

A comprehensive techno-economic analysis of solar energy integration in low-temperature district heating and cooling systems

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ABSTRACT

This study investigates the integration of solar technologies and energy storage at the individual building level within fifth-generation district heating and cooling networks. Nine distinct building configurations are evaluated, incorporating photovoltaic (PV) systems, solar thermal collectors, photovoltaic-thermal (PV-T) systems, thermal energy storage (TES), and electric batteries. The techno-economic performance of these configurations is assessed for three user types: data centres (thermal prosumers) and residential and office buildings (thermal consumers). To capture dynamic interactions among thermodynamic components, an integrated thermal model is developed using an object-oriented methodology. Key findings for a case study in northern Italy show that combining PV systems with solar thermal collectors and energy storage results in primary energy savings of 57 % for residential buildings and 55 % for offices, compared to a reference scenario without solar technologies. Replacing PV systems with PV-T systems of equivalent area eliminates the need for solar thermal collectors, achieving over 50 % space savings. From a techno-economic perspective, the configuration for residential buildings that combines PV systems, solar thermal collectors, batteries, and TES achieves a payback-time (PBT) of 18 years without electricity exports, reduced to 14 years when excess electricity is exported. For offices, the PV-T system proves more cost-effective, achieving a PBT of 14.6 years, reduced to 11 years with electricity exports. The PBTs observed for the PV-only configuration are 5.9 years for offices and 5.8 years for the data centre. In the community-based approach, where investments are made collectively by users, PV-T systems achieve a low PBT of 6.4 years.

1. Introduction

The energy and environmental impact of the building sector has grown significantly in recent years, accounting for approximately 31 % of the global energy consumption and 37 % of greenhouse gas emissions [1]. Space heating, cooling, and domestic hot water (DHW) needs represent the largest contributors to this consumption, collectively accounting for more than 60 % of the building sector energy use [2]. Centralised systems, such as those used in district heating applications, are often preferred over decentralised solutions due to their potential to reduce not only costs but also emissions [5]. To address heating and cooling demands, combined heat and power (CHP) systems have been

proposed as a viable alternative to traditional gas boilers [3], offering notable economic benefits [4]. However, CHP systems themselves contribute to greenhouse gas emissions, prompting the exploration of cleaner alternatives. Hydrogen-fuelled technologies have emerged as a promising alternative, however, hydrogen technology installation costs remain high, and heat provision with hydrogen was demonstrated by many studies [6] to be significantly more expensive than with heat pump systems [7]. To address these challenges, the European Green Deal has outlined a roadmap towards 2050, emphasising the electrification of building thermal demands as a key solution. This plan includes a significant expansion in heat pump installations, targeting 1800 million units by 2050 compared to just 180 million in 2020 [8].

In this context, fifth-generation district heating and cooling (5GDHC)

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Nomenclature*Acronyms*

5GDHC	fifth-generation district heating and cooling
BESS	battery energy storage system
CAPEX	capital expenditure [€]
COP	coefficient of performance [–]
DHW	domestic hot water
EES	electrical energy storage
HVAC	heating ventilation and air conditioning
NOCT	nominal operating cell temperature [K, °C]
OPEX	operating expenses [€]
PBT	payback time
PES	primary energy saving [%]
PS	proposed scenario
PV	photovoltaic
PV-T	photovoltaic-thermal
REV	revenues [€]
SC	self-consumption [%]
SOC	storage systems state of charge [%]
SS	self-sufficiency [%]
STC	solar thermal collectors
TES	thermal energy storage

Symbols

A	surface [m ²]
A_{cs}	tank cross section surface [m ²]
A_{fl}	building floor surface [m ²]
A_{lat}	tank lateral surface [m ²]
c	unit cost [€/kWh]
C_{BESS}	battery capacity [J, Wh]
c_p	specific heat capacity [J/kg/K]
E	energy [J, Wh]
E_{el}	electricity consumption [J, Wh]
E_p	fossil fuel energy consumption [J, Wh]
G	solar irradiance [W/m ²]
h	enthalpy [J/kg]
I	current [A]
k	thermal conductivity [W/m/K]
M	mass of tank water volume [kg]
$\dot{m}$	flow rate [kg/s]
$N_{//}$	number of parallel modules
N_{occ}	number of occupants
P	electricity [W]
p	pressure [Pa]
Q	thermal energy [J, Wh]
$\dot{Q}$	thermal power [W]
$Q_{H,i}$	heat dissipation through the i-th pipe network section [W]
$R_{c,w,i}$	water convective thermal resistance of i-th pipe network section [K/W]
$R_{k,w,i}$	water conductive thermal resistance of i-th pipe network section [K/W]
$R_{k,pip}$	pipe conductive thermal resistance [K/W]
r_p	pressure ratio [–]
sp_{el}	selling price of electricity [€/kWh]
T	temperature [K, °C]
t	time [s]
U_l	tank heat loss coefficient [W/m ² /K]
U_{wl}	heat transfer coefficient of building walls [W/m ² /K]
U_{win}	heat transfer coefficient of building windows [W/m ² /K]
V	voltage [V]
V_{bld}	building volume [m ³]
V_i	volume of i-th pipe network section [m ³]
z	height of tank water volume [m]

Greek

α_{gas}	fraction of gas plant in national grid
α_{pet}	fraction of petrol plant in national grid
γ_{ff}	fraction of electricity produced by grid from fossil fuels
η	efficiency
η_o	optical efficiency of solar thermal technologies
λ	polynomial coefficients of compressor efficiency
π	total revenues [€]
ρ	density [kg/m ³]

Subscripts

abs	absorber plate
air	air properties
amb	ambient properties
b	boiler
bs	balancing station
c	tank cold volume
car	carbon energy plant
ce	photovoltaic cell
ch	chiller
cl	cooling
co	heat pump condenser
comp	heat pump compressor
dc	data centre
dem	electricity/thermal demand
DHC	district heating and cooling
el	electrical
ev	heat pump evaporator
ff	fossil fuels
g	power grid
gas	natural gas
grd	properties of the ground
h	tank hot volume
hp	heat pump
hru	heat recovery unit
ht	heating
in	inlet
inv	investor
is	isentropic
max	maximum
net	district heating and cooling network
nom	nominal conditions
off	office building
opt	optimal
out	outlet
p	primary energy consumption
pet	petrol energy plant
PP,HEX	pinch-point temperature difference
ps	proposed scenario
r	return circuit of district network
ref	standard test conditions
res	residential building
rf	heat pump refrigerant fluid
rs	reference scenario
s	supply circuit of district network
scl	subcooling
sh	superheating
shr	shared
sur	surplus
th	thermal
tot	total
us	district heating and cooling system user
w	water

systems have emerged as a promising solution for integrating water-to-water heat pumps in building districts [9]. Unlike previous generations, 5GDHC systems operate with a decentralised structure where the thermal network interfaces with user “substations”, which essentially function as heat pumps [10]. Rather than directly supplying buildings with heating or cooling energy, 5GDHC systems maintain a low-temperature thermal network that provides an optimal temperature range for heat pump operation. This thermal network acts as a source or sink for heat, depending on the heat pump mode: (1) in heating mode, the thermal network serves as the low-temperature heat source for the heat pump evaporator; and (2) in cooling mode, it acts as the heat sink for the heat pump condenser. This configuration enables the heat pumps to operate with high coefficients of performance (COP) by minimising the temperature lift required for heating and cooling [11].

A defining feature of 5GDHC systems is their operation at low working temperatures, typically in the range 20–30 °C [12]. This characteristic allows users with diverse thermal demands to connect to the same thermal network [13]. For example, heat extracted from one user during cooling can be redistributed to another user requiring heating. Consequently, these systems offer advantages over traditional district heating and cooling systems, including a simplified thermal network infrastructure, reduced distribution line requirements and enhanced overall efficiency [14].

Innovative configurations for user substations have been proposed in recent studies. For instance, Ref. [15] introduces a hydraulic kit that, through an experimental control logic, diverts flow rates to meet thermal demands or heat pump requirements based on network temperatures. Similarly, Ref. [16] presents a hydraulic kit that adjusts the flowrate based on the outlet temperature of the heat pump source side, directing it to either the supply or return circuit.

Optimising the network temperature is a critical factor for efficient operation. For example, Ref. [17] demonstrates monthly cost savings of 10–60 % by using model predictive control strategies that account for users’ requirements and ground temperature, as opposed to constant temperature control. Furthermore, a bi-objective optimisation approach is proposed in Ref. [18] to dynamically adjust network temperatures, reducing energy consumption by 20 % compared to operating constantly at 20 °C.

5GDHC systems can be classified as thermal energy communities [19], with users categorised as thermal consumers or thermal prosumers [20]. This classification stems from the capability of users with opposite thermal demands to exchange energy via the network, promoting thermal neutrality and reducing reliance on the balancing thermal station, which is the centralised unit used to regulate, manage, and redistribute thermal energy within the network. The work of Ref. [21] demonstrates a 31 % reduction in energy demand from the balancing station in a cluster of ten buildings in southern Italy by effectively utilising the presence of prosumers. However, optimising prosumers’ integration is crucial, as unmanaged waste heat from prosumers could adversely impact the balancing station energy consumption. A model predictive control strategy proposed in Ref. [22] reduces balancing station energy consumption by 75 % compared to scenarios where all waste heat is supplied to the network.

1.1. Literature review

The integration of centralised renewable systems within district heating and cooling systems (including previous generations) has been extensively investigated in the literature. Solar-based technologies such as photovoltaic (PV), solar thermal, and hybrid photovoltaic-thermal (PV-T), offer significant energy-saving potential. Their flexibility is further enhanced through the integration of battery energy storage systems and thermal energy storage.

One of the principal advantages of 5GDHC systems, compared to the district heating and cooling systems of previous generations, is their ability to facilitate the integration of renewable energy technologies,

particularly low-temperature solar and geothermal systems [23]. Operating at low temperatures leads to increased efficiency of solar collectors and a reduction in thermal losses [24].

Coupling a PV field with the balancing station of a 5GDHC system has been shown to reduce reliance on the central grid by 30 %, as excess PV electricity generation powers the balancing station and stores surplus thermal energy in the network [25]. Ref. [26] optimises the integration of a PV solar field supplying electricity to a ground-source heat pump serving a district of 50 buildings, achieving primary energy savings of 64 %. Similarly, Ref. [27] develops an energy and economic optimisation method to determine the optimal sizing of renewable central stations in 5GDHC systems, achieving an overall energy efficiency of 84 % through PV fields, wind turbines, solar thermal collectors, and seasonal storage.

In Ref. [28], a dynamic operation strategy for large solar collector fields connected to the balancing station in low-temperature DHC systems increases the solar fraction from 66 % (under fixed temperature conditions) to 79 %. Centralised solar-assisted configurations were further explored in a Mediterranean climate context (Palermo, Italy), where solar thermal collectors are employed to supply absorption chillers for controlling district network temperature during the cooling season. Results show a 20 % increase in primary energy savings compared to the baseline 5GDHC setup without solar energy systems [29]. An economic evaluation conducted in Ref. [30] concludes that evacuated tube collectors used in district heating applications could achieve a payback period of approximately 6.9 years.

Hybrid configurations combining solar thermal collectors with geothermal boreholes has been found to reduce auxiliary heating and cooling requirements while maintaining thermal balance [31]. Moreover, seasonal thermal energy storage integrated with solar energy has the potential to store surplus energy during summer for winter use, achieving up to 70 % emission reductions compared to conventional systems [32]. For instance, Ref. [33] demonstrates that storing excess thermal energy from user substations and centralised PV-T systems during the cooling season in borehole systems allowed 85 % of this heat to be recovered during the heating season in a Canadian district. Similarly, Ref. [34] examines the life-cycle performance of a 5GDHC system, characterised by a campus of 5 buildings in Melbourne, integrating rooftop PV installations, central battery storage and thermal energy storage, demonstrating reductions in electricity demand through a centralised management of the surplus electricity.

Despite the growing focus on centralised renewable energy integration in 5GDHC systems, the potential of decentralised renewable energy solutions at the user level remains underexplored. The decentralisation of renewable energy, particularly solar, is increasingly relevant for urban districts where large-scale centralised systems may not always be feasible [35]. It also contributes to reducing each building reliance on the central grid, enhancing energy autonomy, and enabling suitable energy management strategies that better reflect the specific demand profiles and operational schedules of individual buildings. Moreover, decentralised systems can support grid stability through local generation [36]. This approach is particularly compatible with 5GDHC systems, which are characterised by a decentralised provision of heating and cooling through user substations, a feature not present in previous generations of DHC systems [37]. Ref [38] shows that decentralised configurations can enhance flexibility, reduce distribution losses, and better exploit local renewable sources compared to centralised systems.

The integration of solar technologies and storage systems in the building energy sector is well established [39]. For example, integrating PV systems at the building level to meet heat pump energy needs demonstrated improved self-sufficiency when optimised alongside storage technologies [40]. In addition, PV-T systems have demonstrated the potential to enhance heat pump COP by raising the evaporator temperature with excess thermal energy [41], as demonstrated in dual-source solar-assisted heat pump configurations [42]. Additionally, integrating thermal energy storage has proven to increase flexibility and

enable demand-side response [43].

A limited number of studies have assessed the integration of decentralised solar systems within 5GDHC networks. For instance, Ref. [44] investigates the performance of a 5GDHC system based on 7 residential buildings in three different climatic regions, where PV-T modules are installed on each building roof. These systems supply electricity to the building substation, and the thermal energy is utilised to directly meet the building space heating and DHW requirements, achieving 70 % self-consumption at the user level and a 21 % reduction in the balancing station electricity demand compared to a baseline case without decentralised solar integration.

Ref. [45] investigates the deployment of rooftop solar thermal collectors in a small-scale 5GDHC system. Results indicate that up to 38 % of the produced thermal energy could be shared with users located within 500 m of the source collector through the district network. Similarly, Ref. [46] shows how integrating high-vacuum solar thermal collectors at the user level can satisfy cooling needs of the district network by supplying thermal energy to drive absorption chillers, thereby reducing electricity demand at the central balancing station.

Several modelling approaches have been employed in the literature to assess the integration of renewable energy technologies in DHC systems, including dynamic simulations (developed within TRNSYS [47] or Modelica [48] environments) and co-simulation frameworks [49]. While these studies provide valuable insights in renewable energy

potential, they rely on rigid modelling structures that limit flexibility in representing diverse building demands, district configurations, or decentralised renewable-based systems. Moreover, the integration of control strategies and the detailed representation of user level interactions are often simplified, reducing the capability to fully assess the system's operational potential.

These findings suggest that decentralised solar systems, combined with batteries and thermal storage systems, can enhance system flexibility and reduce the environmental impact of single buildings. However, several critical aspects of decentralised integration within 5GDHC systems remain insufficiently addressed in the literature: (1) How can the low-temperature heat from decentralised solar systems be optimally exploited by user level water-to-water heat pumps? (2) How should surplus thermal and electrical energy be managed to reduce losses or grid exports? (3) What is the effect of decentralised solar technologies on the performance of the central balancing station? (4) How do different decentralised solar and storage system combinations perform energetically and economically within prosumer- and consumer-based 5GDHC configurations from user level and district perspectives?

1.2. Contribution

The aim of this study is to address the identified literature gap by investigating the integration of solar technologies alongside electrical

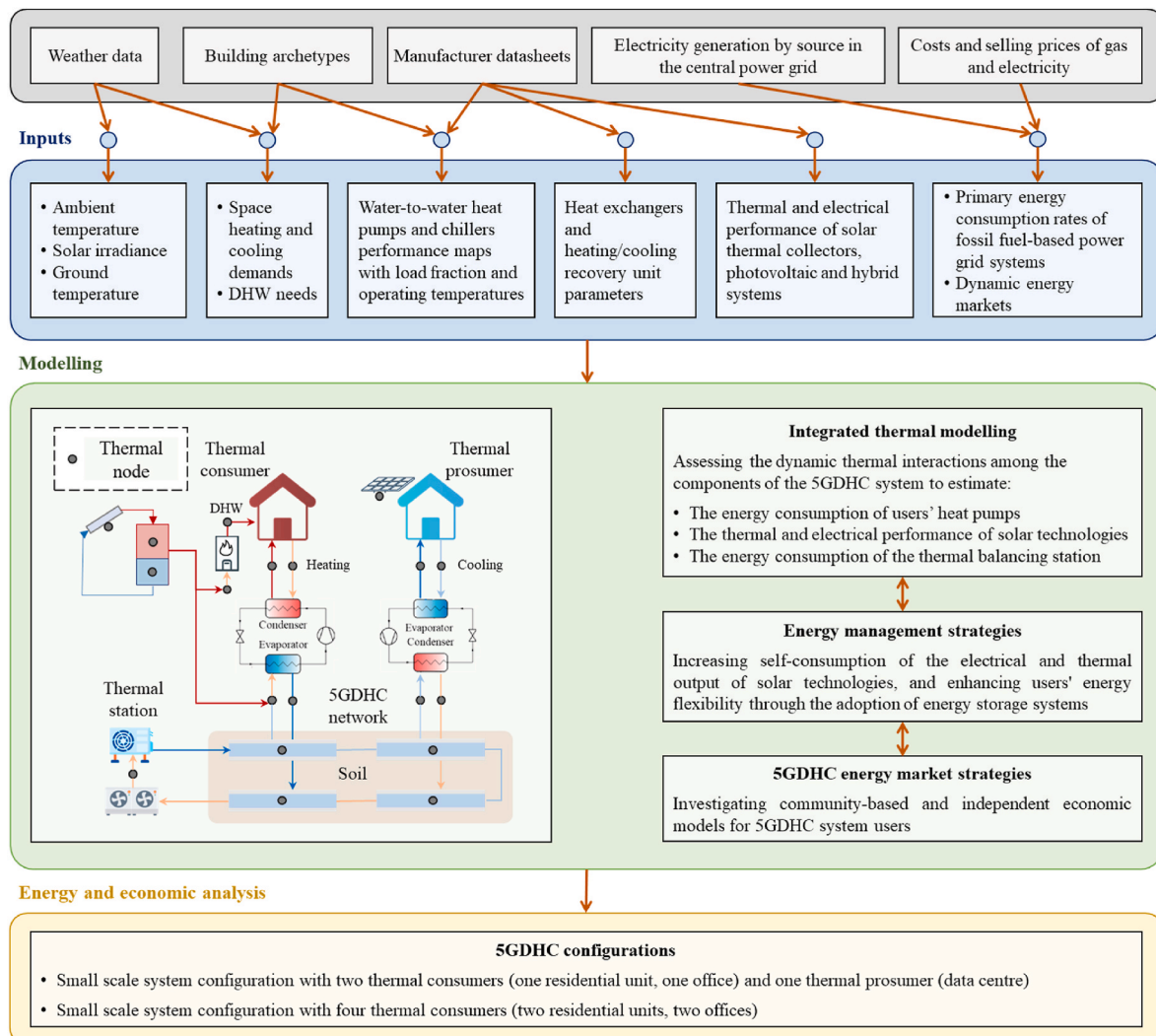


Fig. 1. Schematisation of developed framework. Diverse configurations of solar technologies integrated at user level are investigated for two types of 5GDHC system configurations. Economic and energy analysis are conducted.

energy storage (EES) and thermal energy storage (TES) at individual building level within 5GDHC systems. The primary novelty lies in proposing novel configurations to be integrated within the 5GDHC infrastructure, aiming at maximising the electrical and thermal outputs of solar systems while enhancing self-consumption and improving the performance of individual user substations. The solar technologies examined include PV systems, solar thermal collectors, and PV-T systems, while the focus of EES is on lithium-ion batteries and that of TES on stratified hot-water cylinders. Various configurations are explored to assess the potential interactions between these technology options.

To specifically address how low-temperature heat from decentralised solar systems can be optimally exploited, the study investigates technical configurations where solar-assisted heat pumps can operate more efficiently by increasing their source temperature through solar inputs.

To evaluate how surplus thermal and electrical energy should be managed, storage systems (both thermal and electrical) are included to increase the self-consumption of each user and the corresponding flexibility levels. Furthermore, the potential of sharing electricity surpluses with the central balancing station and thermal energy excesses with the district network is explored.

To assess the impact of decentralised solar integration on user substations, the central balancing station, and the district network, this study develops an integrated thermal model based on an object-oriented methodology. It captures the thermal interactions within 5GDHC systems, accounting for temperature evolution and thermal inertia. This enables a detailed analysis of how decentralised energy inputs influence the operation and energy demand of both the central balancing station and the district thermal network. The object-oriented approach addresses the limitations of existing modelling techniques (e.g., traditional dynamic simulation frameworks) by enabling improved scalability and flexible replicability. The model is designed to adapt a wide range of system configurations, including different user substation layouts, varying numbers and types of buildings, diverse management strategies for decentralised solar and storage systems, and alternative district network topologies.

Additionally, the research evaluates the energy and techno-economic impacts of the suggested configurations by estimating primary energy savings and conducting a payback-time analysis for various user types: data centres (acting as thermal prosumers) and residential and office buildings (acting as thermal consumers). The comparative analysis extends to two distinct small-scale 5GDHC system configurations: one prosumer-based setup comprising a data centre, a residential unit, and an office, and another consumer-based setup featuring two residential units and two offices. The economic assessment incorporates two strategies, one where users operate independently and another that adopts a community-based approach where investments are made collectively.

The proposed user configurations and associated energy management strategies for integrating solar and energy storage technologies are described in Section 2.1. The modelled scenarios, including the two different 5GDHC configurations, are described in Section 3. Results are provided in Section 4 and concluding remarks in Section 5.

2. Methods

This section outlines the methodology used for estimating the energy and economic impact of solar technologies integrated at user level in 5GDHC systems. It is assumed that the existing technologies (i.e., reference scenario) in the modelled 5GDHC system include water-to-water heat pumps to meet heating and cooling demands, and gas boilers to satisfy DHW needs, both integrated at the user level, as well as an air-based heat/cooling recovery unit combined with an air-source heat pump system at the central thermal balancing station to regulate network temperature.

The proposed framework is shown in Fig. 1. Firstly, essential input data are collected, including weather data, building archetypes, manufacturer datasheets for key components, and information on energy

performance and tariffs of the national power grid. These inputs support the energy and economic analysis of the two 5GDHC configurations under investigation: (1) a small-scale configuration with one thermal prosumer and two consumers; and (2) a small-scale configuration with four thermal consumers. This small-scale configuration allows for a detailed analysis of how energy and economic performance vary across different 5GDHC configurations and user types. In larger systems with a higher number of users, the performance of the central balancing station may be influenced by aggregation effects, whereas the behaviour and impact of individual users on the network remain comparable to those observed in small-scale setups.

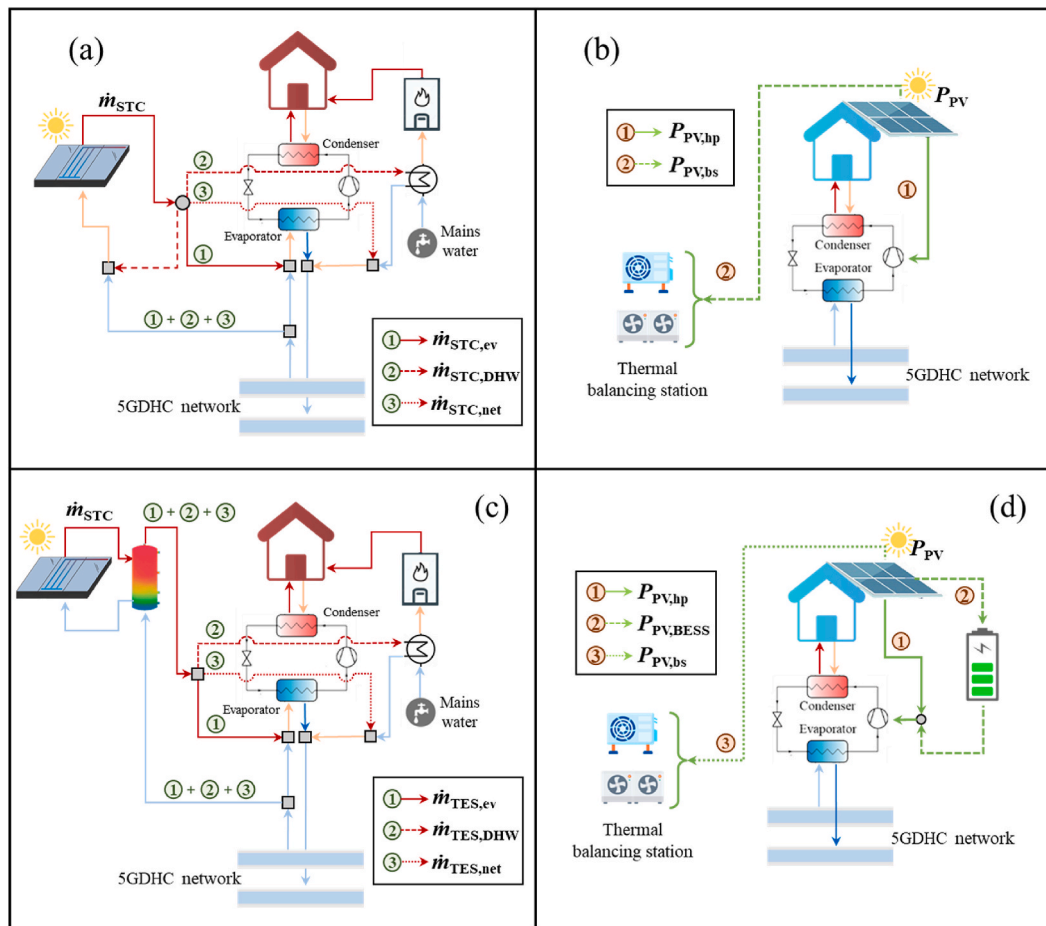
The space heating and cooling demands of users are estimated using a physics-based building model from Ref. [50]. This model simulates heat transfer phenomena involving the interaction of occupied spaces, building envelopes, and the external environment. It also considers internal heat gains from lighting, equipment, and occupants, as well as thermal fluxes due to air ventilation. Domestic hot water (DHW) demands are evaluated using probabilistic data linked to the climatic zone, building archetype, and occupant characteristics [51].

In order to capture the dynamic interactions among thermodynamic components installed at the user level, network pipes, and the balancing thermal station (which regulates the network temperature at a target value), an integrated thermal model is developed in MATLAB using an object-oriented methodology. The core idea behind this approach is to structure the model as a collection of modular objects, each representing a distinct physical component. These include buildings, thermal substations, decentralised units, and network elements. The modelling framework involves developing generic base classes that define common properties and interfaces, meaning that each component is implemented as a custom MATLAB class with its own governing equations, internal variables, and inputs/outputs that interact with other components. More specific elements (e.g., the type of end-user) are implemented as sub-classes that inherit the base functionality. This structure means that modifications and extensions, such as changing a technology's operational strategy, can be made without affecting the rest of the system model.

When compared to established platforms such as TRNSYS and Modelica, the proposed object-oriented modelling framework offers significant benefits in terms of flexibility, scalability and maintainability. In TRNSYS, components must be manually connected in a fixed simulation environment, and in Modelica, advanced customisation requires deep domain-specific knowledge. In contrast, the object-oriented-programming approach allows programmatic reconfiguration of district layouts, enabling easy and fast adaption to new use cases. Changes to one component do not propagate changes to others. This architecture supports a wide range of testing scenarios, facilitates the integration of advanced control strategies, and reduces the development effort when evaluating different system designs or user profiles.

This model serves to solve the dynamic evolution of temperatures at the thermal nodes depicted in the scheme of Fig. 1, enabling assessment of how temperature variations influence user substations and balancing station energy consumption, and the thermo-electrical power generation of solar technologies. Energy management strategies are incorporated into the 5GDHC system model. These strategies include hierarchical utilisation of the thermal and electrical outputs of solar systems and the use of energy storage to enhance self-consumption and energy independence. Additionally, two distinct market approaches are analysed: a community-based approach and individual user investments.

In Section 2.1, we describe the system configurations explored at the end-user level. Energy market strategies for the 5GDHC network are detailed in Section 2.2, and energy performance and economic indicator definitions are discussed in Section 2.3. Appendices A-E provide models of the 5GDHC technologies, including heat pumps, solar technologies, energy storage systems, district thermal network pipes and the thermal balancing station.



2.1. Users' configurations

The first user configuration, presented in Fig. 2(a), introduces a strategy to exploit thermal production when solar thermal collectors or PV-T systems are integrated at the user level. The outlet temperature is not constrained within a fixed range but is determined as a function of the nominal water flow rate circulating in the collectors/PV-T modules, weather conditions, and resulted thermal efficiency as detailed in Appendix B.

In this configuration, the produced thermal energy is used based on a hierarchical logic to: (1) supply heat to the pump evaporator to raise its working temperature, thereby improving its COP; (2) preheat water to reduce the primary energy consumption of the DHW gas boiler; and (3) heat the water returning to the 5GDHC thermal network using a mixing valve, mitigating the cooling effect on the 5GDHC thermal network when it is in a heating-dominant condition. This hierarchical logic prioritises the user's thermal demands, favouring space heating demand over DHW needs. Any surplus thermal energy is subsequently directed to benefit the 5GDHC network if it is required. The presented strategy is specific to the heating operation of users' heat pumps, while, with cooling operation, the thermal energy is exclusively used to satisfy DHW needs.

As shown in Fig. 3, the flow rate diverted to the heat pump evaporator ($\dot{m}_{\text{STC, ev}}$) is determined through an energy balance to ensure that the outlet flow rate matches the evaporator demand ($\dot{m}_{\text{ev}}$) at the optimal evaporator temperature ($T_{\text{ev, opt}}$) that maximises the heat pump COP. If the calculated $\dot{m}_{\text{STC, ev}}$ exceeds the minimum between the flow rate from the solar collectors ($\dot{m}_{\text{STC}}$) and $\dot{m}_{\text{ev}}$, it is limited to this minimum value. When the available flow rate from the collectors ($\dot{m}_{\text{STC}}$) exceeds the evaporator temperature requirement, the surplus flow is directed to the DHW preheater. The required flow rate for the preheater ($\dot{m}_{\text{STC, DHW}}$) is estimated based on the DHW thermal demand ($\dot{Q}_{\text{DHW}}$), the collector outlet temperature ($T_{\text{out, STC}}$), and the pinch point temperature difference of the heat exchanger ($\Delta T_{\text{pp, HEX}}$). As with the evaporator, if the demand is higher than the available flow, $\dot{m}_{\text{STC, DHW}}$ is set to the available flow rate.

Any remaining flow from the collectors is then used to heat the water returning to the district network at the required temperature ($T_{s,net}$). This occurs only when the network is in a heating-dominant condition; in such cases, the recovered excess solar energy helps to achieve a neutral thermal contribution from the user to the network. The required flow rate ($\dot{m}_{STC,net}$) is calculated through an energy balance involving the mixing process, which also combines the flow rates from the evaporator and the DHW preheater. The water loop is closed with the inlet

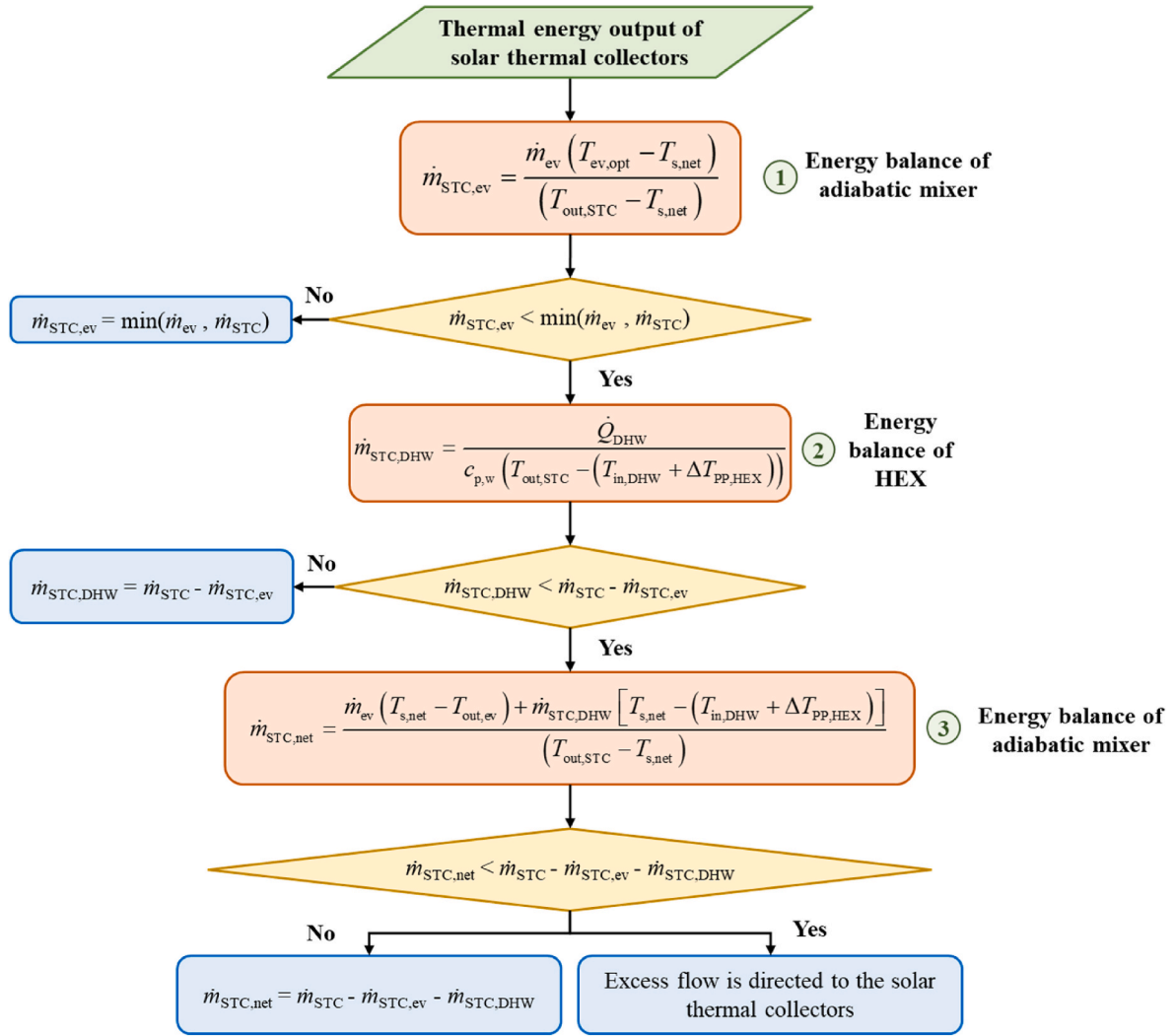


Fig. 3. Flow chart showing energy flow decisions for user configurations with thermal energy production. The hierarchical process prioritises increasing the heat pump evaporator temperature, preheating the DHW, and heating the water returned to the district network.

flow rate of the solar thermal collectors equal to any remaining excess flow at temperature $T_{out,STC}$, mixed with the flow rate (given by the sum of the three diverted load flow rates $\dot{m}_{STC,ev}$, $\dot{m}_{STC,DHW}$, and $\dot{m}_{STC,net}$) from the district network supply line at temperature $T_{s,net}$.

The configuration of Fig. 2(b) shows the utilisation of electricity generation when PV or PV-T modules are integrated at the user level (the electricity generated by these systems is estimated as detailed in Appendix B). The generated power is primarily used to operate the compressor of the user's heat pump. In cases of mismatch between production and demand, any surplus energy is shared with the DHC balancing station to support the operation of the fan in the heat recovery unit and the compressor of the heat pump. This energy sharing strategy is based on the assumption of a virtual energy exchange, where the existing grid infrastructure is still used to operate the electricity distribution.

The configurations depicted in Fig. 2(c) and (d) extend the presented setups by incorporating energy storage systems. A stratified TES system is included for solar technologies that produce thermal energy (solar thermal collectors or PV-T systems). In this setup, the TES system is charged using heat generated by the solar technologies, while the cylinder satisfies the three-load demand following the same hierarchical strategy as previously described and schematised in Fig. 3. The effects of the TES management strategies on its temperature evolution are estimated through the one-dimensional thermal model detailed in

Appendix C. The advantage of this configuration compared to that shown in Fig. 2(a) is that the stored excess thermal energy produced can be utilised during lower production periods, increasing the energy saving potential.

Battery energy storage systems are introduced when electricity-generating technologies (PV or PV-T systems) are present. In these configurations, surplus power is first stored in the battery, and any remaining excess electricity generation is then shared with the DHC balancing station. The amount of stored surplus energy, along with the resulting excess made available for sharing with the DHC balancing station, is estimated based on the evolution of the batteries state of charge, calculated using the energy balance model described in Appendix C.

These energy storage systems, both thermal and electrical, act as backup units to minimise the effects of energy mismatches enhancing self-consumption rates and improve energy flexibility of renewable-based technologies.

2.2. Energy market strategies

Two different energy market strategies are studied, where: (1) the users individually invest in the integration of solar technologies and storage systems; and (2) a community-based strategy is adopted, where investments are made collectively by the users or external parties, and

the resulting revenues and savings are shared based on the amount invested.

The operating expenses (OPEX) and revenues for both strategies are presented below. For the first strategy, the OPEX for each individual user is calculated as follows:

$$\text{OPEX}_{\text{us}} = c_{\text{gas}} \cdot E_{\text{p,DHW,us}} + \sum_{t=1}^{8760} c_{\text{el,t}} \cdot E_{\text{el,hp,us,t}} + \sum_{t=1}^{8760} c_{\text{el,t}} \cdot E_{\text{el,DHC,us,t}} \quad (1)$$

where the three terms represent: the purchased natural gas primary energy to meet the user's DHW needs ($E_{\text{p,DHW,us}}$); the electricity from the grid to operate the heat pump compressor ($E_{\text{el,hp,us}}$) of the user's substation; and the electricity consumption associated to the thermal energy supplied from the 5GDHC system ($E_{\text{el,DHC,us}}$). The unit costs, c_{gas} and c_{el} , represent the fixed cost of natural gas, and the hourly varying cost of electricity.

The cost of energy purchased from the 5GDHC system is proportional to the electricity ($E_{\text{el,DHC}}$) drawn from the grid by the thermal balancing station to stabilise the users' thermal energy contribution. Each user's share of this cost is defined as the ratio of the user supplied cooling or heating energy ($\dot{Q}_{\text{ev,us}}$ or $\dot{Q}_{\text{co,us}}$) to the total thermal energy to be balanced ($\dot{Q}_{\text{net}}$ that it is evaluated as reported in [Appendix E](#)), as expressed in Equation (2):

$$E_{\text{el,DHC,us}} = \begin{cases} E_{\text{el,DHC}} \frac{\dot{Q}_{\text{ev,us}}}{\dot{Q}_{\text{net}}} & \text{if } \dot{Q}_{\text{net}} = \dot{Q}_{\text{ht,net}} \\ E_{\text{el,DHC}} \frac{\dot{Q}_{\text{co,us}}}{\dot{Q}_{\text{net}}} & \text{if } \dot{Q}_{\text{net}} = \dot{Q}_{\text{cl,net}} \end{cases} \quad (2)$$

when the network requires heating ($\dot{Q}_{\text{ht,net}}$), users supplying heat via their heat pump condensers help balance the system and are not charged for additional energy from the central plant. Similarly, when cooling is required ($\dot{Q}_{\text{cl,net}}$), users providing cooling via their evaporators are exempt from this cost. This approach ensures users are only charged when their demand increases the load on the balancing station, encouraging contributions that support system balance.

The total revenues for each user (π_{us}) are calculated by adding the revenues from selling electricity to the grid ($E_{\text{el,sur,us}}$), the revenues from sharing electricity with the thermal balancing station ($E_{\text{el,shr,DHC}}$), and the savings from reduced OPEX ($\Delta\text{OPEX}_{\text{us}}$) respecting to the reference configurations:

$$\pi_{\text{us}} = sp_{\text{el}} \cdot E_{\text{el,sur,us}} + \sum_{t=1}^{8760} c_{\text{el,t}} \cdot E_{\text{el,shr,DHC,t}} + \Delta\text{OPEX}_{\text{us}} \quad (3)$$

where sp_{el} is the selling price of electricity, which depends on the market strategy of the central grid. The electricity shared with the district thermal balancing station is compensated at the power grid's electricity cost.

For the second strategy (collective investment scenario), it is assumed that capital costs and resulting revenues or savings are distributed among participants proportionally to their CAPEX contribution. This reflects a profit-sharing model commonly applied in energy communities. The total revenues of the investors (π_{inv}) are given by:

$$\pi_{\text{inv}} = \left(\sum_{n=1}^{N_{\text{us}}} \pi_{\text{us,n}} \right) \frac{\text{CAPEX}_{\text{inv}}}{\text{CAPEX}_{\text{tot}}} \quad (4)$$

where π_{inv} is a function of the overall gains from all users of the 5GDHC community, and the ratio of the investor's capital expenditures ($\text{CAPEX}_{\text{inv}}$) to the total CAPEX of the community ($\text{CAPEX}_{\text{tot}}$).

2.3. Energy performance and economic indicators

The indices used to assess the energy-economic analysis are the

primary energy saving (PES) and the payback time (PBT). The PES index indicates the percentage of primary energy saved, specifically in relation to fossil fuel sources. The following equations are used to calculate the primary energy consumption of the single user, and balancing station:

$$E_{\text{p,us}} = \frac{E_{\text{th,DHW,us}}}{\eta_{\text{b}}} + \sum_{t=1}^{8760} \frac{E_{\text{el,hp,us,t}}}{\eta_{\text{g,t}}} \quad (5)$$

$$E_{\text{p,bs}} = \sum_{t=1}^{8760} \frac{E_{\text{el,hru,net,t}} + E_{\text{el,hp,net,t}}}{\eta_{\text{g,t}}} \quad (6)$$

where $E_{\text{th,DHW,us}}$ is the thermal energy demand for the DHW needs of each user, $E_{\text{el,hp,us}}$ is the electrical energy demand for space heating/cooling of each user, and $E_{\text{el,hru,net}}$ and $E_{\text{el,hp,net}}$ are the electrical energy needs of the heat recovery unit and heat pump of the balancing station. The efficiency of primary energy conversion for the boiler η_{b} is assumed to be fixed at 0.9, while the efficiency of the central grid η_{g} is dynamic, depending on the rate of fossil fuel used by the central grid for each hour. It is calculated as follows:

$$\eta_{\text{g,t}} = \frac{\eta_{\text{gas}} \alpha_{\text{gas,t}} + \eta_{\text{pet}} \alpha_{\text{pet,t}} + \eta_{\text{car}} \alpha_{\text{car,t}}}{\gamma_{\text{ff,t}}} \quad (7)$$

where η_{g} is a function of: the weighted average of the fossil fuel efficiencies of gas (η_{gas}), petrol (η_{pet}), and carbon (η_{car}) plants, with α representing the weight of each plant type; and the hourly fraction of electricity produced by the grid from fossil fuels (γ_{ff}).

At this point, PES is calculated as:

$$\text{PES} = \frac{E_{\text{p,rs}} - E_{\text{p,ps}}}{E_{\text{p,rs}}} \times 100 \quad (8)$$

The economic index PBT is calculated as follows:

$$\text{PBT} = \frac{\text{CAPEX}}{\Delta\text{OPEX} + \text{REV}} \quad (9)$$

where REV represents the sum of the revenues from selling electricity to the grid and the revenues from sharing electricity with the thermal balancing station.

3. Development of scenarios and main assumptions

The analysed 5GDHC configurations include two small-scale networks located in northern Italy (latitude 45° 27' 51.37" N, longitude 9° 11' 22.24" E). Weather data for the simulations are estimated using the software Meteonorm 8, based on statistical data from the past 20 years [52]. The first configuration consists of a data centre, which acts as a thermal prosumer, along with a residential building and an office building, both acting as thermal consumers. The second configuration aggregates four thermal consumers, specifically two residential units and two office buildings. To evaluate the energy and economic performance of integrating solar technologies and energy storage systems at the user level, an annual simulation is executed for nine distinct scenarios.

The selected user types reflect typical urban building types. The residential sector dominates the building stock in terms of number of units, while office buildings are among the most common non-residential types [53]. Conversely, data centres are well suited to act as thermal prosumers, due to their consistent low-temperature waste heat [54].

These scenarios, detailed in [Table 1](#), are compared to a reference scenario in which no solar technologies and storage systems are integrated into the users' substations. The size and operational strategies of the balancing station, the network distribution, and the users' substations remain consistent with those in the proposed scenarios.

Given the assumptions made, several limitations can be identified in

Table 1

Proposed scenarios configurations of solar technologies (photovoltaic systems, solar thermal collectors, and hybrid photovoltaic thermal systems) and storage systems (battery energy storage systems and stratified TES systems) per user type.

User type	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9
Data centre	PV	PV+ BESS	–	PV	PV+ BESS	PV	PV+ BESS	PV	PV+ BESS
Residential	PV	PV+ BESS	STC+ TES	PV+ STC+ TES	PV+ BESS + STC+ TES	PV-T	PV-T+ BESS	PV-T+ TES	PV-T+ TES+ BESS
Office	PV	PV+ BESS	STC+ TES	PV+ STC+ TES	PV+ BESS + STC+ TES	PV-T	PV-T+ BESS	PV-T+ TES	PV-T+ TES+ BESS

Table 2

Building and heat pump properties for the data centre, residential building and office.

	Property	m.u.	Data centre	Residential	Office
Building geometry	A_n	[m ²]	350	200	350
	Height	[m]	4.5	2.8	3.1
	Windows-walls ratio	[%]	5	15	30
Building U-values	U_{wl}	[W/m ² K]	0.30	0.32	0.26
	U_{win}	[W/m ² K]	1.5	1.5	1.2
Ventilation rate	V_{bid}	[Vol/h]	8	2	6
Internal gain	Lights	[W/m ²]	3	2.5	5
	Appliances	[W/m ²]	300	25	20
Occupants	N_{occ}	[–]	0	8	20
HVAC setpoints	Heating	[°C]	–	20	20
	Cooling	[°C]	18	26	26
Heat pump	Cooling capacity	[kW]	40	10	15
	COP _{nom}	[–]	6.1	5.8	5.9
	Heating capacity	[kW]	–	12	17

(*) Nominal COP estimated at a load fraction of 100 % and a source temperature of 20 °C.

the present analysis. The two small-scale configurations may not fully represent the typical architecture of DHC systems, which usually involve a larger number of users. However, they are appropriate for the objective of assessing the impact that different user level solar integration strategies may have on individual energy and economic performance, as well as on the district network.

While the analysis focuses on a single climatic zone, the selected region in Northern Italy was chosen not only for data availability and relevance but also because its climate is representative of several other European areas with both heating and cooling needs, such as parts of Southern France, the Balkans, and Central Spain. Therefore, while the numerical results are location-specific, the overarching insights, particularly the importance of district-level configuration in determining optimal decentralised energy solutions, can offer valuable guidance for these and other geographical contexts. Additionally, the modular, object-oriented structure of the proposed framework allows for adaptation to different climates, building typologies, and technology sets.

Finally, while this study does not explicitly compare decentralised and centralised solar integration configurations, the literature highlights several advantages of decentralised approaches, particularly in the context of 5GDHC systems [38]. These include the potential to enhance both the energy and economic performance of individual users and the

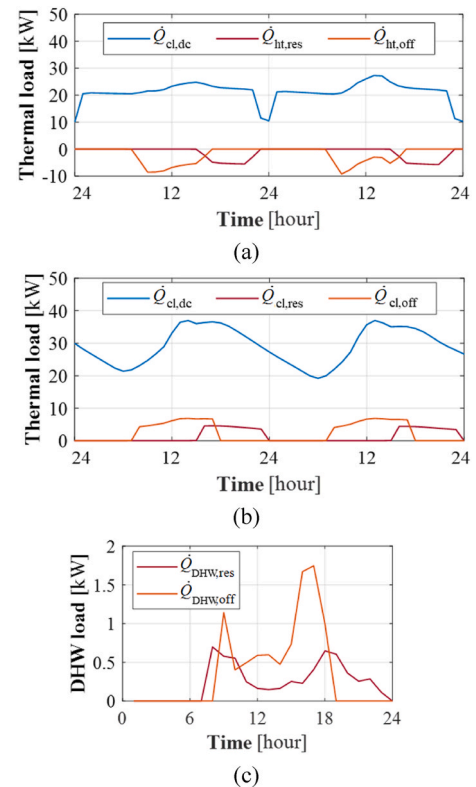


Fig. 4. Thermal load profiles of the three building archetypes (data centre, residential and office): (a) space heating and cooling demand from 31 January to 1 February, where negative values represent space heating demand and positive values represent space cooling demand; (b) space cooling demand from 9 to 10 July; and (c) daily DHW profile for residential and office buildings.

balancing station, greater user autonomy in managing local electricity and thermal production from solar technologies and reduced thermal losses due to the local distribution of solar thermal energy.

3.1. Users' energy demands

The users' thermal demands for space heating and cooling are determined using an in-house building energy performance simulation tool [50]. Key features adopted for the energy simulation of the data centre, residential unit, and office include building geometry, envelope thermophysical properties, ventilation rates, internal gains, number of occupants, and HVAC setpoints (as summarised in Table 2).

The DHW needs for the residential and office buildings (excluding the data centre, which has no DHW demand) are calculated using a probabilistic method based on statistical analyses from Ref. [51]. This method accounts for the investigated climatic zone and building archetypes. The DHW thermal load profile is constructed using the obtained probability rates for each hour of the day, the daily hot water

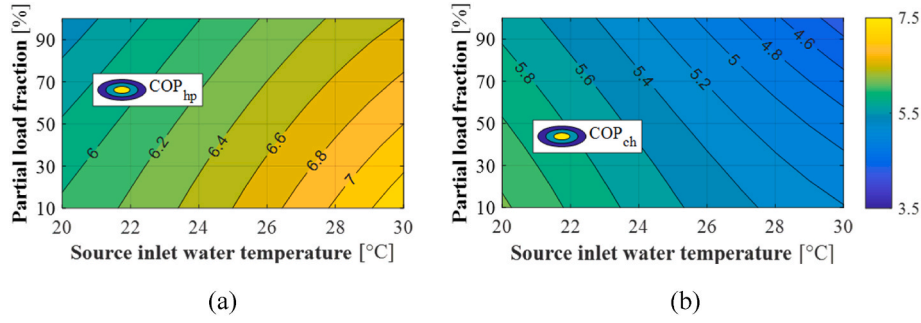


Fig. 5. Heat pump performance map for the residential building as a function of the partial load fraction and district network operating temperature: (a) heating mode; and (b) cooling mode.

needs per person (set at 50 L per person per day in Italy), the number of occupants, the inlet water temperature from the district manifolds (assumed to equal the ground temperature at a depth of 1 m), and the required DHW setpoint temperature of 55 °C.

Thermal load profiles for space heating, cooling, and DHW demand for the three user types are presented in Fig. 4. The required heating and cooling power is shown for two sample days, one in winter (Fig. 4(a)) and one in summer (Fig. 4(b)). The data centre HVAC system operates continuously to cool, the room, even in winter, and ensure the proper electronic equipment functions. In contrast, the heating and cooling demands for the residential unit and office follow statistical occupancy patterns. The office HVAC system operates during working hours (8:00 a.m. to 5:00 p.m.), while the residential HVAC system operates during the peak occupancy period (4:00 p.m. to 10:00 p.m.).

Typical thermal load profiles for DHW demand are shown in Fig. 4 (c). The office DHW demand exceeds that of the residential unit due to the higher number of occupants.

The size of the heat pump systems to be installed for each user is determined based on the results of the building energy simulations. The considered heat pumps are reversible systems, with the nominal size selected based on the maximum cooling capacity according to the peak cooling demand, increased by a conservative margin of 10 %. The heat pump system sizes for each user, including the corresponding maximum cooling capacity, nominal COP, and maximum heating capacity, are provided in Table 2. The heat pump performance map is constructed, as described in Appendix A, considering various fractions of the maximum cooling and heating capacities, as well as the inlet source temperature. The temperatures required to meet the users' heating and cooling demands are 50 °C and 7 °C, respectively. The return temperatures from the users, which serve as the inlet temperatures at the heat pumps load sides, are 30 °C during heating operation and 12 °C during cooling operation. Once the performance map of the heat pump is determined, the COP and associated electricity consumption can be calculated for different user thermal loads.

The performance map for both heating and cooling modes, based on the operating temperatures of the 5GDHC network (ranging from 20 °C to 30 °C) and the thermal load fraction ranging from 10 % to 100 %, is shown in Fig. 5. For brevity, only the map for a residential unit is presented.

3.2. Energy demands of district network configurations

The energy performance of the two investigated 5GDHC configurations is influenced by the thermal interactions between the users and the district network. It is assumed that the supply circuit pipes are thermally insulated to maintain a constant water temperature ($T_{s,net}$) at the set-point value of 20 °C. This temperature value corresponds to the yearly average ground temperature for the investigated case study and was selected to reduce the: (1) insulation investment costs by minimising thermal dissipation to the ground; and (2) balancing station consumptions. The return circuit, on the other hand, consists of uninsulated pipes that interact thermally with the surrounding ground, helping to reduce the energy consumption of the thermal balancing station. The thermal exchange through the ground is evaluated as outlined in the modelling description of Appendix D.

The two configurations exhibit different operational characteristics. The first configuration is affected by the thermal fluxes from the data centre condenser, which raises the network temperature, as illustrated in Fig. 6. This effect can be beneficial during the winter season, as it helps balance the thermal fluxes from the evaporators of the residential and office buildings. However, the thermal energy supplied by the data centre exceeds the cooling energy demand of the consumers' evaporators, resulting in a return circuit network temperature ($T_{r,net}$) that is higher than $T_{s,net}$, as shown in Fig. 6(a). During the summer season, the three users supply thermal energy, raising the return circuit flow temperature. However, heat dissipation through the ground ensures that $T_{r,net}$ remains lower than the outlet temperatures of the users' condensers (Fig. 6(b)), thereby reducing the energy consumption of the balancing

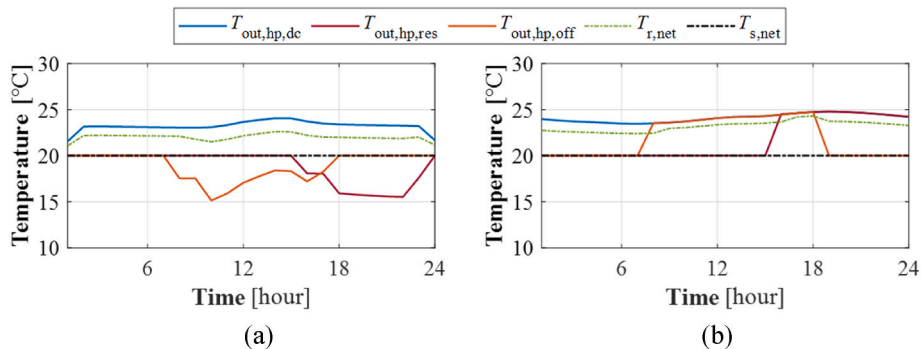


Fig. 6. Thermal behaviour of the 5GDHC configuration with one data centre, one residential building and one office: (a) winter day (31 January); and (b) summer day (9 July).

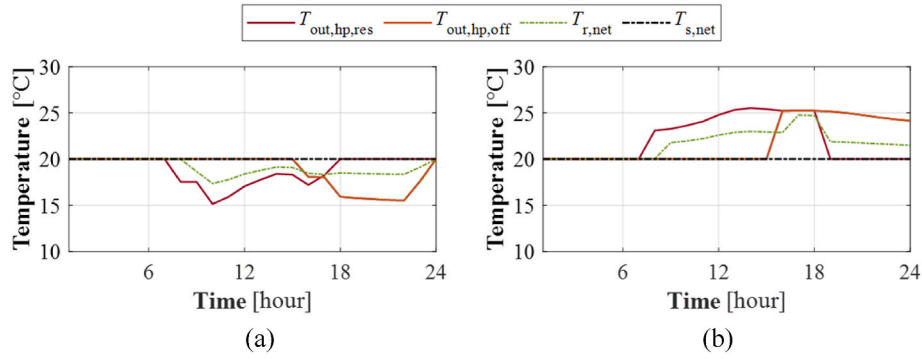


Fig. 7. Thermal behaviour of the 5GDHC configuration with two residential units and two offices: (a) winter day (31 January); and (b) summer day (9 July).

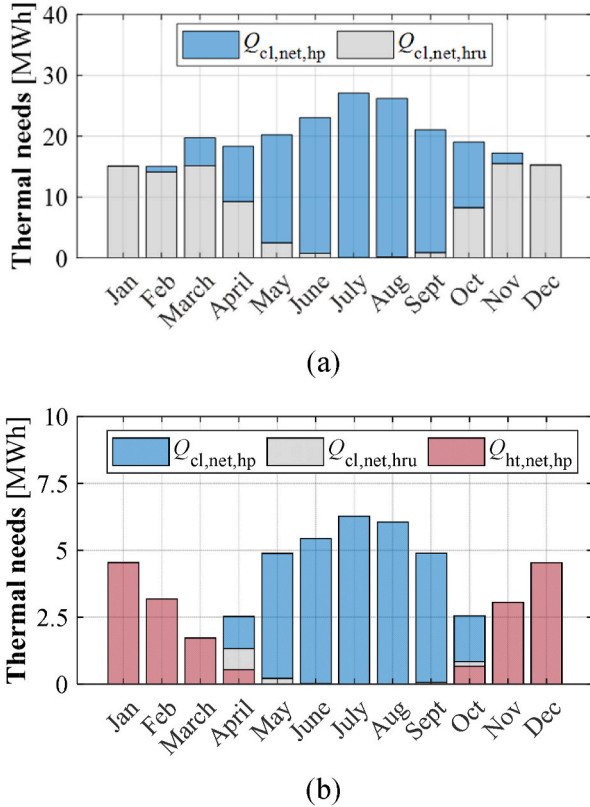


Fig. 8. Energy requirements of the thermal balancing station for: (a) the first 5GDHC configuration (one data centre, one residential unit, and one office); and (b) for the second 5GDHC configuration (two residential units and two offices).

station.

The second configuration is characterised solely by thermal consumers. Compared to the first configuration, during the winter season, the balancing station operates in heating mode (Fig. 7(a)), while during the summer, it operates in cooling mode (Fig. 7(b)) to maintain the desired $T_{s,net}$. The thermal interaction with the ground continues to have a mitigating effect in this configuration, increasing $T_{r,net}$ in winter and decreasing it in summer.

The thermal energy supplied by the thermal balancing station to the network flow rate is presented through a monthly analysis in Fig. 8. This energy analysis is conducted according to the modelling formulations of the thermal balancing station presented in Appendix E. As previously noted, the first configuration consistently requires cooling energy (Fig. 8 (a)). During the winter season, the lower ambient temperatures facilitate the operation of the heat recovery unit, whereas, in the summer, the

network cooling needs are met by the balancing station heat pump. In contrast, the second 5GDHC configuration requires heating energy during the winter, which is supplied by the heat pump. The cooling requirements are met by the heat recovery unit only during the mid seasons, as indicated by the grey bars in Fig. 8(b). It is evident that the impact of the data centre results in a larger balancing station size and higher energy consumption for the first 5GDHC configuration.

3.3. Types and sizes of solar technologies and energy storage systems

The selection of the type and size of solar technologies and energy storage systems is based on certain set criteria. Regarding solar technologies, polycrystalline PV systems, flat-plate solar collectors, and PV-T systems – characterised by polycrystalline cells and a water channel below the PV module – are considered. The choice of these technologies is based on the trade-off between investment costs and energy production potential, as well as the temperature levels achieved by the solar thermal systems, which meet the required thermal needs. The electrical and thermal performance of the solar technologies under investigation is presented in Fig. 9 [55]. For energy storage, lithium batteries and stratified hot-water cylinders (thermally insulated with polyurethane foam, with a heat loss coefficient U_1 of $0.35 \text{ W/m}^2\text{K}$) are assumed.

The sizes of the PV and PV-T systems, as well as the BESS capacity, are estimated by solving a constrained optimisation problem. This problem aims to find the optimal combination of sizes that approaches 60 % self-sufficiency from the power grid, in alignment with the target of the EU Directive “Energy Performance of Buildings” [56], while being limited by the available roof space for the installation of PV and PV-T modules. The available roof surface is calculated by considering the building floor area, multiplied by a factor that accounts for the uncovered area kept free to ensure sufficient distance between the module rows, preventing shading issues. This factor is equal to 43 %, based on a tilt angle of 40° and module dimensions (1.6 m long and 1 m wide).

Regarding the size of the solar thermal collectors and the TES volume, the number of parallel collector strings is determined by the ratio of the annual thermal energy required for DHW needs to the annual thermal energy production. The thermal production is filtered to ensure that the outlet temperature reaches the desired DHW temperature of 55°C . The TES volume is calculated as the daily DHW consumption per person, multiplied by the number of occupants.

The properties of the investigated technologies, the resulting system sizes, and the associated investment costs are provided in Table 3.

3.4. Italian grid primary energy rate and tariffs

The Italian power grid system is characterised by an energy mix in which 53 % of the electricity is produced by fossil fuel-based plants. For the energy and economic analysis, based on 2023 data, the dynamic share of energy generated by fossil fuel-based systems has been obtained from the Italian electricity dispatching system, Terna [58], and is

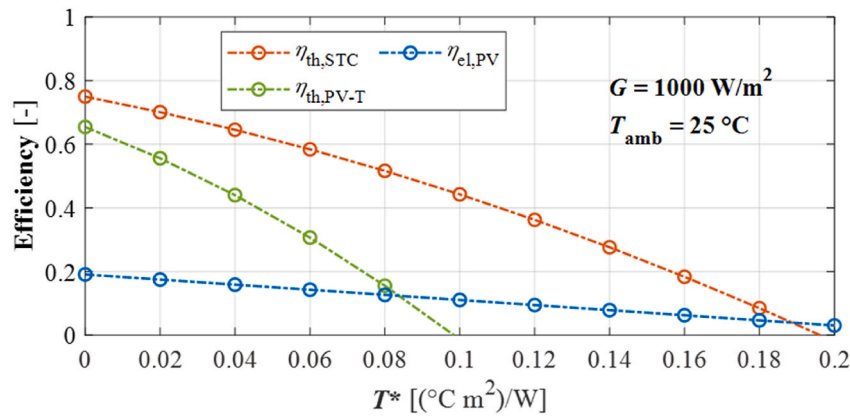


Fig. 9. Electrical and thermal efficiency of integrated solar technologies as a function of reduced temperature: thermal efficiency of a flat-plate solar thermal collector and a PV-T system, and electrical efficiency of a polycrystalline PV module. The reduced temperature (T^*) is calculated as the difference between the absorber plate temperature (or cell temperature for PV module performance) and the ambient temperature under standard test conditions, divided by the solar irradiance in standard test conditions.

Table 3

Characteristics, sizes, and investment costs of solar and storage technologies.

	User	PV system ^(a)	Solar thermal collectors ^(b)	PV-T system ^(a)	BESS ^(c)	TES ^(d)
Covered roof surface [m ²]	Data centre	90.2	–	–	–	–
	Residential	8.2	8.1	8.2	–	–
	Office	9.8	12.1	9.8	–	–
BESS capacity [kWh] TES volume [m ³]	Data centre	–	–	–	65.5	–
	Residential	–	–	–	6.5	0.5
	Office	–	–	–	10.0	1.1
Investment cost [57]						
PV system [€/m ²]	Solar thermal collectors [€/m ²]	PV-T system [€/m ²]		BESS [€/kWh]	TES [€/m ³]	
100	200	450		400	500	

^a The area of a single PV or PV-T module is 1.6 m².

^b The area of a single collector is 2.02 m², with the layout arranged in strings of two collectors in series. The number of parallel strings is determined by the ratio of the total surface area to the number of collectors in series.

^c The capacity of a single lithium cell is 9 Ah, with a cell voltage of 11 V and a current of 5 A.

^d The cylindrical shape assumes a height twice the diameter.

presented in Fig. 10(a). The dynamic cost of energy, sourced from the Italian regulatory authority for energy, networks, and environment (ARERA) [59], is shown in Fig. 10(b).

4. Results and discussion

Sections 4.1 and 4.2 analyse the energy benefits acquired during operation for the different solar and storage system configurations described in Section 2.1. Section 4.3 evaluates the primary energy consumption of individual users and the two 5GDHC configurations (described in Section 3.2) across the nine scenarios outlined in Section 3. Section 4.4 presents the techno-economic analysis based on the strategies in Section 2.2, and Section 4.5 discusses the implications of the results for 5GDHC system development.

4.1. Management of electricity generation in solar-assisted setups

The electricity generation of PV and PV-T systems is strongly influenced by the climatic conditions of the analysed region. Although both systems use the same solar cell material, their performance differs. PV modules dissipate heat through convection and radiation to the surrounding environment, while PV-T systems are cooled by water flowing through a plate exchanger and insulated with a thermal layer on the back of the panel. This insulation traps heat, reducing the PV-T system efficiency. The difference in electricity generation per unit surface area between PV and PV-T systems is shown in Fig. 11. The highest generation rates occur in the summer months due to increased solar irradiance,

with reductions in PV-T electricity generation ranging from 10 % to 11 % (April to August), primarily driven by higher thermal losses.

The proposed management strategy (described in Section 2.1) prioritises the use of electricity to meet the heat pump compressor demand, supply the thermal balancing station heat recovery unit fan and heat pump, and sell any surplus electricity to the grid. This approach maximises self-consumption and reduces grid imports, reducing reliance on the grid infrastructure. Also, sharing energy with the thermal balancing station provides higher energy and cost savings compared to selling electricity to the grid. Integrating battery energy storage further enhances self-sufficiency.

Dynamic results for the proposed management strategies are presented in Fig. 12, focusing on two configurations: PV integration in an office building (Fig. 12(a)) and PV with battery integration in a residential building (Fig. 12(b)). Two sample days are analysed: a winter day (31 January) and a summer day (9 July).

In the office building (Fig. 12(a)), during winter, electricity generation is insufficient to meet the heat pump compressor demand. In contrast, generation during summer exceeds demand, allowing energy sharing with the thermal balancing station and minimal grid injection. The alignment of the office HVAC demand with the PV generation profile achieves acceptable self-sufficiency levels even without batteries. However, in the residential building (Fig. 12(b)), heating demand occurs later in the day, causing mismatch with electricity generation. Battery integration in this configuration improves self-consumption by addressing the mismatch. On the winter day, energy generation is insufficient to fully charge the batteries, while on the summer day, high

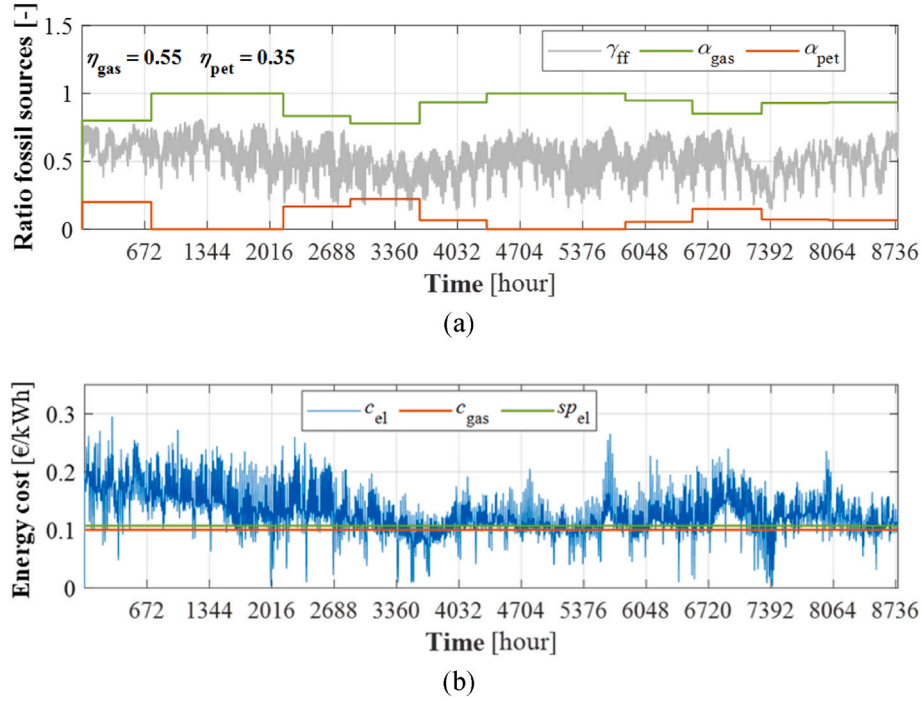


Fig. 10. Energy and economic characteristics of the Italian power grid: (a) the hourly ratio of electricity produced from fossil fuels (γ_{ff}) in 2023 and the fraction α of gas and petrol-based plants operation; and (b) the hourly importing price of electricity (c_{el}), exporting price of electricity (sp_{el}), and price of gas (c_{gas}).

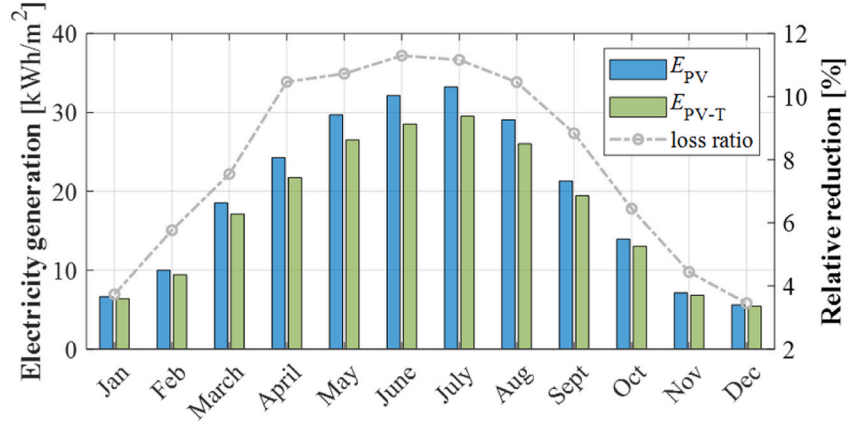


Fig. 11. Comparison of monthly electricity generation between PV and PV-T modules.

generation enables the batteries to meet demand and share surplus energy with the balancing station.

A yearly analysis of the data centre PV system configurations, with and without batteries, is presented in Fig. 13. The integration of batteries increases the renewable energy self-consumed from 65 % to 95 %, boosting grid independence as 61 % of the energy needs are met by PV generation compared to 41 % without batteries. Consequently, energy shared with the balancing station decreases from 26 % to 4.3 %, and grid sales drop from 9.1 % to 1.0 %.

4.2. Management of thermal energy in solar-assisted setups

This section highlights the potential energy benefits of integrating solar thermal technologies, including PV-T modules, with thermal consumers in the 5GDHC system. The proposed strategy aims to achieve three primary objectives: enhancing the heat pump COP, reducing the fraction of DHW demand met by fossil fuels, and improving the balancing station operation by stabilising the network temperature, as discussed in Section 2.1.

The operation of solar collectors coupled with a stratified TES system at the office building is analysed for a winter day (22 February), as shown in Fig. 14. Heat output is available between 8:00 a.m. and 6:00 p.m., as evidenced by the flow rate profiles of the STC arrays (Fig. 14(b)). During this period, thermal energy is stored in the TES or supplied directly to the load side when the storage is fully charged. From 8:00 a.m. to 11:00 a.m., the flow rate supplied from the TES ($\dot{m}_{TES,out}$) exceeds production, reducing the stored thermal energy (Fig. 14(c)). As the TES system discharges, the thermocline reaches the top of the cylinder, leading to a decrease in the temperature of the hot volume ($T_{TES,h}$) due to its reduced thermal inertia, while the cold volume fills with water from the district network at 20 °C.

When thermal production is stored (12:00 p.m. to 4:00 p.m.), the hot volume temperature rises with the outlet temperature of the solar collectors. Once the TES is fully charged, surplus energy is directly supplied to the loads, in this time interval an increase in the solar collectors outlet temperature ($T_{out,STC}$) is observed due to the recirculated water flow rate (5:00 p.m. to 6:00 p.m.). The resulted shares of thermal energy stored, used to raise evaporator temperature, or utilised for DHW, is shown in

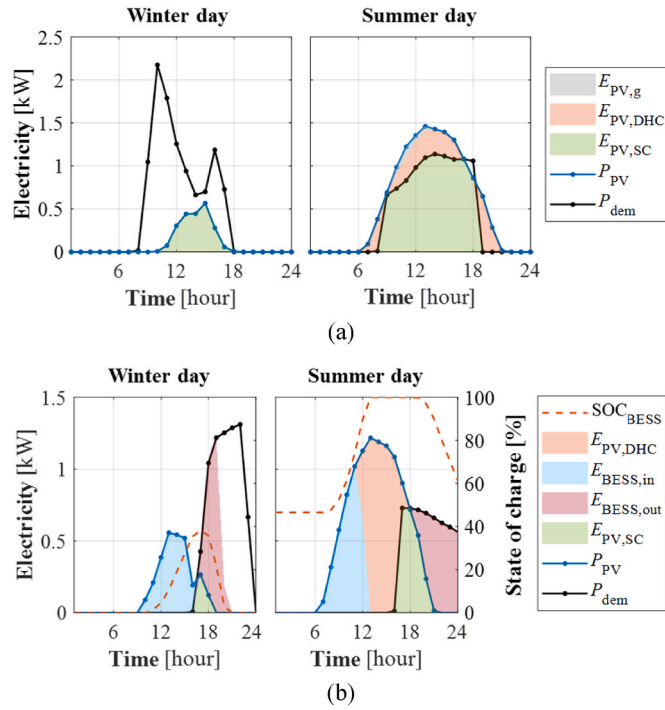


Fig. 12. Energy management of PV system produced electricity for a typical winter and summer day: (a) PV-only configuration at the office building; (b) PV configuration with battery storage at the residential building.

Fig. 14(c).

The advantages of the proposed strategy for the same configuration and day are shown in Fig. 15. The heat pump COP improves significantly due to the elevated evaporator temperature. For instance, at 8:00 a.m., the evaporator temperature reaches 28 °C, increasing the COP by 41 %, from 4.2 in the reference case (20 °C evaporator temperature) to 5.9 (as shown in Fig. 15(a)). This improvement enhances the district network performance by increasing the evaporator outlet temperature beyond the 20 °C network setpoint (Fig. 15(b)), reducing balancing station operation and energy consumption. The strategy also benefits DHW demand. As shown in Fig. 15(c), a relative reduction of 52 % in DHW energy requirements is achieved compared to the reference scenario.

An annual analysis of solar thermal integration with stratified TES for residential and office buildings is summarised in Fig. 16. The heat pump electricity consumption for heating decreases by 6.3 % and 11 % for the residential and office buildings, respectively (Fig. 16(a)). Solar thermal outputs cover 53 % of the DHW demand for the residential building and 53 % for the office (Fig. 16(b)). Additionally, the reliance on the 5GDHC system is reduced, with a relative decrease of 49 % for the office and 5.6 % for the residential building compared to the reference

case (Fig. 16(c)).

4.3. Energy performance analysis

The energy impact analysis of the user system configurations, introduced in Section 3, evaluates the PES rates, which underline the potential to reduce dependence on fossil fuels. This analysis is conducted for each individual user and the balancing thermal station across the two studied 5GDHC configurations (described in Section 3.2).

The annual primary energy consumption of each user integrated with the nine proposed solar system configurations is presented in Fig. 17.

Since the data centre has no heating or DHW demands, only configurations involving the PV system and PV combined with batteries (PS1 and PS2) are analysed. The data centre primary energy consumption amounts to 31 MWh. PES rates of 35 % and 56 % are obtained for PS1 and PS2, respectively. This result demonstrates the energy benefits of integrating battery systems with PV modules, which store surplus energy generated during the day to meet heat pump demands unmatched by direct PV electricity generation.

In the reference scenario, the residential unit and office consume 2.4 MWh and 2.9 MWh of primary energy, respectively, for heat pump operation. For DHW needs, gas boilers consume 2 MWh and 3.1 MWh, respectively. Although DHW demands constitute only 20 % of the total energy needs for space heating and cooling, the comparable primary energy consumption is attributed to the high efficiency of the power grid, largely supported by renewable energy sources.

The results indicate that integrating a PV system alone is not particularly beneficial for the residential unit, achieving a PES rate of only 6.8 %. Conversely, this configuration ensures significant savings for the office, with a PES rate of 20 %, due to the alignment between PV electricity generation and HVAC operational schedules. When batteries are integrated with PV systems, the residential unit shows a significant increase in PES rates, reaching 30 %, while the office experiences a smaller improvement to 23 %.

Solar thermal collectors with TES system (PS3) provide PES rates higher than those of PS1 and comparable to PS2, achieving rates of 27 % and 32 % for the residential and office buildings, respectively. These savings are primarily due to the satisfaction of DHW needs through solar thermal outputs.

The integration of PV-T systems (PS6) yields higher PES rates than users' configuration PS1, achieving 21 % for the residential building and 43 % for the office. However, incorporating stratified TES with PV-T systems (PS8) does not enhance results. For the residential building, the PES rate remains unchanged, while for the office, it decreases to 42 % due to heat dissipation losses in the hot-water cylinder, which reduce the available thermal energy from the PV-T system.

The highest PES rates for the residential building and office are achieved with configurations that include PV systems and solar thermal collectors coupled to both energy storage systems (PS5), reaching 57 % and 55 %, respectively. Another promising solution is integration of the

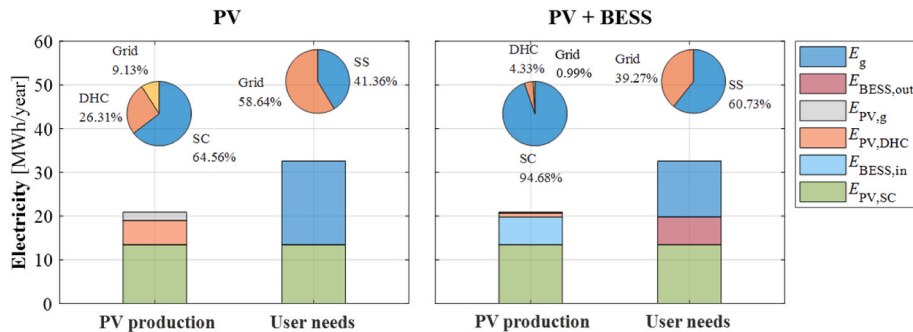


Fig. 13. Annual energy analysis of the PV system and the PV system with battery storage for the data centre, assessing electricity generation utilisation and energy demand fulfilment.

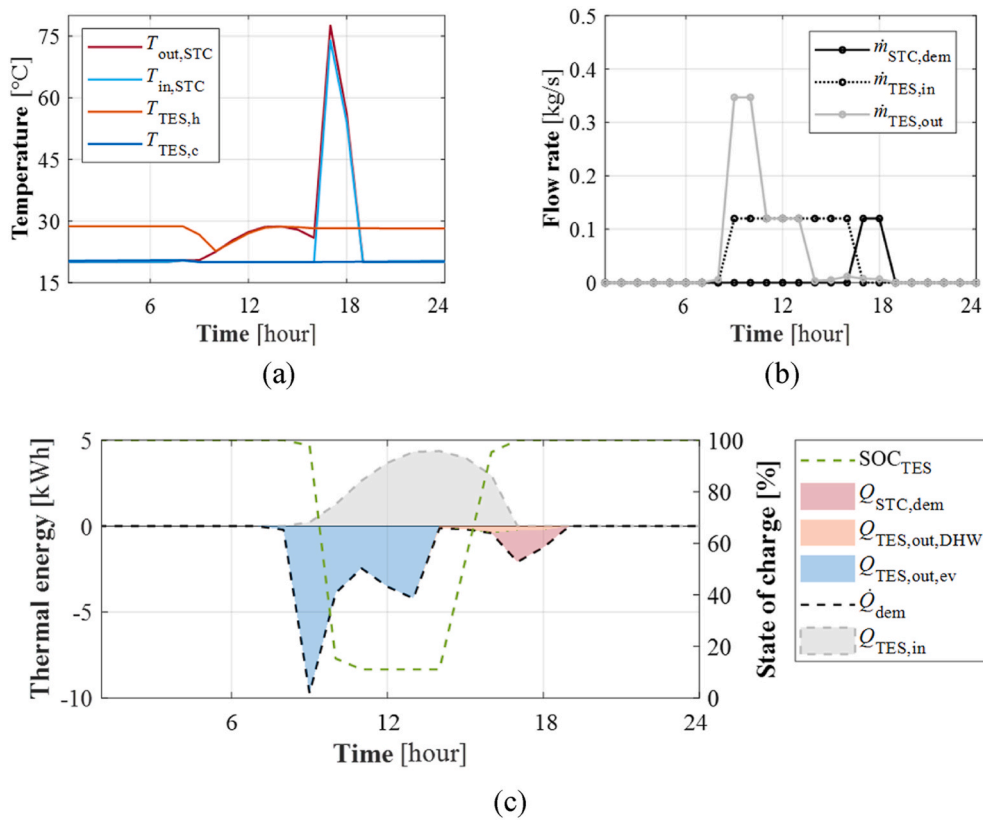


Fig. 14. Energy management strategy for a solar thermal collector system with a stratified hot-water cylinder at the office building, for a typical winter day (22 February): (a) temperature of water inlet and outlet from the solar collector arrays, and stratified cylinder hot and cold volumes; (b) water flow rate for storage charging, storage discharging to the load, and spill flow to meet demand; and (c) thermal energy stored, thermal energy withdrawn for the evaporator, DHW preheating needs, and excess energy used to meet the loads.

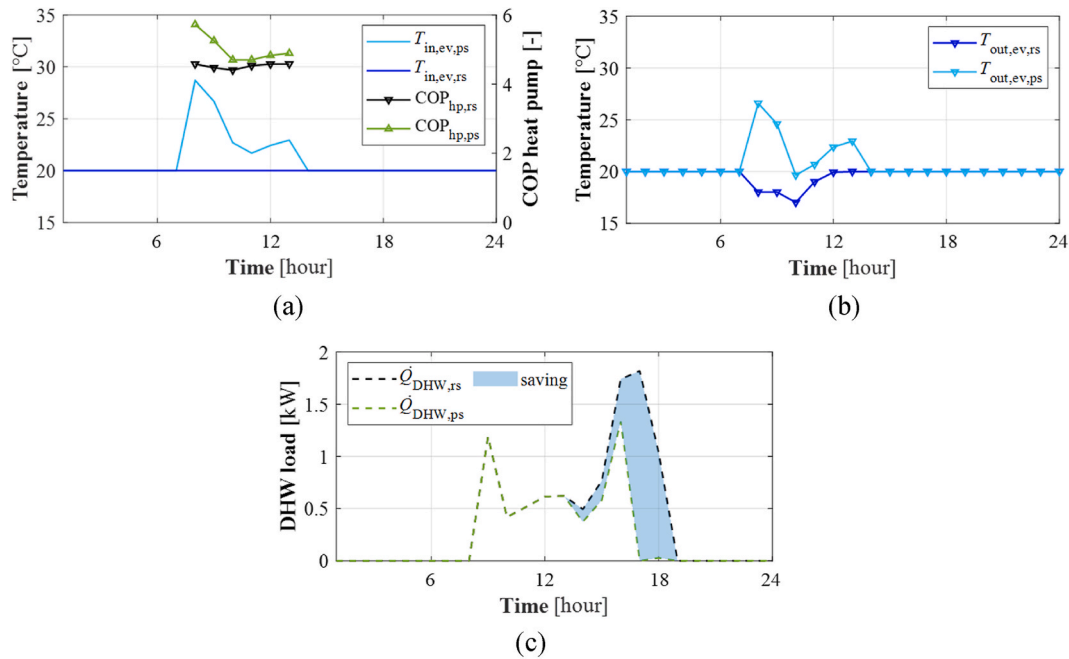


Fig. 15. Comparison of proposed configuration, integrating solar thermal collectors and stratified TES, with the reference scenario (without solar integration) for the office building on 22 February: (a) improvement in heat pump COP; (b) increase in heat pump evaporator outlet flow temperature supplied to the district network; and (c) energy savings from meeting DHW needs.

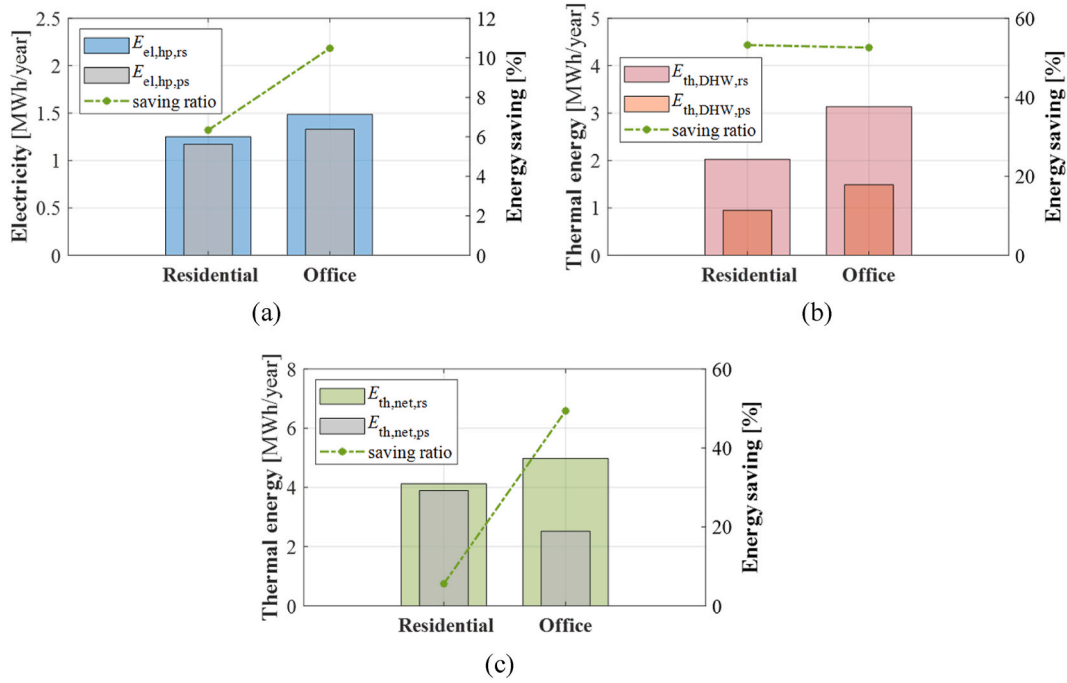


Fig. 16. Annual energy analysis comparing the proposed configuration with solar thermal collectors and stratified TES to the reference scenario (without solar integration) for residential and office buildings: (a) electricity savings for the heat pump; (b) reduction in energy required for DHW needs; and (c) decrease in energy purchased from the 5GDHC system.

PV-T system with battery storage (PS7), which, while achieving slightly lower PES rates of 43 % for the residential unit and 47 % for the office, offers space savings of 50 % and 55 %, respectively, compared to the previous configuration PS5.

The thermal balancing station primary energy consumption, in the reference scenario, amounts to 18.1 MWh for the first configuration, which includes the data centre, and 6.6 MWh for the second configuration, which includes only thermal consumers. These values are shown in Fig. 18. The highest saving rates for the balancing station are obtained with user configurations PS1 and PS6. This result is linked to the possibility of sharing surplus electricity generated by the users to meet the balancing station demands. A PES rate of 29 % is achieved for both 5GDHC configurations with PS1 users' system configurations, while the user system configuration PS6 achieves PES rates of 28 % and 27 % for the first and second 5GDHC configurations, respectively.

As presented in Fig. 18, configurations involving solar thermal collectors result in an increase in primary energy consumption for the first 5GDHC configuration. This increase is attributed to the solar thermal outputs that limit the beneficial cooling effect of the thermal consumers' evaporators, to balance the data centre condenser heat fluxes. Conversely, this condition proves advantages for the second configuration balancing station operations providing a PES rate of 6 %.

4.4. Economic performance analysis

The economic performance of the proposed 5GDHC configurations is evaluated under the two distinct economic strategies outlined in Section 2.2. The first strategy involves individual investments by users in integrating solar technologies and storage systems. The second adopts a community-based strategy, where investments are made collectively, and revenues and savings are shared proportionally to the contributions. The analysis considers dynamic electricity costs, as well as constant natural gas prices and electricity selling prices, for energy shared within the 5GDHC system and surpluses sold to the grid, as presented in Section 3.4.

The economic outcomes of the first economic strategy, summarised

in Table 4, include the CAPEX, saved operational expenses (Δ OPEX), and PBT for each user across the proposed configurations. In this case, the PBT is calculated as the ratio of CAPEX to Δ OPEX. The benefits of revenues from energy sales to the grid and the 5GDHC system on the PBT for each user is highlighted in Fig. 19.

A comparison between the users' configurations PS1 and PS2 indicates that, for the residential unit, PS2 leads to a reduced PBT from 22.9 years to 19.8 years. The higher PBT of PS1 is attributed to the mismatch between the timings of the PV system electricity generation and the residential unit electricity demand. The incorporation of a battery mitigates this mismatch, corresponding to a 65 % increase in energy savings from reduced grid purchases, however, the high investment cost of batteries prevents substantial reductions in PBT. In contrast, for the office, PS1 achieves a PBT of 5.9 years due to the closer alignment between electricity generation and demand patterns. Consequently, the integration of batteries in configuration PS2 results in only a 15 % increase in energy savings compared to PS1, leading to a significantly higher PBT of 24.3 years.

The data centre exhibits a PBT for PS1 comparable to that of the office (5.8 years), and a PBT for PS2 of 14.8 years. The users' configuration with solar thermal collectors and TES system (PS3) demonstrates economic advantages for the office, with a PBT of 16.5 years, which is further reduced to 11.5 years in PS4 through the addition of PV systems.

For the residential building, the optimal users' configuration is PS5, which includes batteries alongside PV systems and solar thermal collectors with TES system. This configuration achieves a PBT of 18 years, even lower than user's configuration PS1 while also offering the highest primary energy saving rate among all scenarios. The PV-T system configuration (PS6) emerges as advantageous for the office, outperforming both PS2 and PS3 in terms of energy and economic metrics. Additionally, PS6 has a PBT of 14.6 years, lower than the 20.7 years for PS5. Despite a slight reduction (12 %) in energy-saving rates compared to PS5, the users' configuration PS6 benefits from reduced rooftop space requirements.

The analysis is extended to include the impact of potential revenues from exporting surplus electricity to the grid and sharing energy within

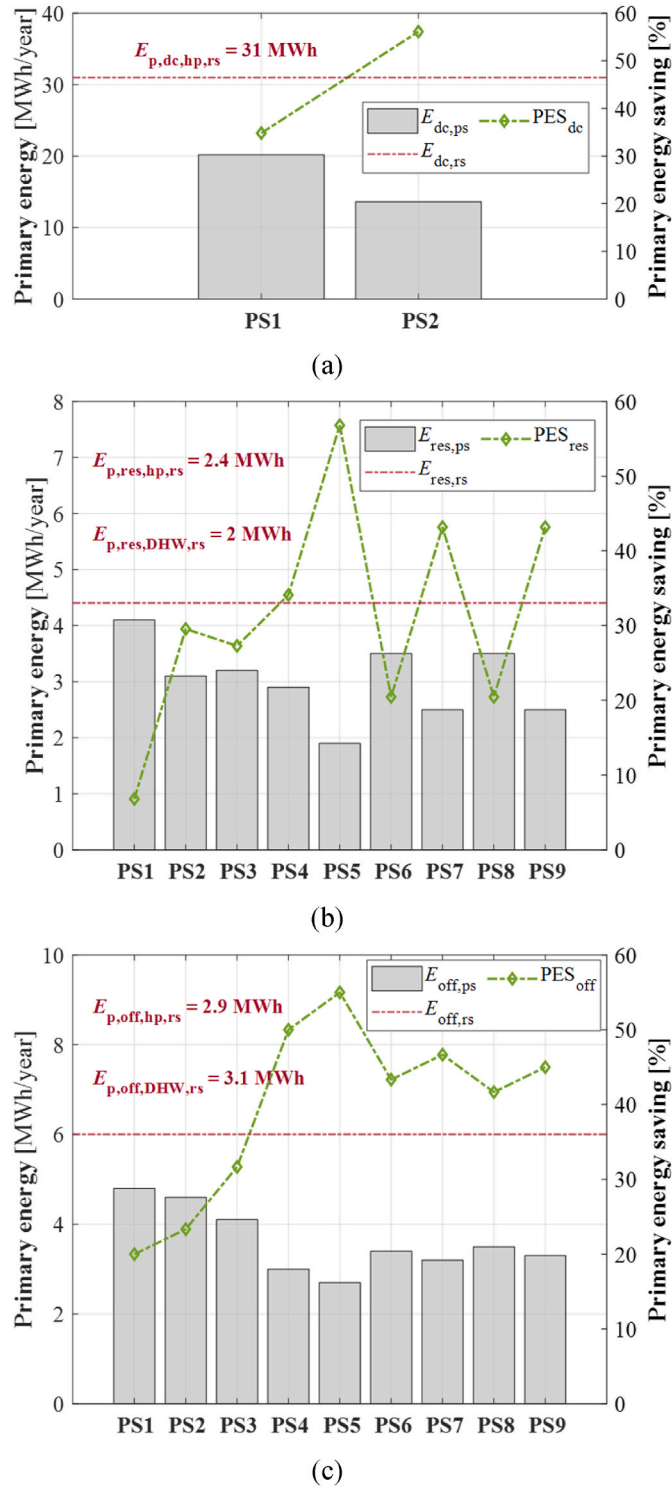


Fig. 17. Annual primary energy consumption comparison between the proposed integration of solar technologies at the user level and the reference scenario (without solar integration): (a) data centre; (b) residential building; and (c) office building.

the 5GDHC system. These results are shown in Fig. 19. The residential building demonstrates the greatest reduction in PBT. For instance, the PBT of PS1 decreases from 22.9 years to 4 years, while that of PS6 is reduced from 38.5 years to 14 years, making PV-T systems a promising option for further investigation.

For the second strategy, which follows a community-based approach, the total CAPEX for installing the technologies and the collective total

revenues, are considered. This strategy allows proportional investment by users or external investors, with total revenues distributed according to investment shares. The results for this strategy, reported in Table 5, reveal differences in economic gains and risk among users' system configurations. For the first 5GDHC configuration, PS5, which integrates PV systems, solar thermal collectors, and both storage systems for thermal consumers, and PV systems with batteries for the data centre, achieves the highest total revenues of €3.2k. The comparable users' configuration PS7 yields total revenues of €3.1k but has a higher PBT of 16 years versus 14.9 years for PS5.

In the second 5GDHC configuration, PS4 offers a balanced trade-off. With a CAPEX of €13.2k, it achieves total revenues of €1.1k (only 21 % lower than the total revenues of PS5) and a reduced PBT of 12.3 years compared to 18.6 years for PS5. Conversely, PS7, characterised by PV-T systems with batteries, offers total revenues of €1.2k but involves a high CAPEX of €29.4k and a PBT of 25.5 years, representing a higher risk. The users' configurations PS6 emerges as a preferred option over PV systems with batteries (PS2), achieving the same total revenues of €0.8k with lower CAPEX and PBT.

4.5. Bi-objective techno-economic analysis

This section presents the results of a bi-objective analysis aimed at comparing the proposed configurations of solar technologies integrated at the user level, considering both technical and economic perspectives simultaneously. The analysis assumes that the proposed system configurations are consistent across all end-users, except in the cases where specific technologies can only be applied to specific user types as detailed in Table 1.

The two key indices investigated are the PES rate and the PBT index, both referred to the overall 5GDHC system configuration. The PES rate represents the primary energy saving rate, calculated based on the energy consumption of all users and the thermal balancing station. In contrast, the PBT index is calculated as a function of the total CAPEX for the installation of the proposed configurations of solar and energy storage technologies across all the users of the 5GDHC system, as well as the total revenues of the entire system. This bi-objective analysis is conducted for the two 5GDHC system configurations considered in this study.

The results of this analysis are presented in Fig. 20, where the proposed 5GDHC configurations are classified into four defined areas. The red area includes configurations characterised by low PES rates and high PBT indices, and these are considered not effective for the investigated purposes. Two grey areas classify configurations for which only one of the two objectives (high PES and low PBT) is achieved. The green area identifies configurations that achieve desirable performance both in terms of PES and PBT.

This analysis demonstrates that the system configuration characterised only by solar thermal collectors with stratified TES in the first 5GDHC configuration (with one thermal prosumer and two thermal consumers) should be avoided due to its low PES and PBT values. This outcome is primarily driven by the characteristics of the data centre, which does not require thermal energy for heating or domestic hot water (DHW).

For the second 5GDHC configuration (with four thermal consumers), the system configuration falling into the red area is the PV system with batteries. This result is mainly influenced by the offices, which exhibit limited energy consumption reductions from battery integration when compared to the high investment cost of the system.

In both 5GDHC configurations, the installation of PV systems at the user level offers the solution with the lowest PBT values, but the PES rates are in both cases less than 30 %. The highest PES rates are achieved by PV systems combined with solar thermal collectors, BESS, and TES in both configurations. For the second 5GDHC configuration, only one system configuration falls within the identified target green area of Fig. 20: PV systems combined with solar thermal collectors and a storage

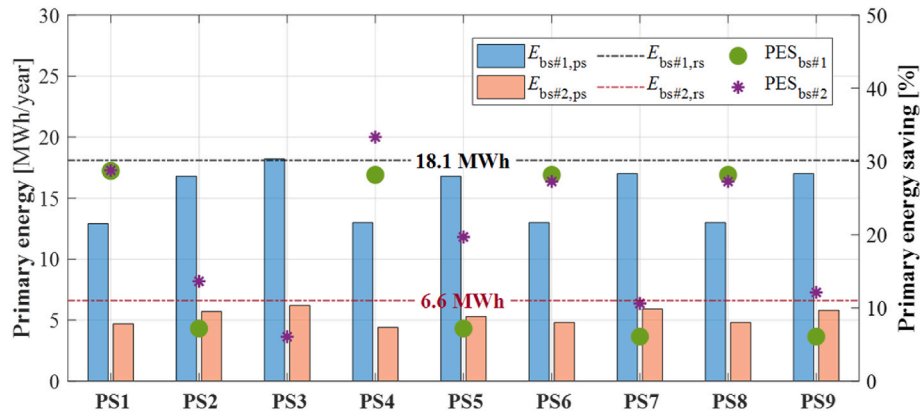


Fig. 18. Annual primary energy consumption comparison of the thermal balancing station for two different 5GDHC configurations: the first configuration includes one data centre, one office, and one residential unit, while the second configuration consists of two residential units and two office buildings. The analysis evaluates the impact of integrating solar technology configurations at the user level compared to the reference scenario (without solar integration).

Table 4

Economic analysis for the strategy where users individually invest in solar technology integration. The table presents the investment costs, annual operational cost savings, and payback time for each end-user across various proposed solar technology integration scenarios.

User type	Variable	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9
Data centre	CAPEX [k€]	9.00	35.2	0.00	9.00	35.2	9.00	35.2	9.00	35.2
	ΔOPEX [k€/year]	1.60	2.40	0.00	1.60	2.40	1.60	2.40	1.60	2.40
	PBT [years]	5.80	14.8	0.00	5.80	14.8	5.80	14.8	5.80	14.8
Residential	CAPEX [k€]	0.80	3.40	1.80	2.70	5.30	3.70	6.30	3.90	6.50
	ΔOPEX [k€/year]	0.03	0.18	0.12	0.16	0.29	0.09	0.23	0.09	0.23
	PBT [years]	22.9	19.8	15.4	17.1	18.0	38.5	27.2	41.2	28.3
Office	CAPEX [k€]	1.00	5.00	3.00	4.00	8.00	4.40	8.40	5.00	9.00
	ΔOPEX [k€/year]	0.17	0.21	0.18	0.35	0.38	0.30	0.34	0.29	0.33
	PBT [years]	5.90	24.3	16.5	11.5	20.7	14.7	24.8	17.0	27.1

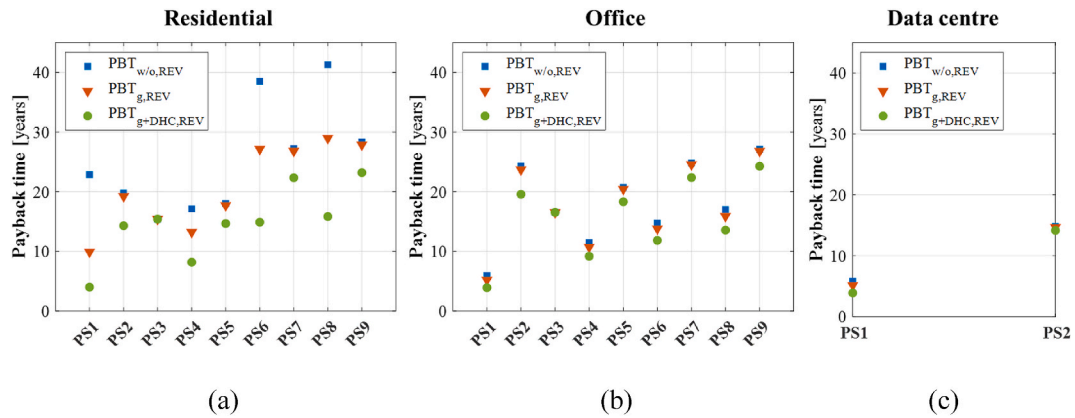


Fig. 19. Improvement in payback time for the proposed solar technology integration scenarios, accounting for revenues from energy exported and shared within the 5GDHC system. Results are presented for: (a) residential building; (b) office; and (c) data centre.

Table 5

Economic analysis for the strategy involving collective user investments or external investors in solar technology integration. The table presents the investment costs, annual operational cost savings, and payback time for the proposed solar technology layouts across various scenarios, considering two 5GDHC configurations: one with one prosumer, one residential unit, and one office, and another with two residential units and two offices.

	Variable	PS1	PS2	PS3	PS4	PS5	PS6	PS7	PS8	PS9
5GDHC #1	CAPEX [k€]	10.8	43.6	4.80	15.6	48.4	17.1	49.9	17.9	50.7
	Total revenues [k€/year]	2.50	2.90	0.30	2.80	3.20	2.70	3.10	2.70	3.10
	PBT [years]	4.30	14.8	16.4	5.60	14.9	6.40	16.0	6.70	16.3
5GDHC #2	CAPEX [k€]	3.60	16.8	9.60	13.2	26.4	16.2	29.4	17.8	31.0
	Total revenues [k€/year]	0.40	0.80	0.70	1.10	1.40	0.80	1.20	0.80	1.10
	PBT [years]	9.00	22.2	14.4	12.3	18.6	20.2	25.5	22.4	27.1

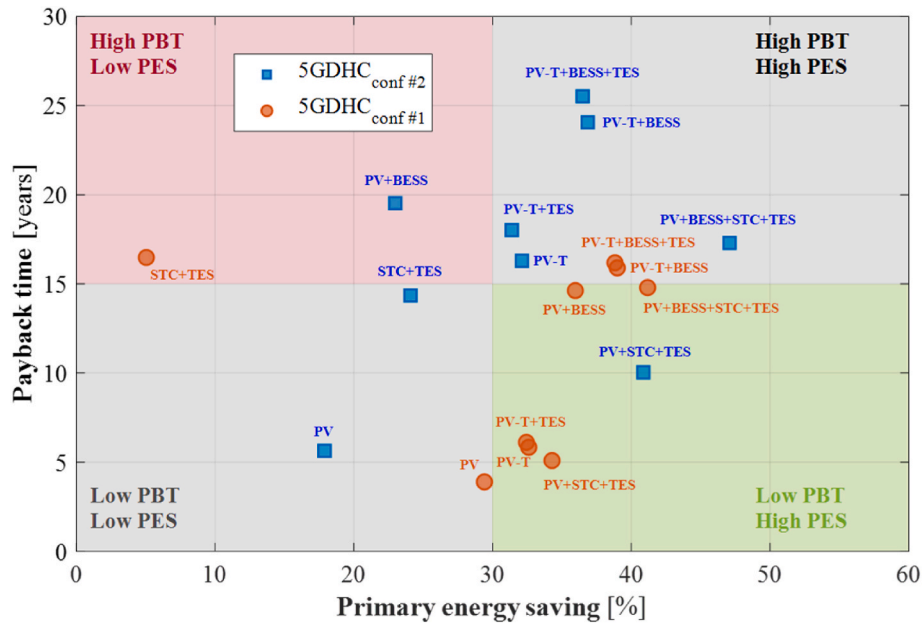


Fig. 20. Bi-objective analysis comparing the PES and PBT for the overall 5GDHC system across various solar technology and storage system installation scenarios. The analysis covers two network configurations: one with one prosumer, one residential unit, and one office, and another with two residential units and two offices. Results are categorised into four areas: low PES and high PBT, low PES and low PBT, high PES and high PBT, and high PES and low PBT.

cylinder. In contrast, among the system configurations for the first 5GDHC configuration that fall within the target green area, the PV-T system emerges as another promising option, offering a favourable PBT of 6 years and strong energy performance with a PES rate of 33 %.

5. Conclusions

Fifth-generation district heating and cooling (5GDHC) systems represent a promising solution to support the electrification of the building sector. This work explores the integration of solar technologies and storage systems at the individual building level of 5GDHC systems. These configurations enhance energy flexibility and improve the integration of renewable energy, reducing the unpredictability of energy sources. The study investigates nine different user configurations, integrating PV systems, solar thermal collectors, PV-T systems, stratified thermal energy storage, and electric batteries. The impact on energy consumption, thermal balancing station energy requirements, and economic performance is analysed across three user types: data centres, which are thermal prosumers, residential buildings, which are thermal consumers, and office buildings, which are also thermal consumers. Results are provided for two 5GDHC system configurations: the first with one data centre, one residential building, and one office, and the second with two residential buildings and two offices.

Key findings from the energy analysis show that configurations with PV systems result in primary energy savings (PES) of 35 %, 6.8 %, and 20 % for data centres, residential buildings, and offices, respectively, compared to a reference scenario without solar technologies. The thermal balancing station benefits from these configurations, achieving a PES rate of 29 % for both 5GDHC system configurations. The integration of batteries, particularly for the residential building and data centre, significantly enhances PES, reaching 30 % and 56 % for the residential building and data centre, respectively.

The addition of solar thermal collectors with a stratified thermal energy storage system in residential and office buildings to increase the heat pump evaporator temperature results in an increase in the heat pump COP during heating, consequently reducing the electricity consumption by 6.3 % and 11 %, respectively. Furthermore, solar thermal energy covers 53 % of the domestic hot water (DHW) demand for residential buildings and 53 % for offices. For these user configurations, PES

increase to 27 % for residential units and 32 % for offices. Meanwhile, the incorporation of PV-T systems yields higher PES (21 % for residential units and 43 % for offices) compared to the PV-only configuration, while also utilising thermal energy production, similar to the configurations with solar thermal collectors.

The highest PES rates (57 % for residential units and 55 % for offices) are achieved with configurations that combine PV systems, solar thermal collectors, and both energy storage systems. The PV-T system with batteries offers significant space savings while also achieving high PES of 43 % for the residential building and 47 % for the office.

The techno-economic analysis reveals that the PV-only configuration integrated into the residential building achieves a payback time (PBT) of 22.9 years when electricity is not exported, which is reduced to 4 years when revenues from exporting electricity are included. The PV-T configuration also benefits from exporting electricity, which reduces its PBT from over 30 years (which is not viable) to 14 years. For the residential unit, the best-performing configuration from an energy perspective – comprising PV systems with solar thermal collectors, stratified thermal energy storage, and batteries – achieves a PBT of 18 years, further reduced to 14 years with exported electricity. In contrast, for the office, the PV-only configuration achieves a PBT of 5.9 years. The PV-T system configuration proves cost-effective for the office, with a PBT of 14.6 years, reduced to 11 years when revenues from exporting electricity are included. The data centre demonstrates a PBT of 5.8 years for the configuration with the PV-only system, rising to 14.8 years when batteries are included, but, in this case, no significant benefits from revenues are observed due to the low level of exports.

For a community-based economic strategy where investments are made collectively by users in the 5GDHC configuration (with one data centre, one residential building, and one office), coupling PV systems with solar thermal collectors and both thermal and electrical energy storage achieves the highest annual cost savings of €3.2k. In the 5GDHC configuration with two residential buildings and two offices, PV systems with solar thermal collectors and stratified thermal energy storage strike a balance between CAPEX and annual cost savings, achieving a PBT of 12.3 years and savings of €1.1k. In contrast, the user configuration with PV-T systems and batteries, while offering cost savings of €1.2k, carries a high CAPEX of €29.4k and a non-viable PBT of over 25 years.

The bi-objective analysis, which evaluates both PES and PBT,

identifies that PV systems with batteries offer the lowest PBT values, though PES rates fall short of the target area for both 5GDHC configurations. The PV-T system emerges as a promising option for the 5GDHC configuration that includes both thermal consumers and prosumers, offering a favourable balance with a PBT of 6 years and a PES rate of 33 %.

It is worth noting that the techno-economic analysis is closely linked to the sizing criteria adopted for the solar technologies and storage systems, as well as to the energy costs and carbon footprint of the electricity grid considered for the specific case study in Northern Italy. While these factors could differ under other conditions, the results of this study are valuable for comparing technologies and estimating techno-economic performance in locations with similar characteristics. Future work will focus on optimising the size and type of solar technologies to achieve their optimal integration within different types of 5GDHC systems. In addition, future research will assess the impact of optimised dynamic network operation, where suitable prediction strategies can regulate the network temperature to maximise the efficiency of users' substations under varying heat pump operating conditions.

In conclusion, this study provides a comprehensive analysis of the techno-economic performance of various solar technology configurations within 5GDHC systems. The findings highlight the potential for significant energy and cost savings when solar technologies are effectively integrated with energy storage, and the provided insights can be used to inform energy policy.

CRediT authorship contribution statement

Giuseppe Russo: Writing – original draft, Visualization,

Methodology, Investigation, Data curation, Conceptualization. **Andreas V. Olympios:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Cesare Forzano:** Writing – original draft, Methodology, Conceptualization. **Chandan Pandey:** Writing – original draft, Methodology, Conceptualization. **Annamaria Buonomano:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Adolfo Palombo:** Writing – review & editing, Supervision, Investigation, Conceptualization. **Christos N. Markides:** Writing – review & editing, Supervision, Investigation, 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.

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Appendix A. Heat pumps

Heat pumps are modelled using a thermodynamic framework with R410A as the refrigerant, which is suitable in space heating and cooling applications [60,61]. The heat pumps are equipped with inverter regulation, allowing the refrigerant flow rate to adapt to users' thermal demands for heating and cooling. The thermodynamic cycle is modelled as a non-linear constrained optimisation problem, solved using an iterative numerical algorithm, and assuming steady-state conditions of the energy balances [62]. Pressure drops are neglected, which is an acceptable hypothesis given the small-medium sizes of the investigated heat pumps. The model identifies the minimum mechanical power required by the compressor (P_{comp}) for various temperature and thermal load conditions. By identifying the COP for each of these conditions, performance maps are generated for varying fractions of user thermal loads, ranging from 10 % to 100 %, and inlet source temperatures from 20 °C to 30 °C in compliance with 5GDHC temperature ranges.

The thermodynamic cycle for heating is shown in Figure A.1. The cycle includes superheating and subcooling phases, with thermal power exchanged at the sink side represented by the space heating demand. The optimisation variables are the evaporator and condenser pressures (p_{ev} and p_{co}). The known parameters include: (1) the temperature differences for superheating (ΔT_{sh}), subcooling (ΔT_{sc}), and the heat exchanger pinch point (ΔT_{pp}); (2) the inlet source side temperature ($T_{in,source}$) and the thermal demand ($\dot{Q}_{sink}$).

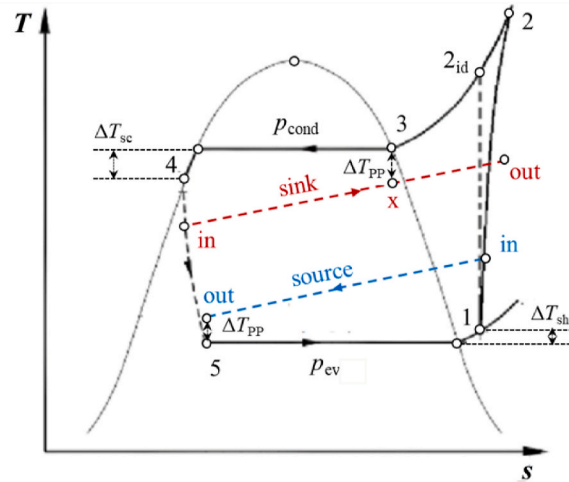


Fig. A.1. Thermodynamic cycle of heat pump during heating operation.

The estimation procedure of thermodynamic properties, problem constraints, and outputs are summarised in Table A.1. The key constraints are the temperature difference between the refrigerant entering the evaporator (T_5) and the water outlet temperature at the heat pump source side ($T_{\text{out,source}}$), and the temperature difference between the refrigerant entering the condenser two-phase region (T_3) and the water temperature on the sink side ($T_{\text{x,sink}}$), which must equal the specified heat exchanger pinch-point.

The actual thermodynamic properties at the compressor outlet are calculated based on the isentropic efficiency ($\eta_{\text{comp,is}}$), expressed as:

$$\eta_{\text{comp,is}} = \lambda_1 + \lambda_2 r_p + \lambda_3 \frac{\dot{m}_{\text{rf}}}{\rho_1} + \lambda_4 r_p^2 + \lambda_5 r_p \frac{\dot{m}_{\text{rf}}}{\rho_1} + \lambda_6 \left(\frac{\dot{m}_{\text{rf}}}{\rho_1} \right)^2 \quad (\text{A.1})$$

where λ_1 to λ_6 are second-order polynomial coefficients derived from experimental data via the least-squares method, as detailed in Ref. [63]; r_p represents the pressure ratio between condenser and evaporator, and ρ_1 is the density at the compressor inlet.

Table A.1
Heat pump thermodynamic model calculations and assumptions.

Variables	Known variables	
p_{ev}	$\Delta T_{\text{sh}} = 2 \text{ } ^\circ\text{C}$	$T_{\text{in,source}} = T_{\text{s,net}}$
p_{co}	$\Delta T_{\text{scl}} = 3 \text{ } ^\circ\text{C}$	$\dot{Q}_{\text{sink}} = \dot{Q}_{\text{dem}}$
	$\Delta T_{\text{pp}} = 5 \text{ } ^\circ\text{C}$	
Thermodynamic properties estimation	Constraints	Outputs
$h_1 = f(p_{\text{ev}}, \Delta T_{\text{sh}})$	$T_3 = T_{\text{x,sink}} + \Delta T_{\text{pp}}$ with $T_{\text{x,sink}} = \frac{\dot{m}_{\text{rf}}(h_3 - h_4)}{\dot{m}_{\text{sink}} c_{p,w}} + T_{\text{in,sink}}$	$\dot{m}_{\text{rf}} = \frac{\dot{Q}_{\text{sink}}}{(h_2 - h_4)}$
$h_2 = f(p_{\text{co}}, \eta_{\text{comp,is}})$		
$h_4 = f(p_{\text{co}}, \Delta T_{\text{scl}})$	$T_5 = T_{\text{out,source}} - \Delta T_{\text{pp}}$ with $T_{\text{out,source}} = \frac{\dot{m}_{\text{rf}}(h_5 - h_1)}{\dot{m}_{\text{source}} c_{p,w}} + T_{\text{in,source}}$	$P_{\text{comp}} = \dot{m}_{\text{rf}}(h_2 - h_1)$
$h_5 = h_4$		

The heat pump COP is determined as the ratio of the user heating or cooling demand ($\dot{Q}_{\text{dem}}$) to the compressor mechanical power (P_{comp}), neglecting mechanical losses:

$$\text{COP} = \frac{\dot{Q}_{\text{dem}}}{P_{\text{comp}}} \quad (\text{A.2})$$

Appendix B. Solar technologies

The outlet temperature of the heat transfer fluid in solar thermal collectors (STC) and PV-T systems is determined through an iterative procedure that considers the system layout (*i.e.*, the number of modules in series and parallel) and system efficiencies (shown in Figure B.1) [64]. The process begins by applying an energy balance to the control volume of a single collector to calculate the outlet fluid temperature ($T_{\text{out,STC}}$ or $T_{\text{out,PV-T}}$). In the initial approximation, the thermal power absorbed by the fluid is assumed to be equal to the solar radiation incident on the collector area (A_{STC} or $A_{\text{PV-T}}$), with the efficiency set to 1.

Subsequently, the collector efficiency (η_{STC} or $\eta_{\text{PV-T}}$) is calculated based on the initially estimated outlet temperature. The energy balance is then recalculated to determine the new outlet temperature value. This iterative process continues until the difference between the outlet temperatures of consecutive iterations is within a small tolerance (ϵ of $0.1 \text{ } ^\circ\text{C}$). At the end of this process, the outlet temperature of the fluid serves as the inlet temperature ($T_{\text{in,STC}}$ or $T_{\text{in,PV-T}}$) for the next collector in series, and the procedure is repeated for all the string.

The thermal efficiency is evaluated as a function of the optical losses of the module (η_0), the thermal losses parameters a_1 and a_2 provided by the manufacturer, as well as the reduced temperature (T^*). The reduced temperature expresses the ratio between the temperature difference of the absorber plate (T_{abs}) and surrounding ambient environment (T_{amb}), and the total incident solar radiation (G). Here, the absorber temperature is approximated as the average of the inlet and outlet temperatures of the heat transfer fluid.

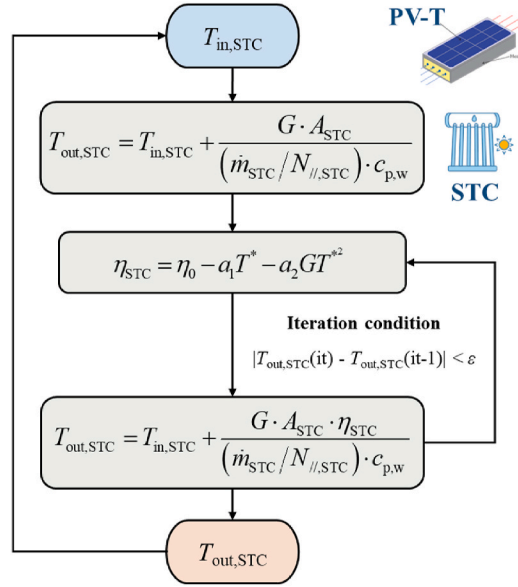


Fig. B.1. Flow chart showing the iterative numerical procedure adopted to assess the outlet temperature of the solar thermal collectors and PV-T modules.

The electrical energy generation of PV and PV-T systems is estimated using a set of established correlations. The system efficiency (η_{PV}) is calculated using a correlation from Ref. [65] that accounts for the nominal test condition efficiency ($\eta_{PV,nom}$), a temperature coefficient (β), and the difference between the actual cell temperature (T_{ce}) and the reference temperature under standard test conditions ($T_{ce,ref}$ equal to 25 °C). The cell temperature is modelled as a function of T_{amb} , the nominal operating cell temperature (NOCT), and the incident solar irradiance (G) [66].

$$P_{PV} = A_{PV} G \eta_{PV} \quad (B.1)$$

$$\eta_{PV} = \eta_{PV,nom} (1 - \beta(T_{ce} - T_{ce,ref})) \quad (B.2)$$

$$T_{ce} = T_{amb} + (NOCT - 20)G/800 \quad (B.3)$$

$$T_{ce,PV-T} = \frac{T_{in,PV-T} + T_{out,PV-T}}{2} \quad (B.4)$$

For PV-T systems, the cell temperature is assumed to be equal to the absorber plate temperature (T_{abs}) at the bottom of the PV layer. This assumption accounts for the thermal interaction between the PV layer and the fluid circulation in the PV-T system [67].

Appendix C. Energy storage systems

The modelling of electric batteries is based on the electricity balance equation that accounts for the electricity stored from the PV or PV-T system surpluses and the electricity withdrawn to meet the electrical demands of users [68]. The state of charge of the battery energy storage system (SOC_{BESS}) is dynamically evaluated:

$$SOC_{BESS}(t + \Delta t) = SOC_{BESS}(t) + \min(P_{PV,sur} \Delta t, (1 - SOC_{BESS}(t))C_{BESS}, V_{BESS}I_{max} \Delta t) / C_{BESS} - \min(P_{dem} \Delta t, SOC_{BESS}(t)C_{BESS}, V_{BESS}I_{max} \Delta t) / C_{BESS} \quad (C.1)$$

where SOC_{BESS} at the time step $t + \Delta t$ represents the percentage of energy stored relative to the capacity of the battery (C_{BESS}). It is a function of SOC_{BESS} at the previous time step, t , the stored electricity, and the electricity withdrawn to satisfy the user electrical loads. The stored electricity surpluses are determined as the minimum value among the available surpluses, the remaining charging capacity of the battery, and the maximum energy that can be supplied to the battery, which is constrained by the maximum charging current (I_{max}) and voltage (V_{BESS}). Similarly, the electricity that can be discharged by the battery is the minimum value among the required load, the available discharging capacity, and the maximum discharging energy.

The stratified TES system is modelled using energy balance equations solved under the assumption of a quasi-one-dimensional transient regime. This approach considers the spatial variation of temperature along the vertical axis of the storage cylinder, where water temperature stratification occurs [69]. The assumption is supported by the hypothesis of uniform temperature within the hot and cold volumes (T_h and T_c) and a constant thermocline. The following mass and energy balance equations are used to simulate the temperature evolution in the TES volumes and to evaluate their charging and discharging processes:

$$\begin{cases} \frac{dM_h}{dt} = \dot{m}_h - \dot{m}_c = \rho A_{cs} \frac{dz_h}{dt} \\ \frac{dM_c}{dt} = \dot{m}_c - \dot{m}_h = \rho A_{cs} \frac{dz_c}{dt} \end{cases} \quad (C.2)$$

where the masses of water in the hot and cold volumes are denoted as M_h and M_c , respectively, and the flow rates of the hot source and the load are

represented by $\dot{m}_h$ and $\dot{m}_c$, respectively. The height levels of the respective volumes are denoted as z_h and z_c .

$$\begin{cases} M_h c_{p,w} \frac{dT_h}{dt} = \dot{m}_h c_{p,w} (T_{in,h} - T_h) - \frac{k_w A_{cs} (T_h - T_c)}{0.5(z_h + z_c)} - U_l A_{lat,h} (T_h - T_{amb}) \\ M_c c_{p,w} \frac{dT_c}{dt} = \dot{m}_c c_{p,w} (T_{in,c} - T_c) + \frac{k_w A_{cs} (T_h - T_c)}{0.5(z_h + z_c)} - U_l A_{lat,c} (T_c - T_{amb}) \end{cases} \quad (C.3)$$

where the inlet temperature of the hot volume, denoted as $T_{in,h}$, is provided by the outlet temperature of the solar thermal collector or PV-T modules, while the inlet temperature of the cold volume, $T_{in,c}$, is supplied by the return line on the load side of the thermal storage, represented by the district heating pipeline network. The energy balance equations incorporate thermal dissipation due to conduction between the hot and cold volumes and losses from the lateral surfaces of the cylinder. These losses are influenced by the heat transfer coefficients, U_l , of the storage lateral surfaces ($A_{lat,h}$ and $A_{lat,c}$) interacting with the ambient environment.

Appendix D. Network pipes

The modelling of the network pipes is based on a set of energy balance equations applied to each section of the network. These equations are solved to determine the temperature variation of water flowing through the pipes while accounting for thermal dissipation into the ground. The thermal behaviour of the pipes is represented using a lumped parameter thermal model operating in a transient regime [70], as expressed below:

$$\begin{cases} \rho_w c_{p,w} V_i \frac{dT_{w,i}}{dt} = \dot{m}_{w,i} (T_{w,i-1} - T_{w,i}) + \dot{Q}_{H,i} \\ \dot{Q}_{H,i} = \left[\left(\frac{1}{R_{k,w,i}} + \frac{1}{R_{c,w,i}} \right)^{-1} + R_{k,pip} \right]^{-1} (T_{grd} - T_{w,i}) \end{cases} \quad (D.1)$$

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

It is assumed that the flow rate in the pipe network is constant and equal to the sum of the nominal flow rates for each user. The flow rate for each user's heat pump is determined based on the maximum cooling load ($\dot{Q}_{cl,max,us}$) using the energy balance equation for steady-state conditions applied to the building control volume:

$$\dot{m}_{us} = \frac{\dot{Q}_{cl,max,us}}{c_{p,w} (T_{out,dem} - T_{in,dem})} \quad (D.2)$$

The cooling energy is supplied to the building cooling unit at a temperature of $T_{in,dem}$ equal to 7 °C and returns $T_{out,dem}$ at 12 °C. With the flow rate known, the diameter of each pipeline portion can be estimated based on a reference velocity of 1 m/s [71].

Appendix E. Thermal balancing station

The thermal balancing station consists of an air-source heat pump system for heating and cooling the network heat transfer fluid, along with a heat recovery unit for adjusting the temperature of the district network. The heat recovery unit operates by dissipating excess heat to the ambient air for free cooling or using ambient heat as a source for free heating, both requiring minimal energy input. The thermal balancing needs of the network are evaluated as follows:

$$\begin{aligned} \dot{Q}_{cl,net} &= \dot{m}_{net} c_{p,w} (T_{r,net} - T_{s,net}) \\ \dot{Q}_{ht,net} &= \dot{m}_{net} c_{p,w} (T_{s,net} - T_{r,net}) \end{aligned} \quad (E.1)$$

where $\dot{Q}_{cl,net}$ and $\dot{Q}_{ht,net}$ represent the network thermal requirements for cooling or heating the heat transfer fluid to the desired temperature ($T_{s,net}$). The fractions of cooling energy ($\dot{Q}_{cl,net,hru}$) and heating energy ($\dot{Q}_{ht,net,hru}$) satisfied by the heat recovery unit are determined as:

$$\begin{aligned} \dot{Q}_{cl,net,hru} &= \frac{T_{r,net} - \max((T_{amb} + \Delta T_{pp,hru}), T_{s,net})}{T_{r,net} - T_{s,net}} \dot{Q}_{cl,net} \\ \dot{Q}_{ht,net,hru} &= \frac{\min((T_{amb} - \Delta T_{pp,hru}), T_{s,net}) - T_{r,net}}{T_{s,net} - T_{r,net}} \dot{Q}_{ht,net} \end{aligned} \quad (E.2)$$

The maximum fraction satisfied by the heat recovery unit depends on T_{amb} and the minimum allowable pinch-point temperature difference ($\Delta T_{pp,hru}$).

The electrical power required by the fan of the heat recovery unit is assessed as follows:

$$P_{el,fan} = \frac{\dot{m}_{hru} \Delta p}{\rho_{air} \eta_{fan}} \quad (E.3)$$

where Δp is the pressure drop across the heat exchanger (assumed to be 50 Pa per unit of volumetric flow rate in m³/s), ρ_{air} is the air density, and η_{fan} is the fan electrical efficiency (assumed to be constant at 0.9) [72]. The air flow rate $\dot{m}_{hru}$ is calculated through Equation (15):

$$\dot{m}_{\text{hru}} = \begin{cases} \frac{\dot{Q}_{\text{cl,net,hru}}}{c_{p,\text{air}}((T_{\text{r,net}} - \Delta T_{\text{PP,hru}}) - T_{\text{amb}})} \rightarrow \text{free cooling} \\ \frac{\dot{Q}_{\text{ht,net,hru}}}{c_{p,\text{air}}(T_{\text{amb}} - (T_{\text{r,net}} + \Delta T_{\text{PP,hru}}))} \rightarrow \text{free heating} \end{cases} \quad (\text{E.4})$$

The remaining network thermal requirements are met by the air-source heat pumps. Heat pump electrical consumptions are determined using the COP performance map generation method described in [Appendix A](#).

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