]	*White-box*	✓	✓	✗	✗	✗
Zheng, X. et al. [14]	*White-box*	✓	✗	✗	✗	✗
Bilardo, M. et al. [15]	*White-box*	✓	✓	✓	✗	✗
Hering, D. et al. [16]	*Black-box*	✗	✓	✗	✓	✗
Reiners, T. et al. [17]	*Black-box*	✓	✗	✗	✓	✗
Khosravi, A. et al. [18]	*White-box*	✗	✗	✓	✓	✗
Wirtz, M. et al. [19]	*Grey-box*	✓	✓	✓	✗	✗

Moreover, white-box models are often easier to validate and verify [49]. Since they are based on well-known physical principles and system components, ensuring the model accurately mirrors real-world system behaviour is comparatively more manageable [51].

1.2. Optimisation and control strategies to improve energy efficiency

The use of thermal energy as an energy vector rather than electricity to satisfy the need for air conditioning in indoor spaces emphasizes the robustness of district heating systems and their lower initial investment and ongoing operating costs [20]. By implementing bidirectional low-temperature networks, this potential for energy and economic savings is further increased [21]. In addition, the operating temperature decrease enhances the adoption and integration of multi-generative renewable energy sources in DH layouts (e.g., geothermal, biomass, and solar based technologies) [22], further boosting their sustainability potential [23]. Solar energy, primarily in large thermal energy production systems, is commonly used for high-temperature district heating applications [46]. In 5GDHC systems, solar energy sources are expected to play a larger role compared to traditional systems [50], thanks to their ability to operate at lower temperatures [24].

To enhance the utilisation of solar energy in the global multi-generative system of low temperature district heating network, seasonal thermal energy storage (STES) proves to be a viable solution [6], allowing for excess thermal energy to be stored during low demand and high production periods and used during peak demand of heating season [25]. Therefore, STES tanks can provide more flexibility in district heating systems by allowing for a more consistent supply of heat transfer rate throughout the year, regardless of fluctuations in energy production or demand [26]. This can result in a more efficient and sustainable use of energy according to lower overall energy costs. In fact, by storing excess thermal energy generated by renewable sources, such as solar or geothermal, seasonal thermal storage can reduce reliance on fossil fuels and contribute to a more sustainable energy system [27].

The use of vapour compression heat pumps as systems for satisfying thermal demands additionally implies a significant process of electrification in the 5GDHC networks. As a result, the possibility of utilising photovoltaic systems and wind turbines [28] by optimising their sizes has been investigated in literature to ensure self-consumption to the network [52] and providing for the possibility of integrating electrical storage systems to ensure greater flexibility [29]. In this context, it is worth noticing that supply temperature optimisation in conventional district heating networks is a standard practise and has received substantial research in the literature. On the other hand, no control strategy has been proposed for 5GDHC networks to optimise their system performance and network operating temperatures. This represents a severe literature gap since 5GDHC systems performance is significantly influenced by the network operating temperature [30]. Indeed, high network temperatures in the summer cause unintended heat losses (excess waste heat energy may be dispersed for free), while low network temperatures in the winter reduce heat losses to a minimum. Moreover, heat pumps and chillers of buildings users are significantly impacted by the network temperature in terms of their coefficient of performance (COP). It worth underlining that, since 5GDHC network can satisfy contemporary heating and cooling loads, the network temperature optimisation represents a not easy task. In this framework, diverse are the works in literature dealing with the topic of 5GDHC network optimisation, as synthesized in Table 2. Here, the optimised variables are listed by grouping them by category, by also citing the related work.

With respect to the network temperature control strategies, these significantly influence the energy performance of 5GDHC systems. In particular, to ensure robust control over network temperature, selecting appropriate energy hub technologies becomes crucial, especially when dealing with fluctuating temperature levels [37].

An example is presented in the study reported in Ref. [38], where an optimisation approach for the 5GDHC network performance was

Table 2
5GDHC network optimisation procedure.

Category	Optimisation Procedure	Cited Work
Hydraulic and Network Design	Hydraulic sizing criteria for pipes	[31]
	Network topology and users' connection	[32]
	Coupling and sizing of energy systems within multi-generation plants	[33]
	Heat transfer fluid supply temperature	[19]
Global Pressure Drop Optimisation	Optimal pipe sizing and supply temperature control	[34]
	Hydraulic control strategy for networks with multiple heat sources	[31]
DH Network Topology Optimisation	Graph-based multi-objective genetic optimisation algorithm	[35]
	Accurate estimation of thermal demands of buildings	[36]
	Optimisation of network topology using minimal spanning tree heuristic method	[32]
Temperature Management and Control	Optimisation of network temperatures, particularly for floating temperature levels	[37]
	Mixed integer linear programming (MILP) model for energy conversion and storage units	[38]
	Mathematical relationship between network temperature and heating/cooling needs	[39]
	Free-floating temperature control	[40]

proposed. This approach utilised a mixed integer linear programming (MILP) model, primarily focusing on optimising the temperature of energy storage systems. The optimisation aimed at enhancing the efficiency of users' heat pumps. However, in Ref. [39], a different network temperature control strategy was introduced, establishing a correlation between the network temperature and individual users' heating and cooling demands. This strategy focused on maximising the district heating system efficiency in meeting user requests but did not consider its impact on the overall energy performance of the 5GDHC system.

A floating temperature control method is presented in Ref. [40] proposing a straightforward yet reliable heuristic for temperature control approach. This method heats up or cools down the main fluid by an external source only when the network temperature is nearing predefined limits. However, this method does not address strategies to improve the efficiencies of the system heat pumps. By focusing on the regulation and control of 5GDHC networks, the model predictive control (MPC) is often suggested as a key technique to optimise the energy performance of DH networks with relation to their control strategies [41]. The MPC algorithm potential is highlighted especially for 5GDHC systems that are heavily influenced by the unpredictable behaviour of renewable energy system and user thermal demands.

Using multi-objective optimisation problems, the control variables are adjusted to maximise the flexibility, energy efficiency, and economic performance of the 5GDHC system. In literature, the key optimised control variables are represented by: water mass flow rate of the pipeline network [16]; mass flow rates of centralised or distributed thermal energy storage units [42]; control operation signal for the management of flexible energy system (e.g., boilers, and CHP), and unpredictable renewable energy systems (e.g., photovoltaic, and wind) [43].

To simulate the control of a thermodynamic system, it is necessary to linearize the models that simulate its behaviour in order to reduce the computational burden. However, the MPC control makes it feasible to retain a higher level of accuracy by avoiding the linearization of the model thermodynamic component. For this reason, the necessity of developing accurate yet extremely flexible dynamic simulation models are connected to both the goals of designing, controlling, and optimising the performance of 5GDHC systems.

1.3. Work contributions

Connecting consumers who have simultaneous thermal demands for heating and cooling is one of the primary features of 5GDHC systems. Network temperature is therefore an important variable for 5GDHC systems. The aim of this work is to demonstrate how significant energy savings for the entire DH system can be obtained by optimising the temperature control of the pipeline network, when the users have simultaneous thermal needs. The multi-objective optimisation has been performed maximising the energy savings of the users of 5GDHC network, dynamically determining the pipeline network temperature that minimises the investigated objective functions using as selecting criterion the maximum curvature point. Further key contributions and novelties of the work focuses on the following aspects.

- Development of a physical model that takes into account the heat dissipations of the network pipes with the ground, the thermal inertia of the heat transfer fluid, and the hydraulic aspects that influence the pressure drops.
- Modelling of the central thermal energy hub (utilised as a balancing station for the pipeline network temperature) and of the heat pump systems of each user using a white-box approach. Modelling the thermodynamic behaviour of each system component, taking into account the effects of their transients operation on the thermodynamic response of the 5GDHC system.
- Estimation of the thermal demands of buildings through a building energy simulation tool that considers the effects related to the thermal inertia of the building envelope and evaluates in detail the distribution of radiative heat fluxes through the glazed elements of the envelope.
- Calibration of the controllers, which regulate the operation of the central thermal energy hub and the users' heat pumps, involves considering the effects of thermal disturbances related to the integration with the 5GDHC network and the energy needs of the users' buildings.

Finally, to demonstrate the potential of the developed network temperature control strategy, an energy analysis was conducted to compare the reference control strategy with temperature within a fixed threshold range value, and the suggested optimised temperature management.

2. Methods

To carry out the previously mentioned analysis, and to validate the reliability of the developed method, a dynamic simulation tool has been created. Specifically, this tool is flexible for designing and optimising the energy performance of 5GDHC systems.

Firstly, the typologies of 5GDHC networks are classified based on the pipeline layout [21].

- Direct cooling and heating with four-pipe network distribution; characterised by branch insulation; and energy stations for regulating the temperature of the heat transfer fluid.
- Indirect heating and cooling with two-pipe distribution, without insulation to increase thermal dissipation with the ground, energy substations positioned between the network and users, and energy stations for balancing heat flows.
- Hybrid systems with two or three pipes for distribution, that operate flexibly, leveraging the potential of both direct and indirect systems.

The method presented in this work and the developed dynamic simulation tool are focused on indirect distribution pipeline networks. This layout is considered as the most advantageous due to the simplicity of the network structure and the adoption of substations with heat pumps, which ensure flexible fulfilment of users' thermal needs.

The dynamic energy modelling of the buildings for thermal loads assessment, the thermodynamic modelling of the heat pumps, and the thermo-hydraulic effects resulting from the integration of these systems with the pipeline network are just a few of the factors that have been considered.

The key aspects of the developed tool have been schematized in Fig. 1. Starting from the users' thermal load estimation, by using clustering criteria, district users are initially categorised according to the type of building and intended use. Consequently, an in-house building energy performance simulation (BEPS) tool [10] is used to evaluate the thermal energy demand on hourly basis, and their peak loads, using appropriate building archetypes [48]. This simulation tool takes into account thermo-physical effects such as the thermal inertia and heat transfer coefficient of the building envelope, the solar geometry which influences the radiative heat fluxes, and the behaviour of the occupants which influences the internal heat gain.

The estimation of thermal load profiles of each user is necessary for the sizing of reversible heat pumps (HPs). The detailed modelling approach for the HPs systems enables the simulation of control techniques, such as the regulation of expansion valve and compressor, allowing the estimation of the energy effects due to partial load operation. Additionally, it is possible to assess the impact of different features (i.e., the refrigerant fluid, type of heat exchangers, type of compressor, geometric characteristics) on the energy performance of the HPs by carrying out sensitivity analysis.

The estimation of the energy fluxes from the heat pumps source side is necessary to size the energy hub used for balancing the network temperature.

The distribution and morphology of the 5GDHC network, with the wide range of hydronic components (e.g., flow reducers, sharp bends, check valves, ball valves, expansion vessels, and pumping units), are all taken into account in the thermo-hydraulic modelling of the pipeline network. Furthermore, heat dissipations with the surrounding ground, pressure drops, and the thermal inertia of the heat transfer fluid are estimated.

The users' heat pump systems are individually sized, undertaking a tuning of the controllers to increase their robustness, considering the thermo-hydraulic interaction with the 5GDHC system. This interaction is influenced by phenomena such as thermal load fluctuation, network temperature fluctuation, and HP system operation transients.

Finally, as last step of the developed model, the network operation optimisation is carried out aimed to increase the primary energy savings of the entire 5GDHC system.

2.1. Building energy modelling

Making an accurate assessment of the space heating and cooling needs of each network users is crucial to correctly size the network stations and substations and to accurately manage/simulate 5GDHC systems. In particular, the adoption of dynamic building energy simulation tools (in opposition to static ones) is crucial for 5GDHC networks to forecast the phenomenon of simultaneous users' demands and determine the probability of balancing the thermal flows of their thermal substations. In this context, a building energy performance simulation (BEPS) tool named DETECt [10], developed in-house by University of Naples Federico II, was used to dynamically estimate the thermal demands of the buildings of the 5GDHC system users. This BEPS tool, which is based on the finite difference method and treats the thermal domain as being one dimensional, consists of a high order resistive-capacitive (RC) thermal network obtained by distributed parameters that enables the calculation of both the internal surfaces temperatures as well as the indoor air temperature and humidity. The following is the differential equation (Ref. [10]) of the RC thermal network used to assess the thermal load of the structure and the temporal evolution of the air node:
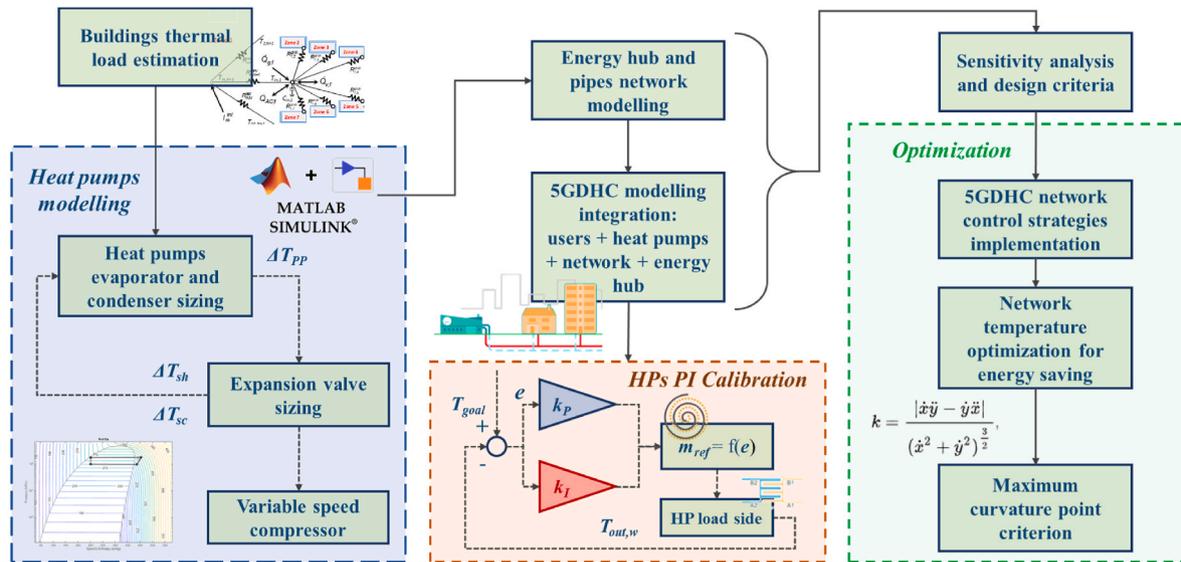
Fig. 1. Overview of the developed tool for modelling and optimisation of 5GDHC systems.

$$C_{air}\frac{dT_{air}}{dt} = \sum_{i=1}^{N}\frac{T_{in,i} - T_{air}}{R_{in,conv,i}} + \dot{Q}_{gain,sens} + \dot{m}_{vent}c_p(T_{amb} - T_{air}) \pm \dot{Q}_{HVAC,sens}$$

Eq. (1)

where C_{air} is the internal air node heat capacity and the terms to the right of Eq. (1) stand for the thermal power fluxes due to transmission, ventilation and heat gains. It can be noted that the radiative heat fluxes among the walls internal surfaces and the solar heat gains through the transparent components were considered for a proper estimation of the internal surface wall temperature ($T_{in,i}$) [10]. The heat gains ($\dot{Q}_{gain,\,sens}$) are given by the contribute due to people, lights, and equipment. The mass flow rate ($\dot{m}_{vent}$) and the outside ambient temperature (T_{amb}) affect the ventilation term of the thermal load. Finally, $\dot{Q}_{HVAC,\,sens}$ represents the thermal load required by the building and necessary to control the internal temperature T_{in} to the desired set-point temperature.

The described BEPS tool requires the following inputs to conduct energy simulations: the weather data of the investigated climatic zone, the envelope properties and orientation of the building, the thermo-physical characteristics of the materials, the schedule patterns for internal heat gain, the profiles of building air change rates, and the set points for temperature and humidity.

2.2. Heat pumps substations modelling

The components of the Simscape Fluid library (Matlab/Simulink) are used to perform the thermodynamic modelling of the substation HPs of the 5GDHC users. The characteristics of this software tool enable a white-box modelling, which allows for a detailed analyses of the sizing and design of the individual thermodynamic components, while also supporting the development of standard and advanced control systems. The schematic representation of the HPs thermodynamic cycle is shown in Fig. 2.

It should be noted that the heat exchangers (evaporator and condenser) interact with the hydraulic circuit of the building HVAC units, or the heat transfer fluid of the 5GDHC pipeline network depending on whether they act as load or source side of the HPs systems. Additionally, consideration has been given to the presence of an accumulator (as depicted in Fig. 2) positioned between the evaporator and the compressor. This accumulator serves to store the refrigerant mass while the heat pump operates at partial loads, thus capturing the dynamic behaviour of these systems. With respect to the adopted modelling approach, each component of the heat pump (evaporator/condenser, thermostatic expansion valve, compressor, and control system) has been singularly and detailed modelled. However, for sake of
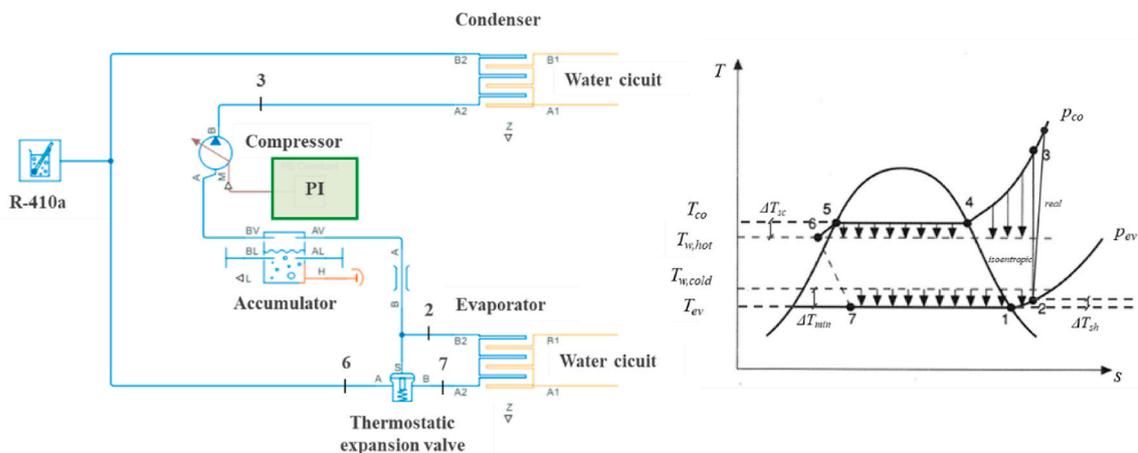

Fig. 2. Heat pump layout schematization and representation of T-s diagram.

brevity, the adopted mathematical modelling is not reported, and detailed description of the heat pump components modelling can be checked in Simscape mathematical reference [44].

2.3. Energy hub modelling

The energy hub, tasked with regulating the temperature of the 5GDHC network, comprises a fuel boiler for heating and a chiller for cooling the network heat transfer fluid. This configuration is essential for managing users' heat fluxes and maintaining optimal network temperature control. Modelling the energy consumption of each user's building and HP system enables the estimation of dynamic thermal fluxes impacting the control volume of the 5GDHC pipeline network. This approach facilitates the accurate sizing of energy hub components. The thermal/cooling energy supplied by the energy hub station is assessed as follows:

$$\dot{Q}_{\text{DHC,network}} = \sum_{i=1}^{N_{\text{b,cool}}} \dot{Q}_{\text{ev,i}} \left(1 + \frac{1}{EER_{\text{HP,i}}}\right) - \sum_{j=1}^{N_{\text{b,heat}}} \dot{Q}_{\text{co,j}} \left(1 - \frac{1}{COP_{\text{HP,j}}}\right)$$

Eq. (2)

where $N_{\text{b,cool}}$ and $N_{\text{b,heat}}$ represent respectively the number of buildings in the 5GDHC network characterised by cooling and heating requests. The heating thermal fluxes related to the source side of HP systems of the i-th users operating in cooling mode are determined as function of evaporator cooling powers ($\dot{Q}_{\text{ev,i}}$) and HP energy efficiency ratio ($EER_{\text{HP,i}}$). Similarly, the cooling thermal fluxes of HP system of the j-th user requiring heating load are determined by the condenser thermal powers ($\dot{Q}_{\text{co,j}}$) and the coefficient of performance ($COP_{\text{HP,j}}$) of users' HP system operating in heating mode.

The chiller of the energy hub has been modelled similarly to the heat pump systems of each user, as referenced in the previous paragraph (2.3. Heat pumps substations modelling). On the other hand, the modelling of the furnace serving as the heating system of the energy hub has been conducted by considering its efficiency. The efficiency (η_{fur}), which depends on the fuel type and partial load factor, serves as key modelling parameter of the furnace and is outlined below:

$$\eta_{\text{fur}} = f\left(\text{fuel}, \frac{\dot{Q}_{\text{DHC,network}}}{\dot{Q}_{\text{fur,nom}}}\right)$$

Eq. (3)

The overall primary energy consumption of the energy hub components system is assessed as follows:

$$PE_{\text{EH}} = \int \frac{\dot{Q}_{\text{ev,ch,EH}}}{EER_{\text{ch,EH}}} \eta_{\text{el,grid}} \, dt + \int \frac{\dot{m}_{\text{DHC,w}} \cdot c_{\text{p,w}} \left(T_{\text{DHC,set}} - T_{\text{DHC,in}}\right)}{\eta_{\text{fur}}} \, dt$$

Eq. (4)

It is important to note that the primary energy of the energy hub chiller ($PE_{\text{ch,EH}}$) is correlated with the effectiveness of the national power grid system ($\eta_{\text{el,grid}}$), whereas the thermal power provided by the furnace is a function of the mass flow rate of water circulating in the network ($\dot{m}_{\text{DHC,w}}$) and its set-point temperature ($T_{\text{DHC,set}}$) influenced by the investigated control strategy.

2.4. Pipes thermal network

The components of the 5GDHC pipeline network were modelled to evaluate both the pressure drops of the working fluid and the heat losses to the surrounding environment.

Regarding the distributed pressure drop of the pipes, it is modelled under the assumptions of incompressible flow, fully developed flow, and negligible gravity effects, using the following equations:

$$\Delta p_{\text{pipe}} = \begin{cases} \lambda_{\text{pipe}} \upsilon_{\text{DHC,w}} \left(\dfrac{L_{\text{pipe}} + L_{\text{eq,pipe}}}{2}\right) \dfrac{\dot{m}_{\text{DHC,w}}}{2D_{\text{pipe}}^2 S_{\text{pipe}}} & \text{if } Re < Re_{\text{l}} \\[2ex] f_{\text{pipe}} \left(\dfrac{L_{\text{pipe}} + L_{\text{eq,pipe}}}{2}\right) \dfrac{\dot{m}_{\text{DHC,w}}^2}{2\rho_{\text{DHC,w}} D_{\text{pipe}} S_{\text{pipe}}^2} & \text{if } Re \geq Re_{\text{t}} \end{cases}$$

Eq. (5)

where, λ_{pipe} is the pipe shape factor, $\upsilon_{\text{DHC,w}}$ is the kinematic viscosity of the thermal liquid in the pipe, L_{pipe} is the pipe length and influenced by the topology of district, $L_{\text{eq,pipe}}$ is the aggregate equivalent length of the local pipe resistances, D_{pipe} and S_{pipe} are the hydraulic diameter and pipe cross-sectional area, Re is the Reynold number of the flow, Re_{l} and Re_{t} are the Reynolds numbers which determine the flow transition from laminar to turbulent, and f_{pipe} is the Darcy friction factors.

The concentrated pressure drop components (such as flow reducers and sharp bends) are assessed using the Simscape Flow resistance (TL) library. Additionally, other hydraulic components of the pipeline network, including check valves, ball valves, three-way valves, expansion vessels, and heat exchangers, are incorporated into the model. For conciseness, essential modelling details can be found in the mathematical references within the Simscape libraries [44].

The thermal losses of the pipeline network components with the surrounding environment are estimated through the following energy balance equation:

$$\rho_{\text{w}} \cdot V_{\text{pipe}} \cdot \frac{du_{\text{pipe}}}{dt} = \dot{m}_{\text{DHC,w}} c_{\text{p,w}} \left(T_{\text{in,pipe}} - T_{\text{out,pipe}}\right) + \dot{Q}_{\text{l}}$$

Eq. (6)

with

$$\dot{Q}_{\text{l}} = \frac{\left(D_{\text{pipe,ext}} - D_{\text{pipe,in}}\right)}{k_{\text{pipe}} S_{\text{lat,pipe}}} \cdot \left(T_{\text{ground}} - T_{\text{in,wall,pipe}}\right)$$

Eq. (7)

where, V_{pipe}, $S_{\text{lat,pipe}}$, and k_{pipe} are respectively the volume, lateral surface, and thermal conductivity of the pipe, u_{pipe} is the internal energy of the heat transfer fluid flowing in the pipe, $\dot{Q}_{\text{l}} Q_{\text{l}}$ is the thermal dissipation with the surrounding ground, $T_{\text{in,wall,pipe}}$ is the pipe internal wall temperature, and T_{ground} is the ground temperature.

2.5. Optimisation problem

The energy efficiency of users' HP substations and energy hub station are dependent on the network temperature, which is a significant variable for 5GDHC systems. For this reason, this research presents an innovative optimisation procedure with the aim of determine the optimal working temperature of the 5GDHC network. In particular, the developed optimisation tool adopts a predictive strategy (with a prediction interval of Δt equal to 24 h and a sampling time t_s of 5 min) that dynamically determines the value of the optimal temperature that minimises the functions of a multi-objective problem represented by the HPs electricity consumption of prosumers ($E_{\text{el,pros}}$) and consumers ($E_{\text{el,cons}}$):

$$f_1 = f(T_{\text{5GDHC}}) = E_{\text{el,pros}} = \int_t^{\Delta t} \sum_{i=1}^{N_{\text{pros}}} \frac{\dot{Q}_{\text{co,pros,i}}(t)}{EER_{\text{HP,i}}(t)} \, dt$$

Eq. (8)

$$f_2 = f(T_{\text{5GDHC}}) = E_{\text{el,cons}} = \int_t^{\Delta t} \sum_{j=1}^{N_{\text{cons}}} \frac{\dot{Q}_{\text{ev,cons,j}}(t)}{COP_{\text{HP,j}}(t)} \, dt$$

The range of values that constraints the temperature of the 5GDHC network (T_{5GDHC} variable to be optimised) is given by the intersection of the sets of values that respectively characterise the winter and summer operation of the HP system.

The maximum curvature point criterion is adopted to identify the optimal solution value of the described optimisation problem; this criterion is formulated as follows:

$$\begin{cases} T^*_{5GDHC} = \text{argmax}(\gamma) \\[2ex] \gamma = \dfrac{\left| \dot{f}_1 \ddot{f}_2 - \dot{f}_2 \ddot{f}_1 \right|}{\left(\dot{f}_1{}^2 + \dot{f}_2{}^2 \right)^{\frac{3}{2}}} \end{cases} \qquad \text{Eq. (9)}$$

where T^*_{5GDHC} represents the optimal working temperature selected as a trade-off to simultaneously minimise the two investigated functions, f_1 and f_2 which are the two objective functions evaluated in Eq. (8), and γ denotes the curvature defined by the examined solutions.

3. Model validation

For validation purposes, the developed dynamic simulation tool was adopted to simulate an existing 5GDHC prototype with the aim of comparing the obtained results to the experimentally gathered data. Regarding the prototype, this is built at the ENEA Portici research center Italy (Fig. 3, left), and its network layout is schematized in Fig. 3, right.

The system is made of eight HP substations, one HP station for balancing the heat fluxes from the source side of the users' HPs systems, and a water-loop circuit that is insulated to avoid thermal dissipations with the ambient air. The key features of the 5GDHC system prototype are reported in Table 3.

The experimental setup investigated involved HP substations operating in cooling mode. Throughout the test, the central HP station controlled the network set-point temperature, which was influenced by the heat fluxes supplied by the condensers of each user's HP system. A heat recovery unit, represented by a plate heat exchanger, recovered thermal energy from the secondary working fluid of the central HP condenser, simulating the thermal loads of 5GDHC network users. A dry cooler, positioned between the heat recovery unit and the central HP station condenser, was employed to modulate the thermal energy supplied to the heat recovery unit.

Temperature and mass flow rate measurements in the experimental setup were facilitated by precision sensors. The temperature was monitored using 4-wire PT100 sensors, featuring a single-element design (Class A IEC 60751) with AISI316L sheathing and a length of 100 mm. These sensors, ensure accurate temperature readings with $-200\ ^\circ\text{C}$–$650\ ^\circ\text{C}$ temperature range and $\pm 0.1\ ^\circ\text{C}$ of accuracy. On the other hand, water mass flow rate was monitored through electromagnetic flow meters, ensuring precise readings across different pipe diameters. For instance, a meter with an accuracy of 2 % within the velocity range of 0.2–1.0 m/s and 1 % within the range of 1–10 m/s is utilised for pipes with a diameter of 25 mm. Meanwhile, a meter with a superior accuracy of 0.5 % across the entire mass flow rate variation range is employed for pipes with a diameter of 50 mm.

Subsequently, this experimental test was replicated with the developed dynamic simulation tool to verify its reliability. The model accuracy was verified by comparing the experimental data sampled during the test and the simulated ones (depicted in Fig. 4). Here are presented the experimental vs. simulated inlet and outlet temperatures of the evaporator of the central HP station (depicted in Fig. 4a); the evaporator of HP substation (depicted in Fig. 4b); the condenser of central HP station, the dry-cooler, and the heat recovery unit (depicted in Fig. 4c).

The results shown in Fig. 4 demonstrate a good agreement between the temperatures obtained with the simulation model and the experimental gathered data, as highlighted by relative percentage discrepancies falling within the error range of ± 2 %. From these outcomes it is possible to state that the model accurately depicts the dynamic evolution of each component, which contributes to its accuracy in simulating the thermal transients of the investigated system.

To further validate the model reliability, the relative percentage errors for each examined property are reported in Fig. 5, along with the average values. Here, a boxplot is used to depict the distribution of the relative percentage errors between simulated and measured data gathered over the time period of the experiment, with a sample time of 60 s, of the variables investigated in Fig. 4. For example, the first box (depicted in Fig. 5) related to the inlet temperature to the evaporator of the central HP station reveals a median value of 1.5 %. Half of the values range from the median to 2 % (maximum value), and the remaining range from -1% (minimum value) to the median. Overall, the investigated properties range within the band of -6 % and 4 % (as depicted in Fig. 5), highlighting the good simulating performance of the developed tool.

Finally, it is depicted in Fig. 6 the comparison of energy efficiency ratios (*EER*) calculated from both measured and simulated electricity consumption and cooling capacity of HPs substations. This comparison
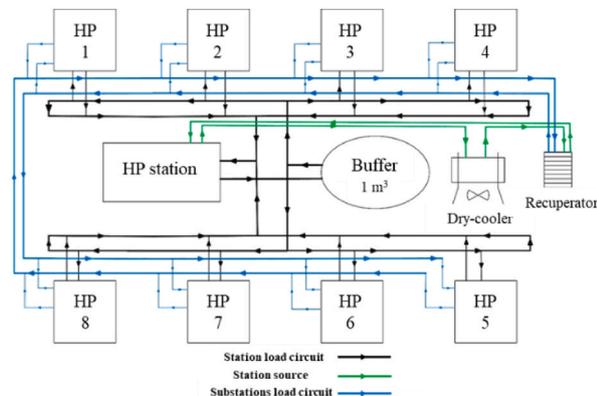
Table 3
5GDHC network prototype characteristics.

Heat pumps					
Typology	$\dot{Q}_{ev,nom}$	$P_{el,nom}$	*EER*	$\dot{m}_{co,w}$	$\dot{m}_{ev,w}$
[−]	[kW]	[kW]	[−]	[kg/h]	[kg/h]
Station	94	20	4.67	19330	16014
Substation	11	2	4.76	2178	1797

Heat recovery unit HEX				
Typology	Flow arrangement	*UA*	$A_{th,exch}$	$\dot{Q}_{HEX,nom}$
[−]	[−]	[W/K]	[m²]	[kW]
Plate	Counter flow	10034	2.2	84

Network pipes		
Typology	D_{ext}	D_{int}
[−]	[mm]	[mm]
primary	58	50
secondary	33	25

Fig. 3. 5GDHC prototype developed at the ENEA Portici research cener (left) and related system layout (right).
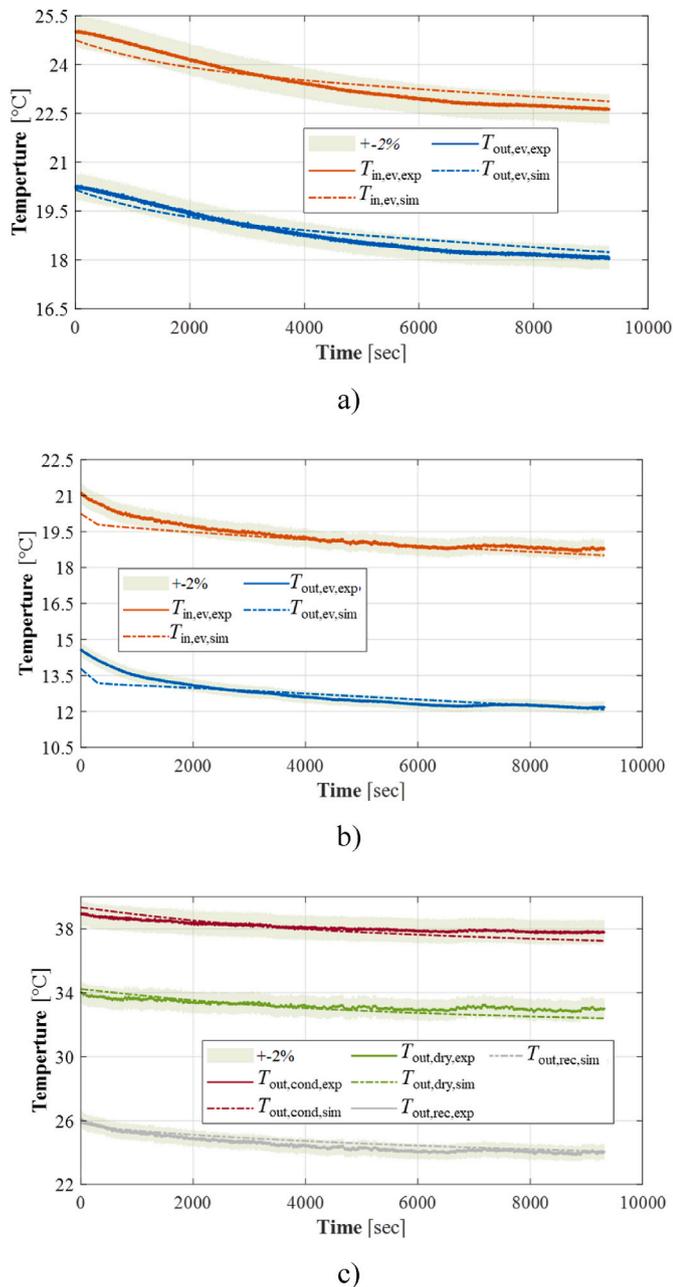
a)

b)

c)

Fig. 4. Temperature comparison among simulated and measured data: a) evaporator of central HP station; b) evaporator of HP substation; c) condenser, dry cooler, heat recovery unit.

is conducted across various operating conditions, combining different reference evaporator temperatures (5, 7, 10, and 18 °C) with different reference condenser temperatures (35, 45, 55, and 60 °C). The relative errors are limited to within ±5 %, and the high R-square value of 0.995 emphasizes the precision of the modelling of these heat pumps.

4. Proof of concept analysis

To show the potential benefits achievable by adopting the proposed optimisation strategy, and to simultaneously prove the capabilities of the developed dynamic simulation tool, a suitable proof-of-concept analysis has been carried out. Such analysis is referred to a hypothetical 5GDHC network supplying a buildings cluster located in the urban area of Milan. In particular, the investigated configuration of the 5GDHC system is depicted in Fig. 7. The primary distribution pipeline comprised

two manifolds: one for the supply line and the other for the return line. Meanwhile, the secondary distribution hydraulic components enable the heat transfer fluid to be drawn from the HP substations of each user.

Furthermore, it is important to emphasize that users are classified as consumers or prosumers based on whether the heat fluxes from the source side of their HP substations fulfil the heat requirements of the pipeline network. In the specific case study, the investigated buildings cluster comprises a data centre (prosumer), three residential buildings (consumers), and two offices (consumers). Details regarding the characteristics of the different buildings, such as geometry, envelope features, and HVAC system parameters, are provided in Table 4.

The energy hub of the 5GDHC system operates to balance the thermal fluxes affecting the network pipeline, ensuring the satisfaction of its thermal requirements, and controlling the operating temperature. Therefore, the thermal needs of both consumers and prosumers HP systems are met without the need for storage or reservoirs.

The analysis of the described cluster was conducted only for the winter season due to the frequent simultaneous loads between buildings acting as consumers and prosumers. Starting from the cluster energy demand, this has been estimated through the building energy modelling tool (described in paragraph 2.1. Building energy modelling) by simulating each building singularly. The obtained thermal power demand is reported in Fig. 8 for a sample winter week (from January 16th to 22nd). It is worth noting that, with knowledge of the thermal power demand for all the buildings in the network, it is possible to size each building HP substation and the energy hub serving as the balancing station of the 5GDHC system. In this regard, Table 5 presents the key HP characteristics for the investigated case study.

In Table 5 it is reported that the nominal load of the furnace ($\dot{Q}_{fur,nom}$) is 15 kW and the chiller of the energy hub ($\dot{Q}_{ev,nom}$) is 25 kW. The network topology and the nominal mass flow rates required by each HP substation, are taken into consideration when sizing the 5GDHC pipeline network.

Once the technical features of the investigated 5GDHC network are presented, it is then necessary to determine its working conditions. As previously mentioned, to ensure good energy performance for both the substations in cooling mode (for prosumers) and those in heating mode (for consumers), it is crucial to establish a range of temperatures for the heat transfer fluid of the network. Temperature is in fact an important variable for 5GDHC systems, and significant energy savings can be obtained by optimising the network temperature, especially when the users have simultaneous thermal needs. In this context, aiming at proving the significance of an accurate network operating temperature, two different control strategy have been analysed for the investigated 5GDHC network.

- **Proposed System 1 (PS1 - standard control logic)**: in case of Proposed System 1, a free-floating network temperature control strategy has been investigated. Here, the energy hub only activates to heat and cool the heat transfer fluid in order to return it to the respective reference values of the bandwidth swing, $T_{DHC, network,min}$ and $T_{DHC, network,max}$ (equal to 20 °C and 28 °C respectively). This control strategy helps to limit the energy balancing station operation due to the network temperature wide permissible range. However, the energy efficiency of each 5GDHC user's substation heat pumps depends on the network temperature. As the network temperature cannot be precisely controlled in this strategy, it results in increased electricity consumption of the HP systems.
- **Proposed System 2 (PS2 – innovative control logic)**, in case of Proposed System 2, a multi-objective optimisation procedure has been investigated. Specifically, it relies on a predictive control strategy with the goal of identifying the temperature value during the Δt 24-h analysis period that minimises the functions relating to prosumers and consumers energy consumption. Using a shorter time frame could result in significant variability that may impact the
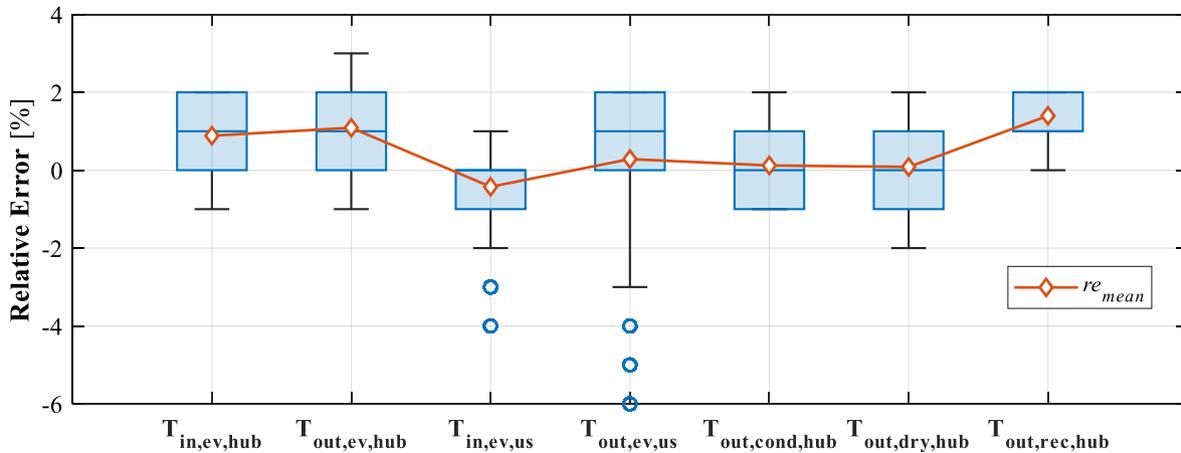
Fig. 5. Boxplot of percentage relative error of temperatures comparison between simulated and measured data.
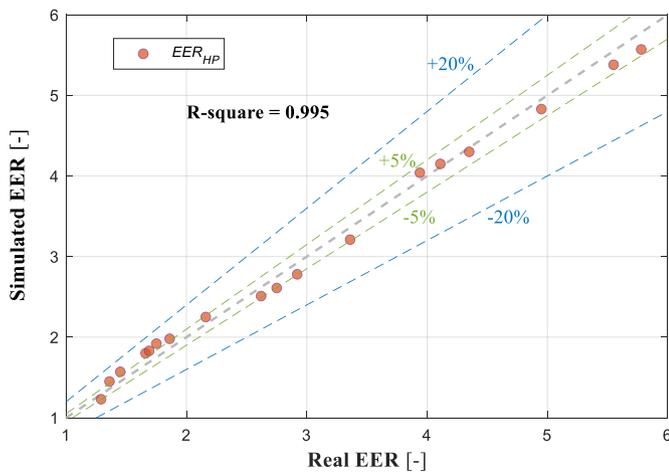

Fig. 6. Comparison among calculated *EER* in measured and simulated conditions of the HP substation.

heat pumps. The electricity consumption from these systems significantly influences the overall electricity usage of the entire 5GDHC system. However, this strategy necessitates longer operation hours for the energy balancing station. Its aim is to accurately control the network temperature based on the set-point values derived from the predictive control optimisation procedure.

The dynamic results from the simulation of the two suggested scenarios, analysing the annual energy savings, are presented in the next paragraph.

5. Results and discussion

The results of the conducted analyses are shown in this section. First it will be presented the results of how it is performed the 5GDHC temperature optimisation in case of PS2 system adoption. Then, an energy-based comparison will be conducted between the investigated scenarios PS1 and PS2.

5.1. Optimisation of temperature pipeline network

In case of 5GDHC network, the partial load ratio, and the temperatures of the secondary fluid on the load and source sides have a significant impact on the efficiency of heat pumps, and consequently, on the efficiency of the entire system. The partial load ratio and load temperature are linked to the building thermal needs and cannot be controlled. It is instead possible to regulate the HP source temperature, represented
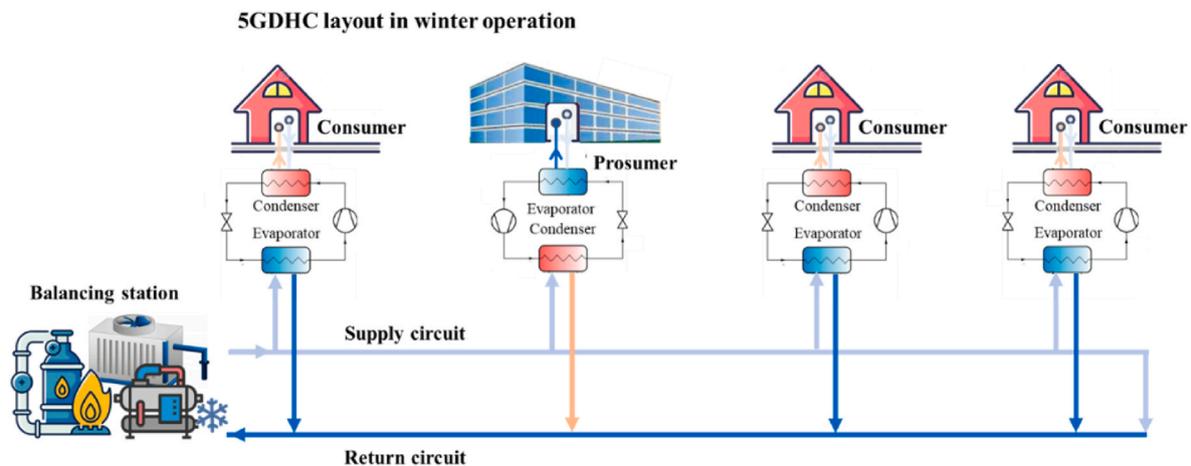
robustness and stability of the controller responsible for governing the operation of the energy hub. The temperature constraints for the 5GDHC network, ranging from 20 to 28 °C, result from the overlapping values that define the operation of the HP system during both winter and summer. In contrast to the previous strategy, this approach focuses on optimising the operation of users' substation

Fig. 7. Scheme and layout of 5GDHC network configuration.

Table 4
Buildings characteristics of the investigated case study.

Buildings energy modelling					
Characteristic	Parameter	m.u.	Data centre	Residential	Office
Buinding geometry	A_{floor}	[m^2]	350	200	350
	heigh$t$	[m]	4.5	2.8	3.1
	WWR	[%]	5	15	30
Buinding envelope	U_{wall}	[W/m^{2}K]	0.30	0.32	0.26
	U_{win}	[W/m^{2}K]	1.5	1.5	1.2
Ventilation	$Vent_{rate}$	[Vol/h]	8	2	6
Internal gain	$Gain_{light}$	[W/m^2]	3.0	2.5	5.0
	$Gain_{app}$	[W/m^2]	300	25	20
HVAC operation	Set point	[°C]	18	20	20

a)

b)

c)
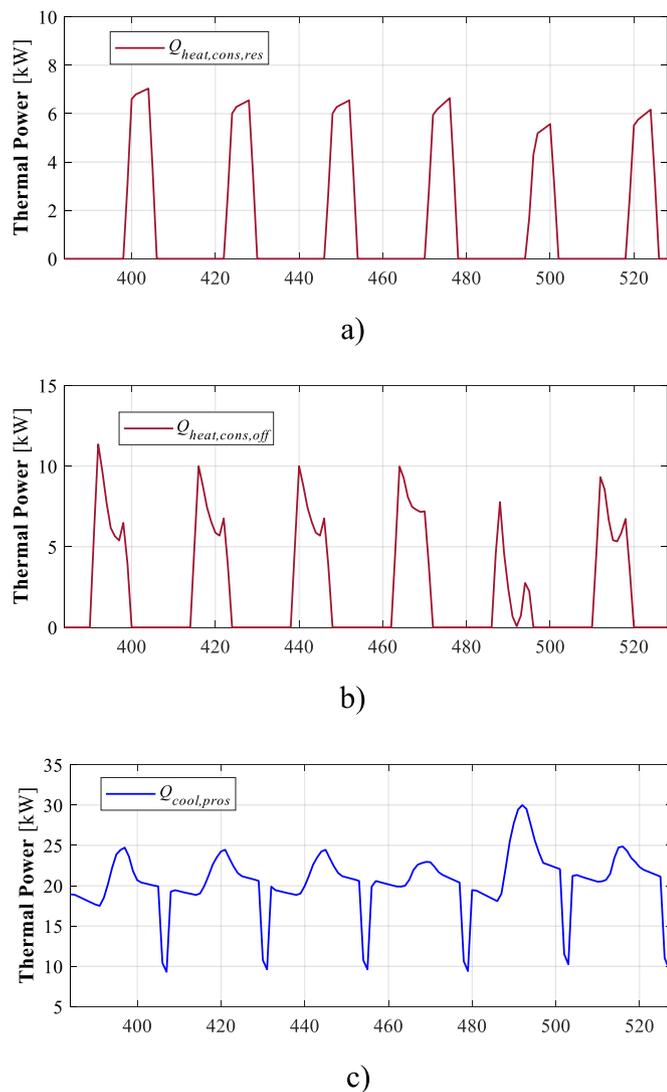
Fig. 8. Buildings thermal loads: a) residential; b) office; c) data centre.

by the DHC network temperature ($T_{DHC, network}$), to improve the overall efficiency of the system.

This paragraph presents the results obtained through the optimisation method applied to control the temperature in the DHC network (i.e., PS2 system). The PS2 system relies on a predictive control strategy with the goal of identifying the daily temperature value, that minimises the objective functions of prosumers' and consumers' energy consumption.

The findings of Fig. 9 illustrate an example of how the multi-

objective optimisation process is applied to the investigated 5GDHC network. In particular, the top graph in Fig. 9 shows the optimal daily temperature for the first month of the year. On the other hand, the bottom graphs in Fig. 9 presents the results of the optimisation method applied to two sample days. Here, the objective functions are represented by the daily electricity spent by the prosumer $E_{el,pros}$ and by all the consumers $E_{el,cons}$. As depicted in Fig. 9 bottom, this situation refers to cases where a minor enhancement in one objective results in a significant deterioration of the other. Therefore, the optimal solution of the Pareto front is evaluated adopting the maximum curvature criterion, and this solution returns the daily network temperature that minimises the electricity consumption of both prosumer, and consumers. Finally, it is worth noticing that the daily optimal working temperature for the network has been calculated for the entire year.

5.2. Comparison of proposed scenarios

In the present paragraph, a comparison between PS1 and PS2 systems performance is presented to investigate their influence on the energy efficiency of the 5GDHC system. Initially, a comparison was conducted to assess the impact of the proposed strategies on the operation of the balancing station. Following this, the investigation delved into the effect of these strategies on the efficiency of the heat pumps for each type of user. Lastly, a comprehensive annual energy comparison was performed to analyse the respective advantages of each strategy.

It is worth noting that, as there are no simultaneous loads during the summer season in the considered case study – only users functioning as consumers – it was preferred to conduct the analysis solely for the winter months.

5.2.1. Energy hub station

As previously described, the energy balancing station consists of a traditional boiler and an electric refrigerant compression chiller. It is important to note that the aim of this study was not to explore technologies promoting energy savings. Rather, the focus was on examining how, within a 5GDHC system, energy savings can be achieved solely through an effective management and control strategy while considering traditional technologies.

The two investigated control strategies, PS1 and PS2, dictate the temperature set-points of the thermal network, consequently affecting the operation of the central energy balancing station. As previously outlined, under the PS1 strategy, the temperature is allowed to fluctuate between a minimum setpoint of 20 °C and a maximum of 28 °C. In contrast, PS2 employs a predictive control approach, solving a multi-objective optimisation problem to derive the optimal daily set-point value aimed at minimising overall users' HPs energy consumption. Through a comparison between the return temperature of the 5GDHC thermal network and these specified set-point values, it becomes feasible to determine the thermal demands to be met by the energy balancing station for both proposed strategies (i.e., PS1 and PS2). At the same time, the return temperature of the network is influenced by the thermal powers of the heat exchangers situated on the source side of the users'

Table 5
Substations HP characteristics.

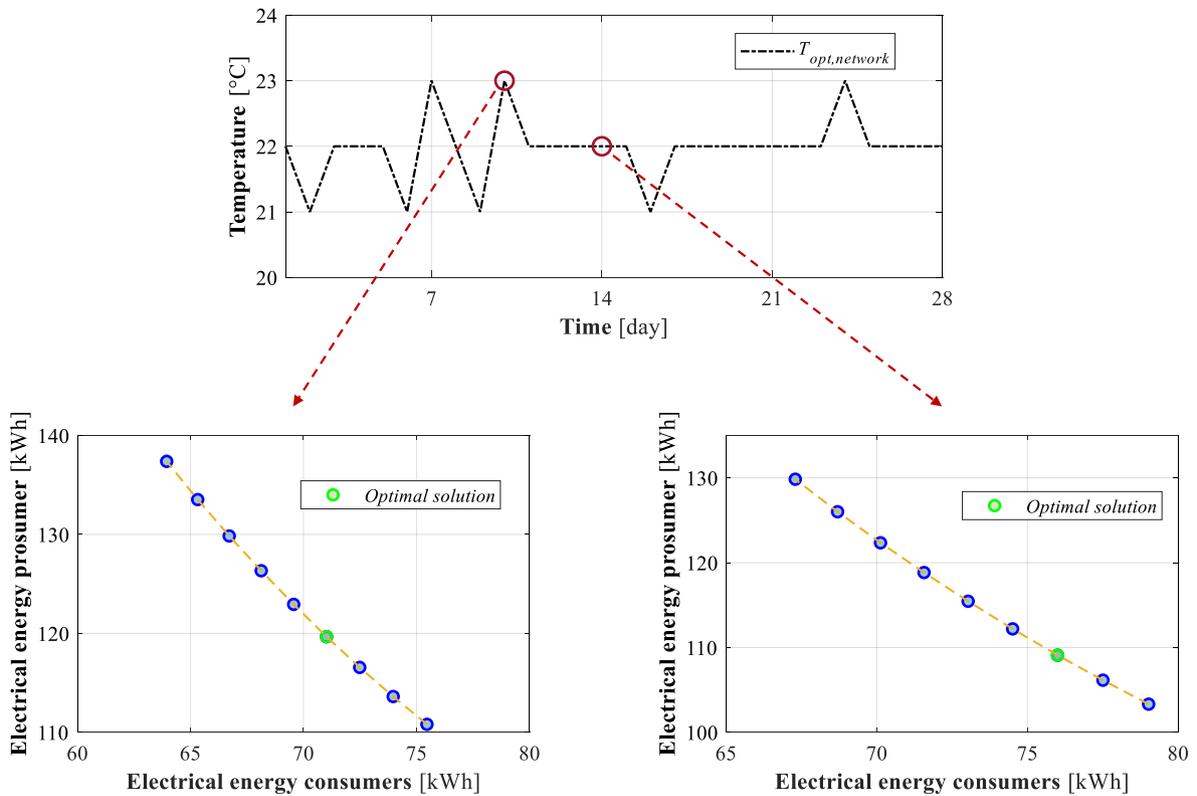| Substation heat pumps.				
Parameter	m.u.	Data centre	Residential	Office
fluid	[–]	R-410a	R-410a	R-410a
$\dot{Q}_{load,nom}$	[kW]	30	10	15
ΔT_{min}	[°C]	3	3	3
ΔT_{sc}	[°C]	2	2	2
ΔT_{sh}	[°C]	5	5	5
$T_{w,set}$	[°C]	7	45	45
$\dot{m}_{w,load}$	[kg/h]	5155	859	1289
$\dot{m}_{w,source}$	[kg/h]	6305	750	1095

Fig. 9. Optimisation procedure to assess the optimal daily temperature of the DHC network.

heat pumps. Specifically, prosumers contribute thermal power in heating from the condenser, whereas consumers provide cooling power from the evaporators.

To emphasize the impact of control strategies (PS1 and PS2) and the heat inputs from the source side of users' heat pumps on the energy

balancing station operation, a three-day duration from January 2nd to January 4th was considered. In Fig. 10a, the blue area represents ($\dot{Q}_{ev,cons}$) – the thermal powers from consumer evaporators, while the red area represents ($\dot{Q}_{cond,\,pros}$) – the thermal powers from prosumer condensers. This figure also illustrates the network return temperature ($T_{w,}$

a)

b)
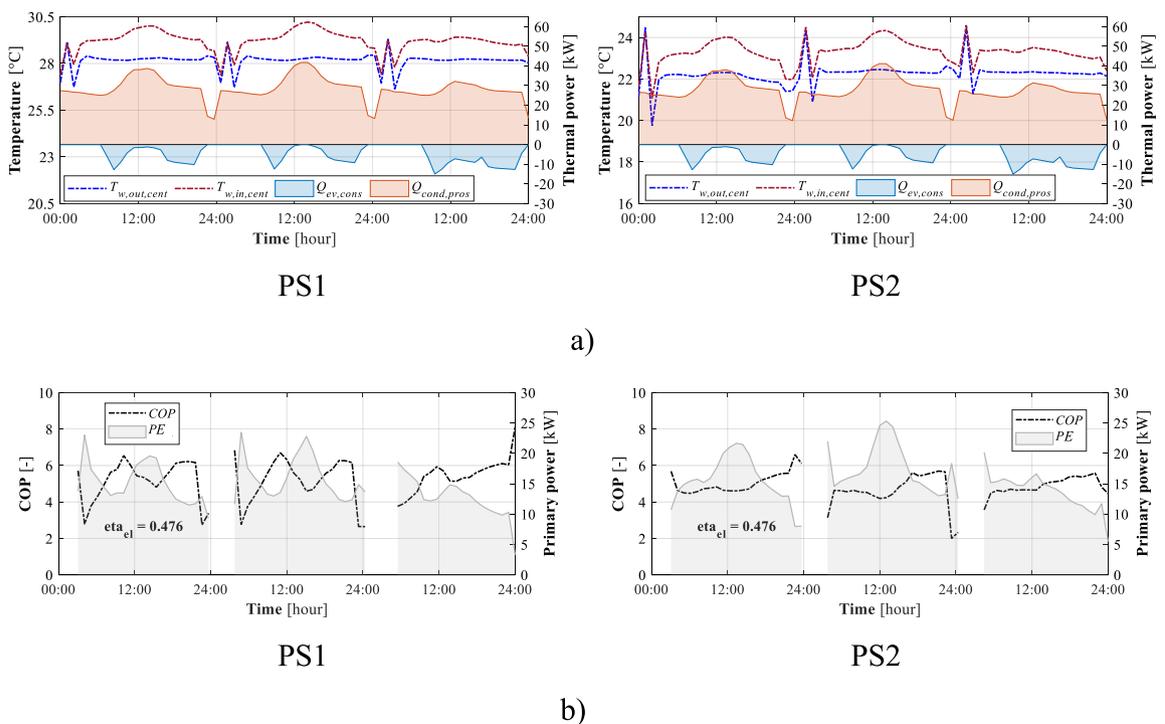
Fig. 10. PS1 vs. PS2. Dynamic profiles results: a) inlet, and outlet water temperature, and network thermal gain; and b) primary energy and energy efficiency ratio of energy hub.

in,cent) as a red dotted line, influenced by previous user heat fluxes inputs, and the supply temperature ($T_{w,out,cent}$) as a blue dotted line, determined by the set-points of the two strategies. The left graph in Fig. 10a corresponds to the results of PS1, while the right graph pertains to PS2. In Fig. 10b, the graphs depict the corresponding primary energy needs of the energy hub (PE_{hub}).

Observing both the PS1 and PS2 systems in the figures, it becomes evident that activation of the energy hub chiller (depicted as the grey area in Fig. 10b) is necessary to cool the heat transfer fluid of the network. This need arises from the higher heat input of the prosumer's condenser compared to the cooling input of the consumer evaporators. In particular, in case of PS1 system, the temperature $T_{w,out,cent}$ stands below 28 °C (maximum value for PS1), whereas the temperature $T_{w,out,cent}$ in case of PS2 system is cooled to 22 °C (optimised temperature for the days under investigation).

These different operations of the central energy balance imply different primary energy demand of the energy hub chiller and therefore different *COP* (depicted with black dotted lines). Specifically, Fig. 10b highlights that the PS2 system, for the investigated time-period, requires a higher primary energy equal to an increase of 5 % respecting to PS1. Furthermore, it is noteworthy that the determination of primary power considers a national electricity grid efficiency ($\eta_{el,grid}$) of 0.476 [45].

5.2.2. User level

The objective of this analysis is to assess the impact of strategies PS1 and PS2 on the energy performance of individual users' heat pumps. The temperature of the heat transfer fluid within the thermal network affects both the efficiencies of the heat pumps and their electricity consumption. To emphasize the influence of these strategies, Fig. 11 compares the *EER* and *COP* indices of the users' heat pumps along with the electrical energy demands of the compressors ($P_{el,c}$). The simulated period corresponds to the three-day from 2nd to 4th of January, matching with the time range of Fig. 10.

Here, for the three network users typologies (data centre - Fig. 11a, residential building - Fig. 11b, office - Fig. 11c), the data obtained from the adoption of PS1 and PS2 system are presented. Starting from the data centre (Fig. 11a), that is the building type behaving as a prosumer, it is possible to notice from the figure that adopting PS2 is particularly beneficial due to the significant increases in the *EER* (black dotted lines in the figure) and decreases of required electrical power (green areas in the figure). On the other hand, with respect to the residential and office buildings (that behave as consumers), there are no appreciable differences between PS1 and PS2 (see Fig. 11b and c).

For this specific case, the enhanced energy performance observed in the prosumer's heat pump is due to the network temperature in the PS2 scenario that is equal to 22 °C, respecting to 28 °C experienced in the PS1 scenario (see Fig. 10a). Indeed, this temperature difference,
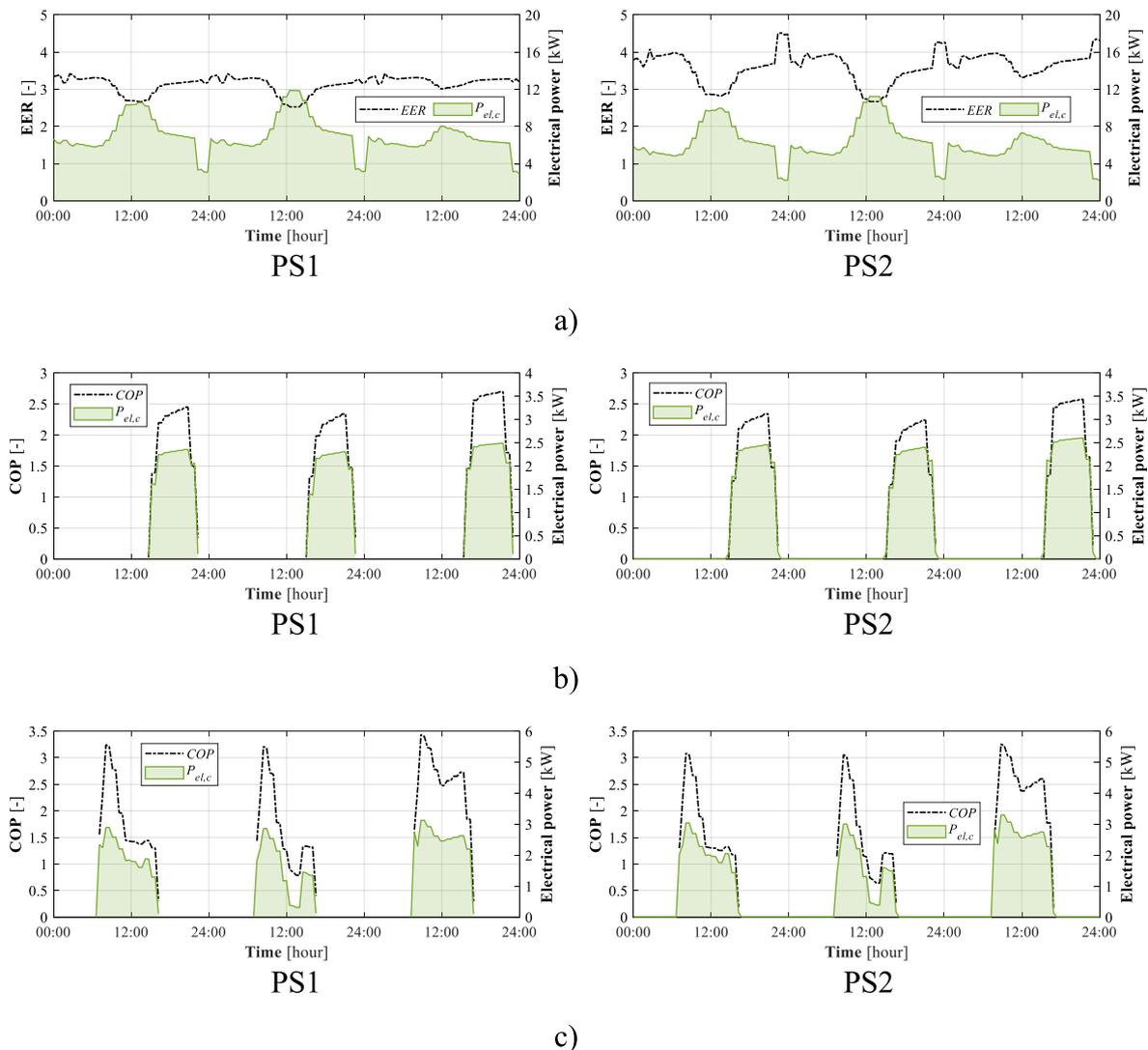

Fig. 11. PS1 vs. PS2: HPs performance and electrical power for three sample days in case of a) data centre; b) residential building; c) office.

between PS1 and PS2 strategies, affects the source side of the prosumer's heat pump, narrowing the gap between the condenser and evaporator temperatures. As a result, there is a reduction in the electrical power required by the compressor. Conversely, for consumer heat pumps operating in heating, the higher temperature in the PS1 scenario favours a reduction in compressor electrical consumption. However, the substantial difference between the source and load temperatures, in heating operation of the heat pump, limits the benefits of increasing consumer evaporator temperatures compared to the prosumer scenario.

5.2.3. Energy performance analysis

To assess the overall energy performance achieved by the 5GDHC system under the two investigated strategies, PS1 and PS2, an analysis was conducted throughout the entire cooling season.

At first, a comparison between the heat pumps efficiency obtained in the two different scenarios was undertaken. The histograms in Fig. 12 demonstrate how the data are distributed and the probability density of the observations that fall within the range of *COP* values that were under investigation.

In the cases of the consumers buildings, the HPs work in more efficient conditions as it is highlighted in Fig. 12a and b. Regarding the residential users, it was obtained a higher probability to work with high efficiencies in the second proposed strategy respecting to the reference free-floating temperature control. Indeed, this is demonstrated in Fig. 12a where the observations for the second proposed strategy in the *COP* bins of 2–2.5 and 2.5–3 are greater than the reference case. Whilst the offices HPs, as reported in Fig. 12b, experience a higher probability in the *COP* range 3–3.5 with the optimised control strategy PS2. The same analysis was conducted for the prosumer of the network. As it can be seen from the histogram in Fig. 12c, the optimised strategy PS2 allows the HP to work in conditions which achieve efficiencies higher than 3.5 that cannot be reached by the reference scenario PS1.

Starting from this analysis of users' heat pump efficiencies, a comparative study is presented in Fig. 13, illustrating the monthly primary energy consumption differences between the two proposed strategies. As previously reported for the assessment of the primary energy it was considered an efficiency of the electricity grid equal to 0.476 [45].

In Fig. 13a and b, the primary energy consumption for the residential building and office, respectively, is depicted. It is noticeable that the discrepancy between the analysed scenarios is minimal, consistent with the findings described in the previous Fig. 12a and b. For the residential building, the annual primary energy consumption under PS2 amounts to 5.82 MWh/year, indicating a 3 % reduction compared to PS1. Conversely, for the office, the annual consumption under the PS2 strategy totals 6.68 MWh/year, showcasing a 2 % reduction compared to PS1.

Fig. 13c emphasizes the comparison between the PS1 and PS2 systems, highlighting the energy advantage of PS2 for the district prosumer. The reduction in energy requests is evident across all examined months, as indicated by the total energy value (right axis). With the adoption of PS2 (blue dotted line), there is a significant energy savings of 13 MWh/year compared to PS1 (blue dotted line) corresponding to a percentage reduction of 20.5 %.

The same analysis presented for the prosumer and consumers in Fig. 13 have been conducted for the energy hub, and reported in Fig. 14. The PS2 strategy, employing predictive temperature control for the thermal network, seems more energy-demanding compared to the free-floating strategy of PS1. This discrepancy arises from the difference in approach between the two strategies. Unlike PS2, PS1 allows the network to function within a broader temperature range (i.e., 20–28 °C), minimising the need for frequent activation of the energy hub systems. Consequently, this limitation leads to reduced energy consumption compared to the PS2 case, which conversely necessitates adherence to a specific temperature set-point.

PS2 system shows a convenience over PS1 only in January and December (see Fig. 14), and the associated primary energy consumption
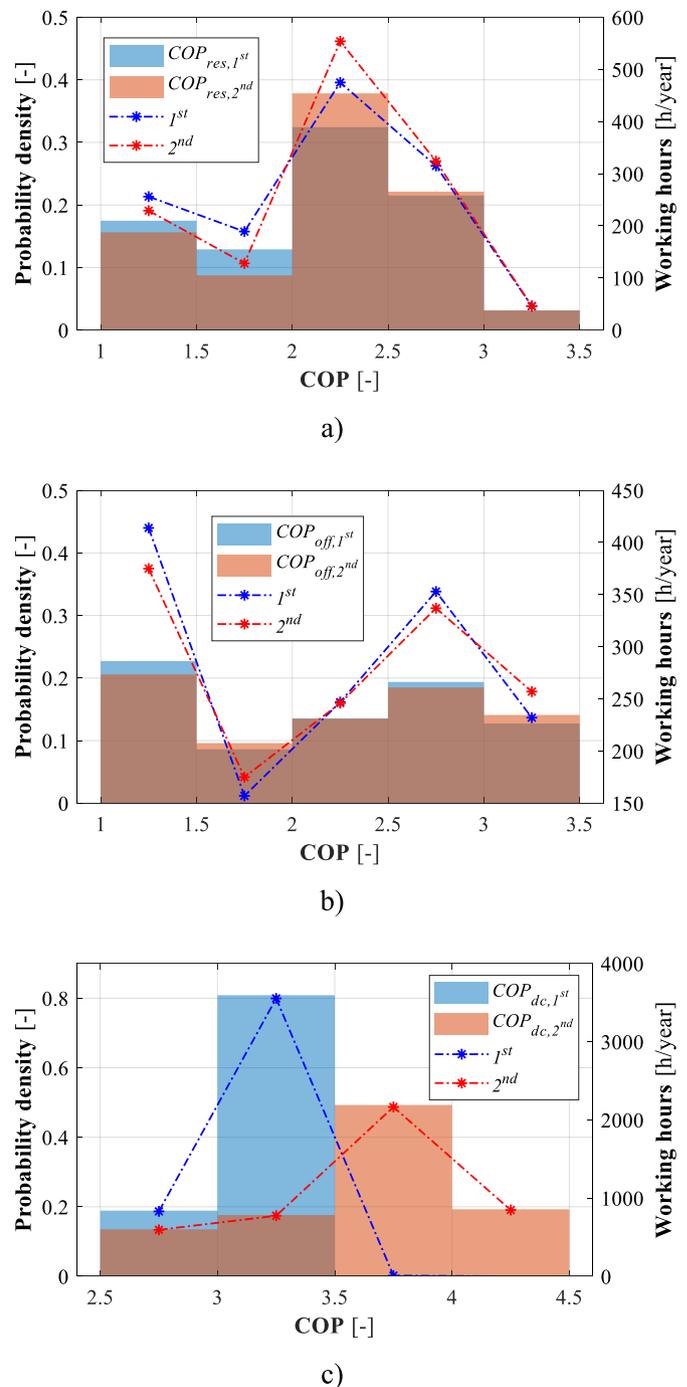

Fig. 12. PS1 vs. PS2: users' heat pumps COP probability density: a) residential; b) office; c) datacentre

is 5.4 % higher than the PS1 strategy.

Finally, the comparison of the total primary energy used by the 5GDHC system was then done. According to a community perspective, the case study under investigation envisions the substations and station being combined, along with centralised management. Fig. 15 demonstrates how cost reduction at the prosumer substation ensures system-wide savings that balance and overcome the energy hub excessive consumption. The fact that the data centre substation uses more energy than the power station explains this outcome. A total primary energy saving of 10.3 MWh/year (corresponding to a percentage reduction of 6.5 % compared to the reference strategy PS1) is possible overall under the network temperature optimisation scenario using daily predictive
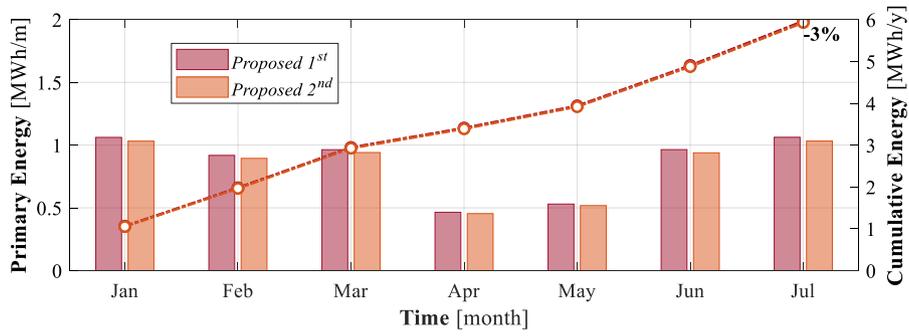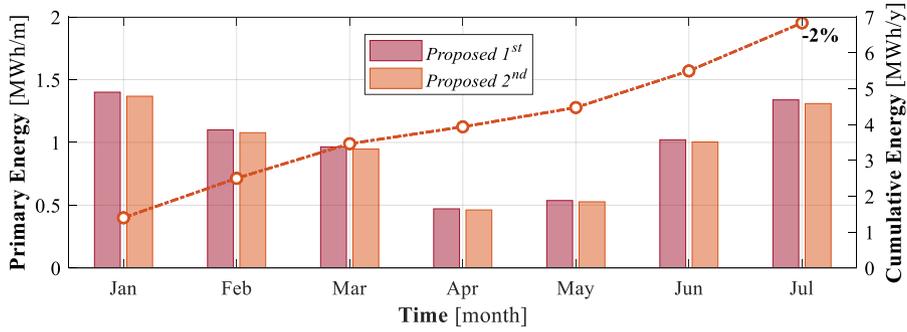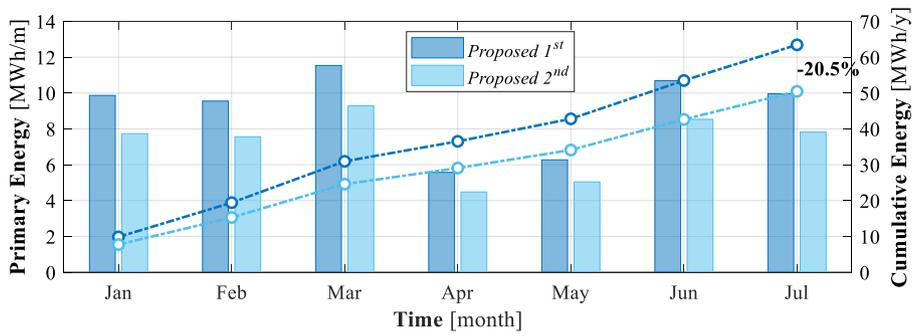
Fig. 13. PS1 vs. PS2 primary energy consumption on yearly and monthly basis: a) residential building; b) office; c) data centre.
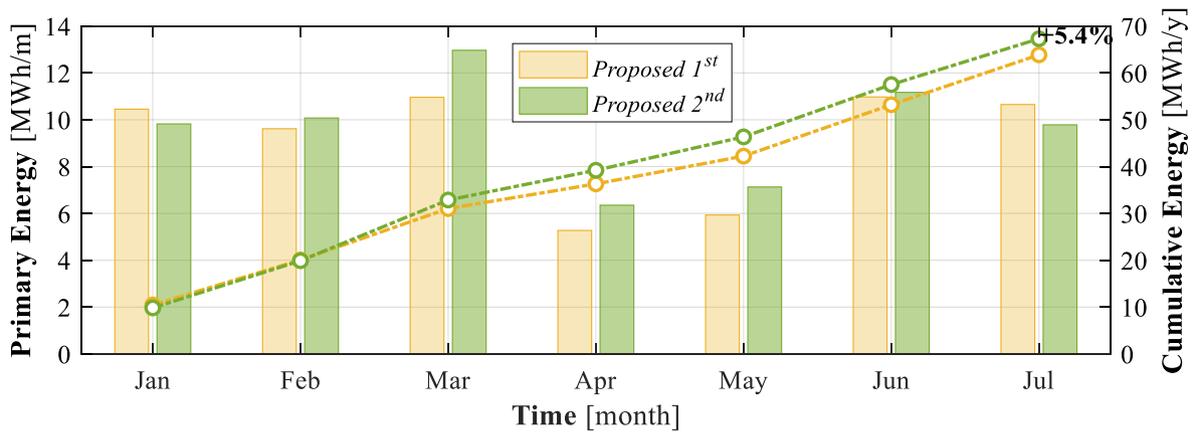

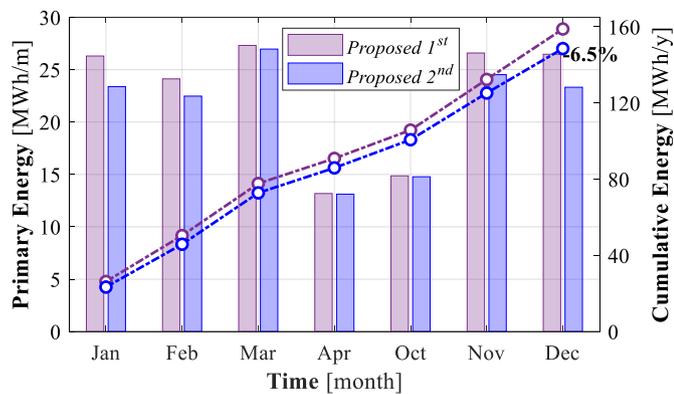**Fig. 14.** PS1 vs. PS2: energy hub primary energy consumption on yearly and monthly basis.

Fig. 15. PS1 vs. PS2: overall 5GDHC system primary energy consumption on yearly and monthly basis.

logic.

6. Conclusion

The advancement of generations has resulted in a decrease of the heat transfer fluid temperature in district heating and cooling networks, which has increased the possibility in poly-generative, renewable based, district heating and cooling networks. In turn, such occurrence has raised the need in the creation of powerful yet adaptable tools for the sizing, optimisation, and management of these systems. Among the others, an ideal setup that ensures greater flexibility and potential for exploitation of waste and renewable energy sources is the indirect 5GDHC. Given the above, in this work a comprehensive simulation model for 5GDHC systems energy assessment has been developed and experimentally validated. In particular, the developed simulation tool adopts a white-box modelling approach allowing for high-accuracy analyses and fine controls. To verify the tool reliability, it underwent an experimental validation procedure by exploiting the data collected from an existing prototype built at the ENEA Portici research center (Italy). To verify the developed tool potential, it is adopted to test a novel control strategy for the 5GDHC network temperature management. Optimising the network working temperature can result in higher system efficiency and convenience. To guarantee the stability and robustness of the control system, the optimal temperature value is determined every 24 h. A multi-objective problem was used in the optimisation process to find the best solution that simultaneously minimises prosumers' and consumers' daily electricity costs. The convenience of such novel control method is verified through a proof-of-concept analysis consisting of a 6 buildings 5GDHC network in Milan (that included 1 prosumer building and 5 consumer ones). For comparison purposes, a standard free-floating network temperature approach is also investigated. The results of the proposed optimisation scenario demonstrated a saving of 13 MWh/year of primary energy for the prosumer buildings. On the other hand, the energy hub uses 3.8 MWh/year more primary energy, but the entire 5GDHC system is 6.5 % (equal to 10.3 MWh/year of primary energy saved) more energy efficient overall than in the reference scenario, proving the potential benefits in adopting the proposed methodology. The implementation of a clustering methodology may be investigated in the future in order to find the best network configuration for increased thermal self-balancing capabilities. Future research will also investigate how to incorporate renewable energy sources to increase energy efficiency and lower CO_2 emissions.

CRediT authorship contribution statement

A. Buonomano: Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **C. Forzano:** Writing – review & editing, Visualization, Validation,

Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **L. Mongibello:** Writing – review & editing, Validation, Project administration, Funding acquisition, Data curation, Conceptualization. **A. Palombo:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **G. Russo:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, 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.

Data availability

Data will be made available on request.

Acknowledgments

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