Energy 301 (2024) 131531

Contents lists available at ScienceDirect

Energy

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

Development and optimization of an energy saving strategy for social housing applications by water source-heat pump integrating photovoltaic-thermal panels

Andrea Vallati [a], Miriam Di Matteo [a], Mukund Sundararajan [b], Francesco Muzi [a], Costanza Vittoria Fiorini [a,*]

[a] DIAEE Department of Astronautical, Electrical, and Energy Engineering, "Sapienza" University of Rome, Via Eudossiana 18, 00184, Rome, Italy
[b] Bharath Institute of Higher Education and Research, Chennai, India

ARTICLE INFO

Handling Editor: Dr. Henrik Lund

Keywords:
Renewable energy
Photovoltaic-thermal collectors
Building energy efficiency
Social housing
Dynamic simulation
Experimental validation

ABSTRACT

Residential buildings account for 84 % of Italy's built environment, playing a pivotal role in the EU's aim to cut GHG emissions by 55 % through enhanced energy efficiency and climate adaptation. This necessitates comprehensive energy retrofit initiatives, especially in sectors like social housing, which has been relatively overlooked in terms of energy efficiency strategies. This study focuses on a multi-story building from the 1980s in Rome, implementing an innovative energy system proposed by the RESHeat European project. This system, aimed at standardizing energy retrofits for late 20th-century social housing, leverages the underexplored potential of water-source heat pump (WSHP) systems. The novelty of this research extends to its examination of multi-family housing, a sector that has seen less attention compared to public spaces and smaller residential buildings. Through experimental validation and annual dynamic simulations using TRNSYS and Simulink, the research compares the existing heating system with a proposed upgrade that includes a WSHP and Photovoltaic-Thermal (PVT) panels. This upgrade demonstrated a significant efficiency improvement, achieving an annual COP of 6.1 for the WSHP and a 36 % Primary Energy Savings (PES) from the PVT panels, showcasing the effectiveness of these technologies in enhancing the energy profile of multi-family residential buildings.

1. Introduction

It's widely acknowledged that the building sector ranks among that highly energy-consuming, due to both phases of construction and demolition but also in operation. At this stage, climate change in particular has a significant impact, resulting in an increasing demand for cooling and in thermal systems being undersized or oversized compared to future needs [1]. In urban areas, the first step to accomplish the energy efficiency and carbon neutrality objectives set forth by the European Union for the year 2050 [2,3] is therefore to adopt energy conservation measures (ECM). Several studies have focused on management of internal loads, enhancement of envelope insulation and optimization of heating, ventilation and air conditioning system work. To identify a series of interventions that can be widely applied to existing buildings with similar characteristics is a strategic approach to speed up the achievement of international sustainability objectives. In retrofitting, one indispensable consideration concerns the construction year, a factor that cannot be overlooked since it significantly affects the insulation grade of the envelope and the type of thermal systems, as well as the construction trends. In numerous Italian municipalities the energy efficiency improvement necessitates of special actions for which it is mandatory to take into account the building context, involving the knowledge of materials, construction features, and so forth [4].

Several studies explore retrofit measures for residential buildings across Italy and Europe, providing insights into current trends and technologies. In [5] an overview of the implementation of interventions for renovating historical and heritage buildings is offered, assessing the feasibility and advantages of different retrofit approaches. The authors underline how the payback time of a single or combination of interventions is a key factor in the decision of the action to be taken, recalling that it varies for the same energy measure from colder to warmer zones. Renovations focused solely on the building envelope show limited effectiveness for residences powered by oil and gas, because fossil fuel consumption is not sufficiently reduced across the entire building stock. Despite a 2.5 % annual renovation rate and an

* Corresponding author.
E-mail address: costanzavittoria.fiorini@uniroma1.it (C.V. Fiorini).

https://doi.org/10.1016/j.energy.2024.131531
Received 20 January 2024; Received in revised form 11 April 2024; Accepted 3 May 2024
Available online 11 May 2024

Abbreviations

ATER	Agenzia Territoriale per l'Edilizia Residenziale
DC	Dry Cooler
DHW	Domestic Hot Water
ECM	Energy Conservation Measures
HFM	Heat Flow Meter
HP	Heat Pump
KPI	Key Performance Indicator
MAP	HP characteristic map
NGB	Natural Gas Boiler
PV	Photovoltaic
PVT	Photovoltaic-Thermal
TES	Thermal Energy Storage
WSHP	Water-Source Heat Pumps

Symbols

$c_{p,w}$	Average fluid specific heat (J/kgK)
$\dot{m}_{w,HP}$	mass flow rate of HP heat transfer fluid (kg/h)
$\dot{m}_{w,PVT}$	Mass flow rate of PVT heat transfer fluid (kg/h)
A_{PVT}	Collector area (m^2)
C_f	Capacity factor (−)
$E_{el,DC}$	Dry Cooler Electricity demand (MWh/yr)
$E_{el,EB}$	Electric Boiler Electricity demand (MWh/yr)
$E_{el,HP}$	Heat Pump Electricity demand (MWh/yr)
$E_{el,PVT,net}$	PVT Electricity net sharing (MWh/yr)
$E_{el,PVT,sc}$	PVT Electricity self-consumption (MWh/yr)
$E_{el,PVT}$	PVT Electricity production (MWh/yr)
$E_{el,aux}$	Auxiliary devices Electricity demand (MWh/yr)
$E_{el,build}$	Building Electricity demand (MWh/yr)
$E_{el,demand}$	Overall Electricity demand (MWh/yr)
$E_{in,HP}$	Heat Pump Input Energy (MWh)
$E_{in,NGB}$	Natural gas Boiler Input Energy (MWh)
$E_{th,DHW}$	Domestic Hot Water Thermal Energy demand (MWh/yr)
$E_{th,HP,e}$	Heat Pump Thermal Energy demand (cold side) (MWh/yr)
$E_{th,HP}$	Heat Pump Thermal Energy production (MWh/yr)
$E_{th,PVT,st}$	PVT Thermal Energy production and storage (MWh/yr)
$E_{th,demand}$	Overall Thermal Energy demand (MWh/yr)
F_R	Collector heat removal factor (−)
I_t	Solar radiation on collector tilted surface (W/m^2)
$P_{cold,HP}$	Refrigerating power from evaporator to cold well (W)
$P_{el,DC}$	Electric power input DC (W)
$P_{el,HP}$	Electric power demand HP (W)
$P_{el,PVT}$	Electric power output PVT (W)
$P_{th,DC}$	Thermal power output DC (W)
$P_{th,HP}$	Thermal power output HP (W)
$P_{th,PVT}$	Thermal power output PVT (W)
Sm^3	Standard cube meter (m^3)
$T_{PVT,cell}$	Temperature of the PVT cell (°C)
T_{amb}	Ambient temperature (°C)
$T_{in,HP,e}$	Temperature at evaporator inlet (°C)
$T_{out,HP,e}$	Temperature at evaporator outlet (°C)
T_{top}	Temperature of the water at TES top (°C)
$T_{w,HP,c}$	Temperature of water in HP condenser (°C)
$T_{w,HP,e}$	Temperature of water in HP evaporator (°C)
$T_{w,out,PVT}$	Temperature of outlet water of PVT (°C)
U_L	Heat overall loss coefficient and bottom heat loss (W/m2K)
c_{el}	Temperature coefficient of maximum $P_{el,PVT}$ (%/°C)
$f_{PE,i}$	Primary energy conversion factor for the i-th energy vector (−)
η_{el}	Overall cell electrical efficiency (−)
η_{th}	Overall thermal efficiency (−)
COP	Coefficient Of Performance (−)
EER	Energy Efficiency Ratio (−)
f_{SC}	self-consumption fraction (−)
f_{sol}	Overall solar fraction (−)
$f_{sol,el}$	Electrical solar fraction (−)
$f_{sol,th}$	Thermal solar fraction (−)
NOCT	Nominal Operating Cell Temperature (°C)
PE	Primary Energy (MWh/y)
PE, nREN	Primary non-renewable Energy (MWh/y)
PE, REN	Primary renewable Energy (MWh/y)
PES	Non-Renewable Primary Energy Savings (MWh/y)
sCOP	Seasonal Coefficient Of Performance (−)
LHV	Lower Heating Value (kWh/m^3)
$\tau\alpha$	Transmittance-absorptance product of collector (−)

Subscripts

C	Cooling
c	condenser
DC	Dry Cooler
DHW	Domestic Hot Water
e	evaporator
el	electricity
H	Heating
HP	Heat Pump
M	Measures
ng	natural gas (CH_4)
NGB	Natural Gas Boiler
NOCT	Standard test condition (irradiance = 800 W/m^2; module temperature = 20 °C, wind speed 1 m/s)
operating	operating
rated	rated
S	Simulated
S0	Current Scenario
S1	RESHeat Scenario
sc	self-consumption
w	water

average 65 % energy reduction achieved per dwelling, the overall decrease remains inadequate. Thus, envelope renovations in residences supplied by fossil fuel, should shift towards combined approaches, integrating efficiency enhancements in the building envelope alongside transitioning to alternative heating systems [6].

In residential structures, where hot water generation, spaces' heating and cooling can be managed by a single system, the air-to-water heat pump (HP) offers distinct advantages, encompassing cost-effectiveness and straightforward installation. Throughout the colder seasons, the Coefficient of Performance (COP) of this apparatus diminishes concurrently with the building's peak energy demand. Additionally, it is typically engineered to fulfill the maximum load while predominantly operating under partial load conditions, resulting in substantial seasonal performance reduction [7]. Addressing these challenges, hybrid systems that interconnect air-source heat pumps with parallel or series-connected backup heaters have exhibited promising potential. Nevertheless air-source heat pumps incur higher operating costs due to significant seasonal fluctuations in the heat source temperature. In contrast, water-source heat pumps and geothermal heat pumps exhibit superior performance and reduced operational costs because of the higher heat source temperatures.

In general, if the goal is to maintain a high COP, some operational issues can be encountered with single-source heat pump arrangements, notably in cold regions: in conditions of low outdoor air temperature, the outdoor heat exchanger of air-source HPs frosts [8,9], whilst in case of inconsistent heating and cooling loads continued operation of ground-source heat pump system (GSHP) can cause thermal imbalance of the soil [10,11].

In case of solar assisted heat pumps low solar irradiance during certain periods of the year, in addition to its instability, lead to an intermittent performance of the solar energy systems, hence requiring a high number of collectors, which means a substantial upfront capital investment and issues in the installation process due to the wide committed area [12]. To overcome these concerns, avoiding performance and operation reliability decreases, some studies tried to take advantage of composite heat pump system, which enable flexible running modality.

In [13] the viability of a multi-source hybrid heat pump system in different cold regions of China was demonstrated. A double-source heat pump unit, able to run as a separate heat pipe mode and vapor compression heating mode, was added to a ground-source heat pump. The system, with a summer COPc around 7.6 and a winter COPh around 3, showed a 49.21 % rise in mean COPh and a 36 % increase in annual COP compared to GSHPs operating under equivalent conditions. The addition of the double-source heat pump, accounts for 9.59 % of the initial investment, leading to a static payback period of four years.

In [14], a TRNSYS simulation model for a solar-assisted groundwater source heat pump system is proposed, along with a year-round operation control strategy. The model incorporates a new dual-interface solar and groundwater heat storage module, Type299. Experimentation validates the model's accuracy using a case system in Shenyang. Results indicate a significant rise in annual solar energy utilization. Over ten years, the new system effectively maintains groundwater temperature, demonstrating improved stability and efficiency: it achieves a 36.8 % rise in annual average temperature and a 23.8 % higher comprehensive performance coefficient compared to the original system.

A recent review researches conducted on solar assisted ground source heat pump systems [15] gave as highest values 5.7 and 13.5 for air source heat pump's COP and system's relying on latent heat energy storage tank. Among the solutions to increase the COP include the application of PCMs, which reduces heating load and electrical consumptions or even alternative refrigerants: the use of R22 compared to R744 increases COP of 28.8 %, whereas, thanks to its low critical temperature and high operating pressure, R410A turns out appropriate for low temperature heat pumps. Moreover, future directions for researches and developments to match for higher efficiency of the systems in question are highlighted. First, the optimization of their application in buildings which consume large quantities of primary energy, such as tertiary-use buildings, and their work under different weather conditions such as low ambient temperatures, high humidity, and windy environments; advanced control strategies and the experimentation of environment-friendly refrigerants are also recommended.

Nevertheless, solar energy and environmental air energy exhibit an isotropic distribution in cold regions and the ambient temperature remains low in scenarios of reduced solar radiation, posing challenges in fulfilling heating requirements. A more reliable set-up consists in a solar-ground source heat pump heating system to exploit in full solar and shallow soil energy.

In [16], the experimental findings indicated that throughout the heating season in all cold regions of Turkey, the average Coefficient of Performance of the apparatus was approximately 3, with the COP of the HP measuring around 2.7. Solar collectors, featuring modified flat-plate water collectors, transfer heat to the water-source evaporator; during the day, heat from the evaporator is stored in the ground, enhancing the HP and system's COP. Collector efficiency rose from 33 % to 54 % during the coldest months.

[17] presents an experimental study on a ground-coupled heat pump combined with PVT collectors integrated into a 180 m^2 private residence. This system prioritizes solar heat for domestic hot water, redirecting excess energy to the ground via boreholes once the preset temperature is reached; this way, it effectively balances ground loads, extends solar collector operation, and mitigates overheating issues. Despite high domestic hot water solar fraction, ground temperature fluctuations near boreholes reduced COP by 14 %. Solar heat injection mitigated this effect, particularly in summer. After 11 months of operation, 6253 kWh are extracted from the ground, and additional 2121 kWh are solar heat injected, constituting 34 % of the total extracted heat.

The average COP achieved in heating mode is 3.75, whilst the domestic hot water solar fraction remained consistently above 60 %. Optimal circulation pump control is crucial for COP enhancement. Continuous operation of one pump yielded a lower average COP (2.6) compared to synchronized operation (3.35). Thermal solar collectors could reduce borehole numbers and installation costs, but additional pump electricity consumption may lower seasonal performance.

In the PV/T coupled ground source heat pump system in Ref. [18], the soil provides 73.4 % of heat load, with photovoltaic cells contributing 24 % of electricity generation. Operational efficiency is high, with a mean COP of 3.99 during heating and 3.96 during cooling. Comparative analysis favors temperature difference control methods over time control. Heat collection efficiency during storage is 37.4 %, with soil heat storage efficiency at 84.4 %. Soil temperature fluctuations remain favorable for sustained performance, especially in cold regions. Minimal soil internal energy loss and stable temperatures ensure long-term system effectiveness.

Okumiya and Zhang [19] designed solar-ground source heat pump system for an office building in Beijing, proposing a novel operation strategy for transition seasons. Two winter operation strategies were compared. In the first one, solar collectors and ground heat exchanger are installed in series. The second one stores solar heat collected during the day in a tank, releasing it at night to recharge GHE and restore soil temperature. The system's parameters were optimized. Simulation results over 3 months of winter heating favored the first strategy in Beijing, because it maintanes and restores soil temperature better in cold climates. A transition season strategy proposed keeping the heat pump off and directly connecting ground heat exchanger to fan coil heat exchangers, reducing annual electricity consumption by 20.86 %. ground heat exchanger length variations had a greater impact on system's COP than collector area.

Less researches have dealt with heat pump systems relying on air-ground composite source so far. The combined use of technology clearly reduces electricity consumption: a HVAC system resulting from a ground-source heat pump combined with and an air-source heat pump, in addition to ensuring a high EER, achieves electricity consumption levels approximately equal to 60 % of that obtained by an air-source heat pump, and to 82 % of that by a ground-source heat pump [20]. Another strategy to face the challenge associated with these systems lies in ensuring their proven effectiveness in cold climate conditions through the implementation of heat storages. Water-Source Heat Pumps (WSHPs) are renewed for their high efficiency in heating and cooling, as they leverage the relatively stable temperature of water which can derive from ground system or from different water sources as lakes, rivers or ponds. Surface WSHPs were proposed in Ref. [21] as efficient alternatives for conventional cooling and heating systems. Challenges related to freezing during heating operations are addressed through a proposed heat source compensation operation, enhancing thermal energy utilization. Moreover water source technologies are suitable for large scale heat recovery. Zhou et al. showed the potential of Water source heat pumps for waste heat recovery from data centers facilities to achieve carbon neutrality [22]. Numerous urban wastewater treatment facilities release treated tail water with consistent flow rates [23]. Tail Water Source Heat Pumps adeptly harness heat from this purified water, markedly diminishing energy consumption for building heating, and integrated with Thermal Energy Storage (TES) enables to fulfill peak load shifting objectives. The average Coefficient of Performance for this kind of HP units and for the comprehensive system is 7.08 and 4.41, correspondingly. In contrast to a gas-fired boiler, the envisaged system attains a notable reduction in carbon emissions, by 62.53 %. Ma et al. addressed challenges in systems exploiting solar energy and air source heat pumps for hot water production by employing TRNSYS to simulate a solar-coupled HP. The analysis compares the efficiency of the introduced combined configuration and an ordinary air source heat pump, revealing the new system's capability to supply water at 50 °C [24].

The shift to the electricity-driven technology, caused by the replacement of traditional heating generators, namely Natural Gas Boilers (NGBs) with HP systems [25], if decreases emissions due to the direct utilization of fossil fuel, transfers the load to the electricity sector [26]. This way demand for Primary Energy (PE) remains high, unless resorting to on-site production of renewable energy to satisfy energy needs of buildings. Photovoltaic (PV) panels installation, like that of solar collectors, is the most implemented intervention for distributed energy production so far, this makes heat pumps powered by PV systems [27] the cornerstone technology of the decarbonization pathway through renewable aided electrification.

[28] investigates the potential of High-Temperature Heat Pumps based on the vapor compression cycle to replace fossil fuel-fired boilers for generating high-temperature water and steam. This examination is crucial for industries. Different cycle configurations and natural refrigerants are compared based on two primary metrics: the coefficient of system performance and exergetic efficiency. It identifies ammonia and water as preferable working fluids under specific conditions: the first one preferred for source and sink temperatures lower than 60 °C and 110 °C, respectively, while water serves as a better working fluid at higher temperatures. The need for further improvement in compressor technologies for these solutions to be competitive in terms of cost and operational reliability was pointed out. A lack of the work is that the analysis is highly dependent on the case study's settings, and the results may not be directly applicable to all industrial or residential scenarios.

It is however noteworthy that the solar energy share which can be directly converted into electrical power is only 10–20 %, while the rest is dissipated as heat, leading to loss in power and devaluation [29]. This hesitates also in high operating temperature, responsible for cell's structural damage over time and reduction of service life. Hence, it is crucial to plan a method for cooling these units [30]. In photovoltaic/thermal (PVT) systems, which produce electrical power meanwhile providing thermal energy [31], the fluid flowing in PVT system decreases PV panels' temperature collecting excess heat, thus suitable for DHW or space heating [32,33]. In PVT assisted direct-expansion heat pump the panels are directly responsible for heating the working fluid of the HP; such a cooled PVT panel can achieve higher electrical efficiency than an uncooled one, along with ensuring a relatively high COP [33].

PVT and HP can work with a storage tank interposed [34]; in Ref. [35] an interesting alternative was given to sensible heat storages, suggesting an integrated thermochemical and phase change materials based latent heat thermal storage system.

Cost-competitiveness of the water storage makes WSHP easy to be proposed for short-term domestic applications, also in large scale refurbishment. Water source heating system prospect promising and viable solution to be applied to energy districts; the coupling with photovoltaics means further exploiting the potential of energy communities, mainly founded on the sharing of electricity from PV.

With the emergence of Energy Communities, district heating and cooling is deemed an efficient and low-environmental impact solution to cover the requirement for thermal energy of buildings. The possibility to employ low-temperature heat is a noticeable benefit of district heating and cooling networks, originated by combined heat and power engines, heat pumps powered by photovoltaic electricity, energy from other renewable sources like biomass and geothermal energy, and waste heat from industrial processes. By applying a proper control to impede overheating and optimizing the demand-supply balance in relation to building typology, primary energy uptake and CO2 emissions of districts can be even more decreased [36]. In Ref. [37], a bidirectional heating/cooling network of 5th generation is formulated, incorporating water-to-water and ground-source heat pumps along with a photovoltaic array. Specifically tailored for a 50-building district in Madrid, this network allows to reach a PES of 64 % and to lower CO2 emissions by 76 % in comparison to the prevailing conditions. The district's electricity need meet by the photovoltaic field, only equal to 30 % by the delineated design, could be enhanced by the integration of a supplementary energy storage; it will help in mitigating grid balancing challenges, optimizing power production alignment with the real-time demand. The efficacy of the aforementioned strategy can be moreover heightened by incorporating proper energy storage systems, facilitating increased utilization of renewable thermal energy sources. An illustrative case is presented by Todorov et al. [38], where winter and summer temperature control is entrusted to groundwater heat pumps associated to underground aquifers to store thermal energy.

However, looking at European scenario, few studies implement retrofit strategies at neighborhood or wider scale [39]. Looking at the built environment, several studies pointed out Public social building stock poses a challenging reality, experiencing energy poverty, which contradicts the UN Sustainable Development Goals (SDGs) [40]. Besides suffering for envelopes not adequately insulated, due to various economic and technical factors [41,42], low-income households encounter difficulties in maintaining comfortable living conditions in social housings, that incur in obsolescence in terms of energy and structures.

In the operation phase of residential buildings, plural energy fluxes are included, mainly depending on constructive features and systems for heating, cooling and DHW production. The scant uniformity in the housing stock, and in the corresponding systems' arrangement, adds complexity to this spectrum of energy flows; however knowing them in their singularity is mandatory to compare their energy performance.

Extensive analyses of effective energy consumption in both residential and non-residential buildings have been conducted so far [43,44]. Numerous EU projects have developed databases with the aim of characterizing the building stock to make deductions and comparisons also from an energy point of view [45]. On the other hand few studies on energy utilization in social housing buildings exist [46]. Thus the research must fill the gap of energy consumption limited understanding in the abovementioned typology, delve into occupants' behavior and factors contributing to the Energy Performance Gap.

Dynamic modelling of solar heating systems relying on PVT technology is crucial to manage electrical and thermal peak load shift, with the purpose of minimizing dependence on grid energy in favor of self-consumption [24,47,48], as well as to assess fluctuations in source-side storage tanks. The systematic development of models provides a solution to the challenge highlighted in Ref. [49], concerning issues in designing heat pump systems, due to the limited and variable available catalog data. Subsequent enhancements to the model should concentrate on its performance during low-temperature or nocturnal operation, as well as on the anomalies due to condensation and frosting. In Ref. [50], the implementation and validation of PVT collector model in TRNSYS shows that, for significant thermal capacities, thermal outcomes have a less accurate fit of the dynamic behavior, meaning the significance of determining accurately the thermal capacity of PVT.

In recent literature there is room for the economic aspects that induce some considerations on their still not exhaustive development. While the paper of Bergamini et al. [28] thoroughly examines the thermodynamic and technical aspects of HTHP, it provides limited insight into the economic implications, such as installation costs, operational costs, and potential savings, which are critical for stakeholders considering such a replacement. Ref. [51] focuses on the environmental impact of replacing an all-electric boiler with an air source heat pump through a life cycle assessment. The analysis demonstrates that ASHPs, particularly those paired with underfloor heating, can achieve environmental amortization within a conservative lifespan of 10 years, and that the choice of heat emitters significantly affects the environmental amortization time: underfloor heating systems requiring the shortest time to offset their environmental impact compared to more traditional radiators. Cost considerations, including installation, maintenance, and operational expenses, are crucial for homeowners and were not detailed in the study. Luo et al. [52] explored the thermo-economic performance of replacing a coal-fired boiler with a Groundwater Heat Pump system for greenhouse heating and cooling. The results show that despite higher capital costs, the GWHP system offers better economic performance in terms of Average Energy Price (AEP) and suggests its potential as an alternative to traditional boilers. Anyway the study does not provide detailed analysis on the impact of these initial costs on the overall economic feasibility for potential adopters. The applicability of its conclusions is influenced by local conditions, in addition the study covers a one-year monitoring period, which provides valuable insights but may not fully capture the long-term performance, maintenance needs, and potential technical challenges associated with GWHP systems.

1.1. The RESHeat project and aim of the study

In this research context fits RESHeat Project [53], whose objective is to design a system based on renewable energy, intended for thermal control of residential buildings, encompassing both heating and cooling functions.

The common line for the international partners provides for the use as primary energy that from solar source

through PVT modules, and the adoption of heat pumps and cold/heat buffers to supply the heat to the housings by means of fan coil units. In a preliminary study a similar heat pump system was simulated implemented in a compact office situated in Cracow, Milan and Rome [54]. The findings shown that, when for the PVT are set thermal efficiency equal to 0.6 and electrical efficiency equal to 0.15, and for the heat exchanger of the storage vessel an efficiency equal to 0.9 is considered, the heating demand is fulfilled in Rome for 70 %, in Milan for 62 %, in Cracow for 47 %. As expected, where the availability of solar radiation is limited and the outdoor air temperature is lower, the case of Milan and Cracow, the experimental facility does not guarantee an adequate heating provision. To extend the heat pump's coverage during the heating season, limiting the use of an auxiliary system, a viable strategy is to resort to a TES system. The RESHeat project in Poland, therefore, involves a sun-tracking PVT-based system connected to a buried unit for thermal storage [55].

In the Italian version of RESHeat project, serving as water heat pump's source, a hot water storage tank replaces the underground heat accumulation unit.

In this paper this alternative is addressed. With the aim of defining a retrofit procedure applicable to the urban scale, a case study representative of a widespread type in the urban fabric of Rome's area was chosen to be used as training site: an existing social housing building with 13 apartments constructed around 1980 in Palombara Sabina (Italy). The reference building sample stems from urban planning initiatives aimed at coordinating interventions concerning economic and social housing, started in Italy during the 1960s. Arising from the developmental context which interested Europe prior to the enactment of energy performance regulations, this sample serves as a representative archetype. Consequently, the insights garnered from its analysis can be extrapolated to an international context, particularly within regions sharing similar climatic conditions.

To correctly implement the proposed system, a detailed thermal loads and energy demand analysis was assessed on a validated model of the building in the current configuration. As regards the energy system, it consists in centralized heating powered by a NGB, combined with autonomous production of DHW by an electric boiler in each apartment. The improvement involves the replacement of generators with a water source heat pump coupled to cooled photovoltaic panels, the insertion of two storage units, one source-side and the other load-side, and fan coil instead of radiators. This way, besides an integrated generation of heat, summer cooling and power production were introduced. During heating season, with the low-temperature heat from the panels, the heat pump's cold well is replenished; during the remaining months, when the panels can provide heat at higher temperatures, they are coupled with the system deputy to domestic hot water production. Every subsystem of the thermal facility was analytically modeled in TRNSYS.

The components were individually validated through experimental campaigns.

For the energy analysis hourly simulation during a whole year were performed. System's efficiency was evaluated with reference to average seasonal and monthly COP of the heat pump. The main energy cosiderations concern production and consumption of thermal energy, along with the generation and absorption of electrical power. Additionally, to express the penetration of renewables in heat production, the achieved solar fractions were presented. Primary energy savings and avoided CO2 allowed to quantify the potential of the proposed solution compared to the current state.

The present work has therefore the objective of using the building in Palombara Sabina as pilot case to enhance a centralized heating system for mild climates, so as to propose it as ideal approach to be extensively applied to the whole social housing real estate erected during the 1970–1990s, in view of an urban scale energy retrofitting.

The novelty of the proposed study is based on the following key aspects.

- It is the counterpart of the Polish proposal for RESHeat Project: the focus on shifting systems away from Natural Gas during periods of low supply from RES facilities, achieved through TES devices, is adapted to mild climates thanks to water storage. This presents an opportunity to deepen WSHP systems, which is relatively underexplored in the literature.
- The renewable energy-based integrated system, proposed for social housing and modeled with dynamic software, is validated through on-site experimental campaigns.
- The methodology adopted to define the plant design allows seasonal optimization of the HP operation, with the introduction of the chiller, which in future developments can also be considered as a double source heat plant.
- The topic of energy retrofitting is enriched through an in-depth analysis within the context of social housing. This represents a widespread typology both nationally and internationally, requiring urgent intervention to address energy weaknesses associated with its low performance. Improving these structures could lead to a massive decarbonization of the building stock, aligning with the perspectives of carbon neutrality by 2050.
- In the literature, energy retrofitting is often applied to public environments, primarily offices, or in residential settings to apartments or small-scale buildings, mainly single or double-family homes, while the field of multi-family residences, such as the present case study, is still relatively underexplored.
- Through Carbon Avoidance Evaluation, a preliminary estimate of the environmental impact of energy systems is provided. This approach aims to align with regulatory requirements such as EPBD and Life Cycle Assessment (LCA) analysis, currently under development, while also facilitating future comparative analyses among different energy systems based on location, intended use, and occupancy profile.

2. Materials and methods

As previously stated, this work falls within the RESHeat European project, which involves the implementation of an innovative experimental system on three demo sites, two in Poland and one in Italy. Specifically, this article discusses the results obtained from simulations on the Italian location. It's crucial to emphasize that the building selected for this purpose is representative of a widely spread typology in

Italy, particularly in the Lazio region. Therefore, an additional goal of this work is to evaluate the extendibility of the results to the entire building stock represented by the analyzed building.

The residential building under study, the edification period of which can be traced back to the 1980–1985 years, is placed in Palombara Sabina (DD 2012), a town 30 km far from Rome in northeast direction, and belongs to Agenzia Territoriale per l'Edilizia Residenziale (ATER). In the three floors above ground are distributed thirteen flats served by two stairs, whereas the basement houses cellars and technical rooms. The structure is in reinforced concrete, and the building envelope aligns with construction techniques of that ages. The choice focused on this type of building as representative of a widespread building heritage in Italy and Europe. More specifically, the reasons for the selection are set out in Ref. [56].

The research intend to raise plant's reliance on renewable energy, while ensuring optimal energy efficiency. The baseline objectives include an average annual coefficient of performance equal to 5 for the heat pump and a 70 % coverage from renewable sources [57]. To optimize the building's energy consumption, two scenarios were studied: first, the existing heating system, followed by an analysis of the RESHeat system, which replaces the NGB with a water-source heat pump assisted by a cooled photovoltaic system.

The subsequent sections account in-depth explanations of the two plant configurations – the original building system and the energy optimization system (RESHeat System) – along with the Key Performance Indicators (KPIs) chosen for the discussion.

2.1. Current heating system

The building's heating system relies on a natural gas boiler featured by maximum heating capacity of 69 kW and an efficiency of 0.96. The useful heat vary among a minimum of 51.8 kW and a maximum of 65 kW. The modulation of power output depends on the boiler outlet temperature, configured at 80 °C. The radiators, which differ in size and characteristics, have their powers calculated according to the UNI 10200 standard [58]. The operation period of the heating system goes from November to April, following a double scheduling: the daily working hours are 8 from November 15 to March 15, programmed from 14:00 to 22:00, reduced to 5 between March 15 to April 15, from 16:00 to 21:00. The centralized heating system does not supply the water-sanitary plant; hot water is generated autonomously by each apartment through its own electric boiler. This system has been previously studied [56], and the current research seeks to formulate innovative energy solutions to be applied to the real case.

The methodology begins with the selection and analysis of the building. Subsequently, the architecture and the original system are modeled using TRNSYS software, followed by model validation using historical data and measurements from the previous phase. Once validated, the utilization of the model is for the purpose of RESHeat system simulation and comparison with the existing heating system (Fig. 1). The detail of the dynamic model and its validation is explained in the following section. Meanwhile, the building loads obtained from the analyses are reported below.

As previously mentioned, the building was modeled and validated in Ref. [56], from this it was possible to derive the thermal loads of the building and the annual energy requirement for heating and cooling. The energy assessment of the ATER building revealed an annual heating energy demand of 54.92 MWh/y and an annual cooling energy demand of 37.70 MWh/y, while the domestic hot water (DHW) demand is 48.5 MWh/y. Fig. 2 illustrates the monthly energy requirements as previously described obtained by the building model previously validated in Ref. [56]. To assess the DHW energy demand, a consumption rate of 55 L per person for a total of 50 people was considered. Additionally, a standard daily hourly profile of a residential user [59], as depicted in Fig. 3a, was used for the evaluation. The DHW energy demand was calculated, and the electrical energy consumption for domestic hot water with a traditional electric boiler ($E_{el,EB,DHW}$) was determined, considering an electrical power of 1200 W per apartment. Estimating an

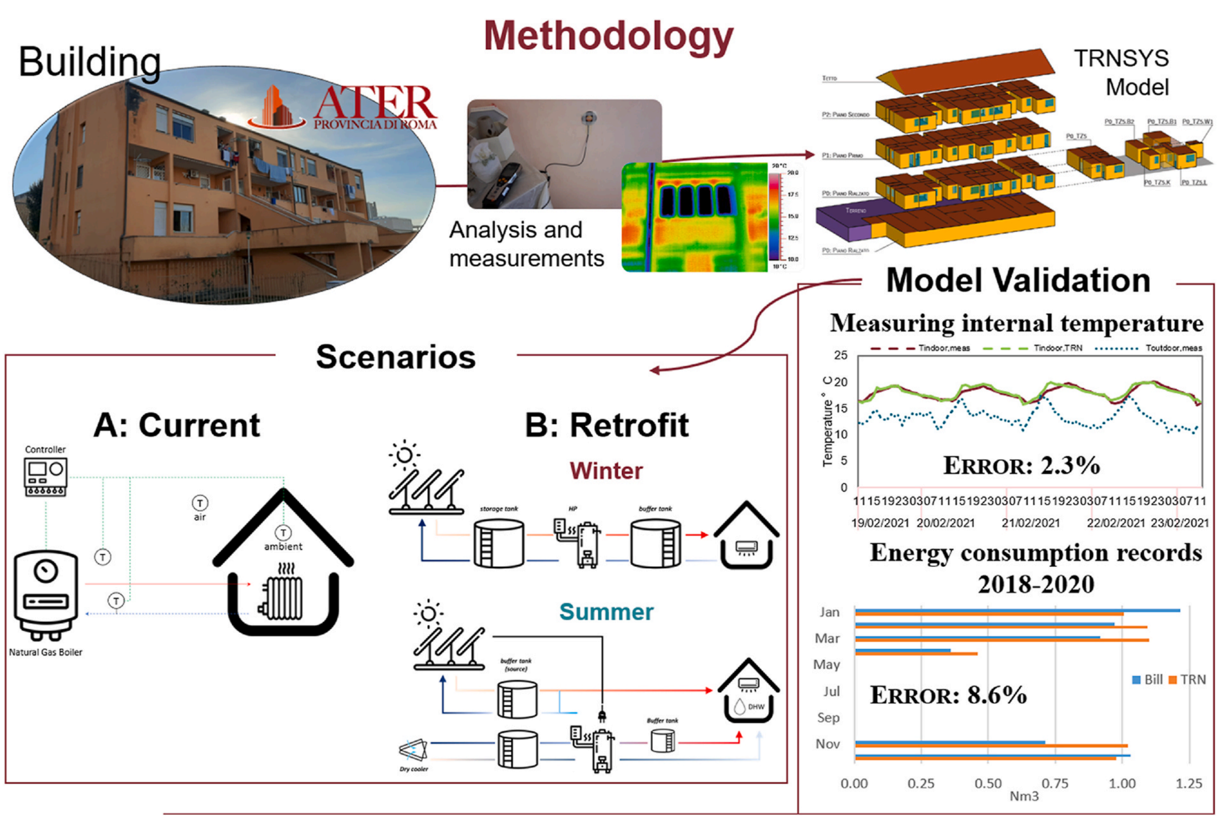


Fig. 1. Methodology chart.

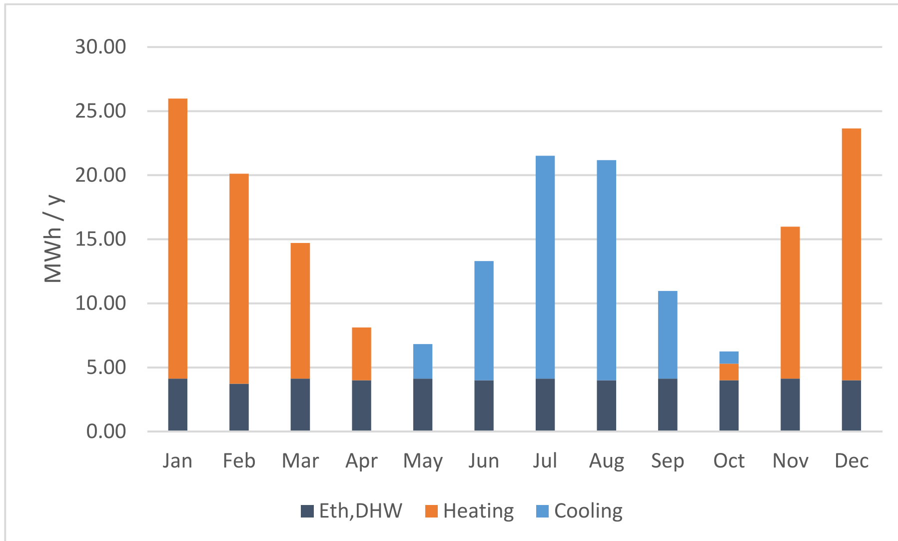


Fig. 2. Thermal energy demand.

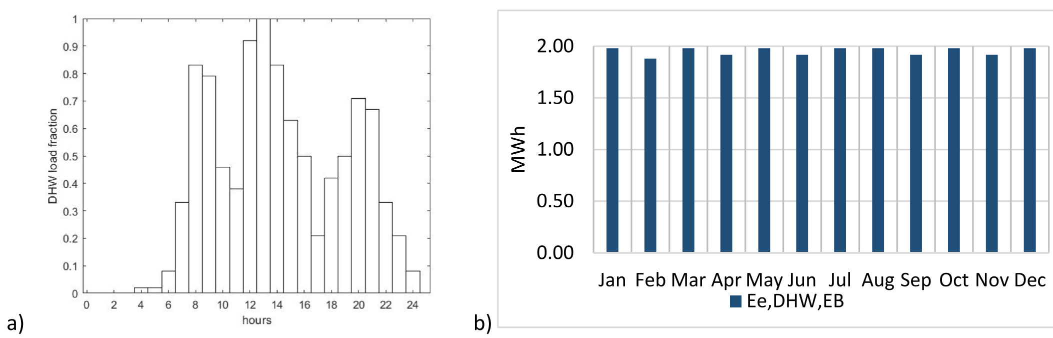


Fig. 3. a) hourly daily fraction of domestic hot water load [56]; b) Estimated DHW electrical consumption.

electrical consumption for DHW equal to 64.65 MWh/y (Fig. 3b).

2.2. *Italian RESHeat system*

The proposed system is developed to facilitate the integrated generation of heat, cooling, and power. It is shown in Fig. 4. Key components comprise a water source heat pump (2), a hybrid photovoltaic system (1), and two distinct thermal energy storage units (on source side (3) and load side (4) of the heat pump). In the system, a water-to-water heat pump is employed for generating thermal energy to meet both winter requests for heat and summer requests for cool. This system is integrated with a photovoltaic plant comprising 75 panels, which are cooled by a 3 m^3 buffer tank (3) on the heat pump's source side. Additionally, this tank is linked to a dry cooler (DC) necessary for heat removal during the summer. On the heat pump's load side, connections are made to fan coils for both space heating and cooling. The RESHeat system's control mechanism is strategically designed to optimize the utilization of RESs. The operational principles governing the control

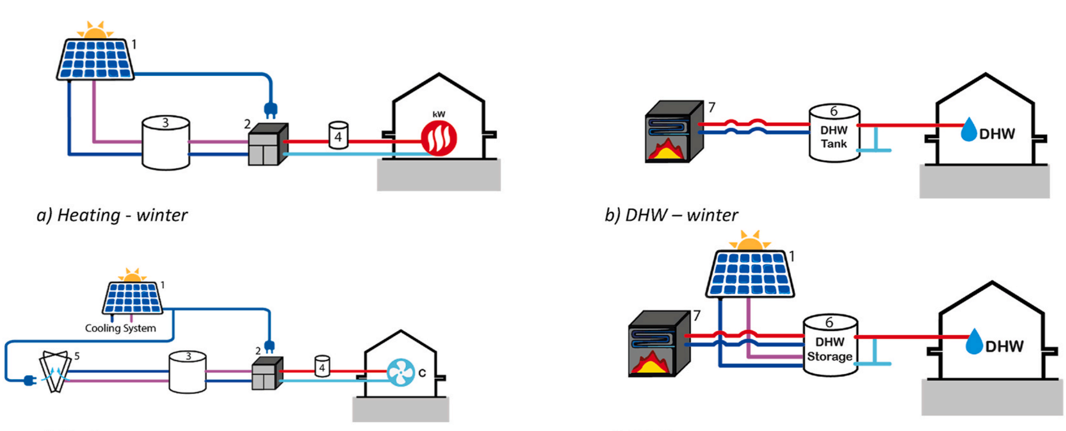


Fig. 4. RESHeat system.

system are the following: the circulation pump is triggered when in the heat exchanger beneath the PV panels the temperature exceeds 20 °C ± 2 °C. During the winter period, the heat pump is activated when inside the inertial storage tank (4) the temperature falls below 45 °C ± 5 °C. The heat pump operates between 5 a.m. and 11 a.m., and between 4 p.m. and 10 p.m., in accordance with Italian regulations [60]. In the summer period, the heat pump is activated when the temperature of the inertial storage tank (4) exceeds 15 °C ± 5 °C. During summer, the dry cooler is switched on to facilitate the heat pump's operation, especially when the temperature of the heat storage tank (3) exceeds 20 °C.

During winter season, heat generated by the heat pump, as well as in summer months cold produced to meet increased demand for cooling, is stored in a buffer tank (3). For enhancing the efficiency of the heat pump the synergistic utilization of PVT panels is crucial. During the winter, the cooling circuit of the photovoltaic system feeds the 3 m^3 buffer (3), yielding thermal energy used to hold the average temperature inside the tank around 15.45 °C, thus increasing the efficiency of the HP. Simultaneously, the temperature of the liquid inside (3) is lowered by the heat pump's output at the evaporator-side, ensuring a proper cooling source for the panels. In summer season the heat production from the photovoltaic panels is employed for domestic hot water, while, if the heat into the TES (3) connected with the condenser side of the HP is in excess, it is dissipated by a dry cooler.

This way, the supply of domestic hot water is turned from autonomous to centralized and integrated with the production of heat by the PVT during summer, whilst in the winter period, when the panels are able to provide heat only at low temperature, they are disconnected from the DHW, serving as an energy source for reintegration of the HP's cold well (Fig. 5). A gas boiler (7) is used as a back-up heater for DHW when thermal energy from PVT is insufficient.

2.3. KPI

Six Key Performance Indicators (KPIs) have been selected to assess the impact of the proposed system from an energy-environmental perspective and with the objective of evaluate the seasonal energy performance. Among the goals of the study is the optimization of the thermal system, with the first benchmark being the efficiency of the heat pump and the achievement of a coefficient of performance, averaged throughout a year, greater than 5.

The seasonal coefficient of performance (sCOP) of the heat pump was calculated as thermal energy production ($E_{th,HP}$) to electrical energy consumption ($E_{el,HP}$) ratio over the entire heating season:

$$sCOP = \frac{E_{th,HP}}{E_{el,HP}} \tag{1}$$

Subsequently, starting from the thermal and electrical energy requirements and the energy produced by the thermal-photovoltaic field, the following KPIs were evaluated to assess the penetration of renewable energy into the system: thermal solar fraction ($f_{sol,th}$), electrical solar fraction ($f_{sol,el}$), and overall solar fraction (f_{sol}) [61].

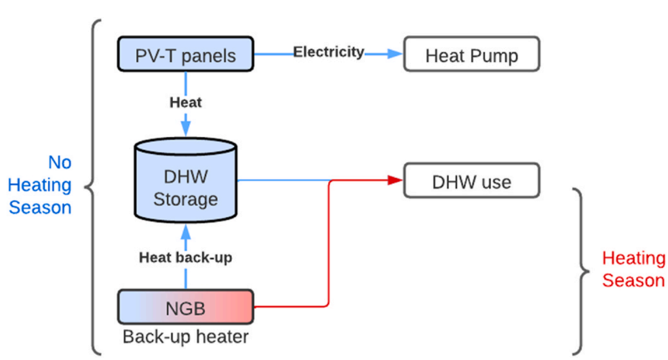


Fig. 5. DHW summer scheme.

$$f_{sol,th} = \frac{E_{th,PVT,st}}{E_{th,demand}} = \frac{E_{th,PVT,st}}{E_{th,HP,st} + E_{th,DHW}} \tag{2}$$

$$f_{sol,el} = \frac{E_{el,PVT}}{E_{el,demand}} = \frac{E_{el,PVT,sc} + E_{el,PVT,net}}{E_{el,HP} + E_{el,DC} + E_{el,aux} + E_{el,build}} \tag{3}$$

$$f_{sol} = \frac{E_{th,PVT,st} + E_{el,PVT}}{E_{th,demand} + E_{el,demand}} \tag{4}$$

To complete the energy evaluation, the primary energy associated with each scenario was calculated by Eq. (5), for the current scenario (S0), and Eq. (6), for the proposed one (S1); non-renewable Primary Energy Savings (PES) corresponding to the improved scenario were estimated (Eq. (7)) by comparing its Primary non-renewable Energy with that of the initial state, where no interventions were made.

The primary energy need per generator (PE_{HP}, PE_{NGB}) are determined by Eq. (5) and Eq. (6) multiplying the primary energy conversion factor ($f_{PE,i}$) [62] and the energy supplied to the generator during the given timeframe, taking into account that the involved heat generators are fueled by different energy sources: electricity and natural gas.

$$PE_{NGB} = LHV * Sm^3_{CH4} * f_{PE,ng} = E_{in,NGB} * f_{PE,ng} \tag{5}$$

$$PE_{HP} = E_{in,HP} * f_{PE,el} \tag{6}$$

where:

$f_{PE,ng}$ = natural gas = 1.05

$f_{PE,el}$ = electricity = 1 if the HP is fed by the PVT electricity and f_{PE} = 2.42 if the HP is fed by the electricity take from the grid.

LHV means Lower Heating Value of methane and Sm^3_{CH4} is for Standard cube meter of methane. $E_{in,HP}$ is the energy demand from the gas boiler, namely methane, whilst $E_{in,NGB}$ is that from the heat pump, namely electricity.

For the calculation of PE_{nREN} the conversion factor remains the same of that in Eq. (6) for NGB, while for electricity from grid $f_{PE,el} = 1.95$ was considered.

$$PES = 1 - \frac{PE_{nREN,S1}}{PE_{nREN,S0}} \tag{7}$$

Finally, the tons of CO2 avoided with the proposed scenario were assessed, taking into account the self-consumed energy from renewable sources and not drawn from the national grid, as well as the CO2 saved not combusting fossil fuels [63].

The equation below outlines the various values considered, with S1 subscripts indicating values associated with the new system, and S0 subscripts indicating values related to the original system.

$$tCO_{2av} = \left(tCO_{2el,HP,H} + tCO_{2el,HP,C} + tCO_{2ng,DHW}\right)_{S1} - \left(tCO_{2el,PVT,sc}\right)_{S1} - \left(tCO_{2ng,NGB,H} + tCO_{2el,EB,DHW}\right)_{S0} \tag{8}$$

The terms $tCO_{2el,HP,H}$ and $tCO_{2el,HP,C}$ represent the tons of CO2 emitted for the production of heat during heating and cooling by the HP, related to electric consumption deriving from RESHeat application. Meanwhile, $tCO_{2ng,DHW}$ indicates the tons of CO2 emitted to produce domestic hot water through the gas boiler, used as a back-up heater when thermal energy from PVT is not sufficient. To these quantities, we subtract the tCO2 not emitted due to electric self-consumption $\left(tCO_{2el,PVT,sc}\right)$, the amount in charge at the natural gas boiler (NGB) before the substitution by the heat pump $tCO_{2ng,NGB,H}$, and that arising from electric boilers' work until their elimination as domestic hot water generators $tCO_{2el,EB,DHW}$.

For the calculation, emission factors for electrical energy ($F_{CO2,el}$) and methane ($F_{CO2,NH4}$) were considered, with values of 0.2457 tCO2/MWh and 1.6 tCO2/MWh, respectively [63].

3. Model description and validation

This section outlines the numerical model employed for simulations, providing detailed descriptions of key components such as heat pump, cooled photovoltaic panels, thermal storage and dry cooler, as well as meteorological data and the building itself. In addition to the parameters and equations underlying the model, the second part of this section is dedicated to its validation.

3.1. Weather data

For incident solar radiation (a) and air temperature (b) the hourly variations over 24-h are shown in Fig. 6, referring to the winter period. Any possible value appears depicted by the orange dots, comprised between the upper red curve, which represents the maximum reachable values, and the yellow line at the bottom, corresponding to the trend of minimums. With a horizontal average solar radiation of 1478 kWh/m^2 Y.

3.2. Building's thermal model

The geometrical and thermophysical characterization of the building and the estimation of its energy demand was carried out by way of the plugins TRNSYS 3D and TRNBuild [64].

The model of the building begins defining and drawing the thermal zones in TRNSYS 3D (SketchUp plugin). Once the geometric model was completed, the.idf file was imported into TRNSYS Building. There, for each thermal zone, it is mandatory to specify the initial indoor temperature and relative humidity values and the required data for evaluating the overall features of the zone, which include infiltration rate, internal gains and comfort parameters of the building occupants. Also the thermophysical properties of the considered zone's boundaries, such as walls and windows, must be specified.

The information file which TRNBuild originates accordingly outlines outputs and required inputs of Type 56. By this type the building model is inserted in TRNSYS workspace, namely Simulation Studio.

Heating and cooling equipment are modeled as separate components in Simulation Studio. Therefore, the outputs derived from the zones of Type 56 act as inputs for the equipment models, which for their part provide heating and cooling inputs for the zones.

An examination of the building's energy behavior was first performed using TRNSYS 17. The model underwent validation through data of envelope's thermal transmittance and internal temperature collected in on-site measurements and by referencing energy consumption records from the years 2018–2019 and 2020. The assumed stratigraphy for the structure under consideration is shown below. From Table 1, calculations give a theoretical global heat transfer coefficient equal to 0.78 W/m^2K. Such result derived by the embracement of surface thermal resistances quoted by the ISO 6946 [65] standard, along with a 20 % increase to account for aging effects. Such percentage was deduced as average among the values for thermal insulating material and polystyrene concrete layer reported in UNI 10351 [66]. This Italian standard suggests percentage increases to be applied to the thermal conductivity of materials for taking into account factors like compaction of bulk materials, moisture content and aging under standard operating conditions. The percentage increase for the catalogued materials ranges from 10 % to 50 %.

Table 1
Thermal features of the opaque envelope.

Material	Depth [m]	Λ [W/mK]	R [m^2K/W]
External laminar layer			0.04
Gypsum plaster	0.02	1.00	0.02
Hollow brick	0.12	0.36	0.33
Insulation	0.03	0.09	0.33
Air Cavity	0.05	0.25	0.20
Hollow brick gypsum covered	0.08	0.36	0.22
Internal laminar layer			0.13
U-value		**0.78**	**W/m^2K**

Because of the scarce thermal inertia of the analyzed wall, given suitable boundary conditions with regard to thermal stresses, the Heat Flow Meter (HFM) measured significant instantaneous thermal transmittances. Based on these, invoking the well-established progressive average method outlined in ISO 9869-1 [67], a U-value of 0.8 W/m2K was found. Therefore, the assumed stratigraphy in Table 1 can be deemed realistic, in line with the experimental findings. Theoretical and experimental U-values exhibit a deviation of +10.45 %.

3.3. Combined photovoltaic-thermal panels (PVT)

Double glass panels of the type ZXM6-LD60 were applied to the roof of the case study housing in Palombara Sabina, in conformity with the grant agreement, and taking into account its geometry. The panels quantity was established at 75 units, arranged in groups of 5 to form 15 strings, leading to a total area of 124 m^2 equivalent to an electric capacity of 23.2 kWp. An overall flow rate of 3150 l/h circulating across the entire system was yielded, assuming for each panel in the series a constant flow rate of 30 l/h. The main parameters of the panels from data sheet and assumed in the model are reported in Table 2.

According with [68] the mathematical model equations are the following:

$$\frac{NOCT\ T_{ref}}{I_{ref}} + T_{amb} \tag{9}$$

$$\eta_{el} = \eta_{el,std}\left[c_{el}\left(T_{pv,cell} - T_{cel,std}\right) + 1\right] \tag{10}$$

$$P_{el} = \eta_{el}\ I_t\ A_{p,surf} \tag{11}$$

$$P_{th,PVT} = A_{p,surf}\ F_R\ \left[I_t\ \tau\alpha - \left(T_{w,in} - T_a\right) U_L\right] \tag{12}$$

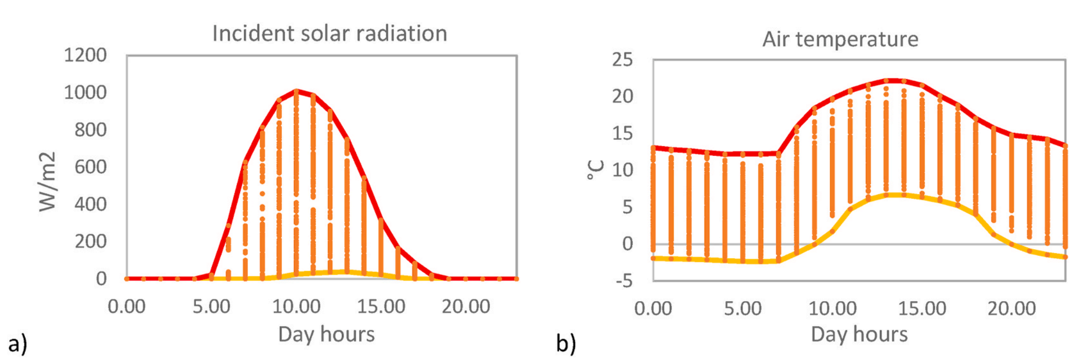


Fig. 6. Hourly variation over 24h in the heating season of: a) incident solar radiation; b) air temperature.

Table 2
Model parameters.

Parameters		Value
Collector Area	1.67	m^2
Collector Fin Efficiency Factor	0.7	–
Fluid Thermal Capacitance	3.92	kJ/kgK
Collector plate absorptance	0.92	–
Number of glass covers	2	–
Collector plate emittance	0.09	–
Loss coefficient for the bottom and edge losses	20	kJ/hm^2K
Collector slope	30	degrees
Transmittance absorbtance product	0.9	–
Temperature coefficient of PV cell efficiency	0.0032	1/K
Temperature for cell reference efficiency	25	°C
Packing factor	0.8537	–

$$F_R = \frac{\frac{NOCT\ T_{ref}}{I_{ref}} - \frac{\tau\alpha}{U_L}}{\frac{T_{w,in}-T_a}{I_t} - \frac{\tau\alpha}{U_L}} \quad (13)$$

$$\eta_{th} = \frac{P_{th,PVT}}{P_{incident}} \quad (14)$$

$$T_{w,out,PVT} = P_{th,PVT}\ \dot{m}_{w,PVT}\ C_{p,w} \quad (15)$$

The experimental setup, installed on July 6, 2022, consists of two cooled photovoltaic panels, connected in parallel for the hydraulic part and series for the electrical domain. The cooling system consists of two independent coils, each with six pipes. The PV modules used in this experiment are Bifacial Double Glass Mono PV module of ZXM6-LD60, type 310, from Znshinesolar manufacturer [69]. The module comprises 60 mono-crystalline cells with dimensions of 156 × 156 mm. The module's width is of 997 mm and the height of 1679 mm, with an area of 1.67 m^2 (net 1.46 m^2). At standard test conditions, the nominal power of the module is 310 Wp with 18.62 % electrical conversion efficiency. The technical data of the module is given in Table 2. The experimental system is located in a laboratory of the Astronautical Electrical and Energetic Engineering Department of Sapienza University of Rome. The latitude and longitude of the site are 41.958352 and 2.504975, respectively. The azimuth of the building is 178° and the module tilt angle of 30°. The measurement data used to test the photovoltaic panel are the following: outdoor climatic parameters, outlet and inlet temperature of the panel, thermal flow transferred to the water and flow rate in the hydraulic circuit. The measuring tools are thermal energy probes for detecting thermodynamic quantities and a climatic control unit for determining meteorological data. The weather data are based on the values collected by Meteoblue archive [70] of the Roma-Urbe Airport, since a climate control unit was not installed in the laboratory site. The following parameters were collected: air temperature (2 m elevation corrected), direct, diffuse and global shortwave radiation, cloud cover total, wind speed and direction (10 m).

The experimental campaign was conducted during two non-consecutive days, on July 27 and August 5, for 8 h (Fig. 7). Each measurement describes the initial conditions of the plant and the weather conditions.

The first campaign was conducted on July 27, 2022, from 9 a.m. to 4.15 p.m. The measurements were taken with a 15 min time step. The outdoor climatic measures were as follows: outdoor air temperature 28 °C, wind velocity 5.7 km/h while the cloud cover was 0 from the start to the measurement until 3.30 p.m. and three oktas before 3.30 p.m. [70]. The hydraulic circuit on the side of the panels was already in operation at the beginning of the measurement campaign. Therefore, there was no stagnant water in the panels. The initial temperature at the inlet of the panels was 28.9 °C. In contrast, the temperature at the outlet was 32.6 °C, with a ΔT of 3.7 °C.

As reported in Tables 2 and 3, the data sources for the parameters and model inputs are mainly: the technical data sheet of the panels, measured data related to the heat transfer fluid, readings by the climatic control unit and the characteristics of the installation.

Temperature and flow rate at panel inlet have been used as input data, as well as environmental temperature, wind speed and horizontal radiation measured by the climatic control unit located in Roma-Urbe airport. The PVT outlet temperature ($T_{w,out,PVT}$) as well as the thermal power ($P_{th,PVT}$) produced, measured (M) and simulated (S), were then

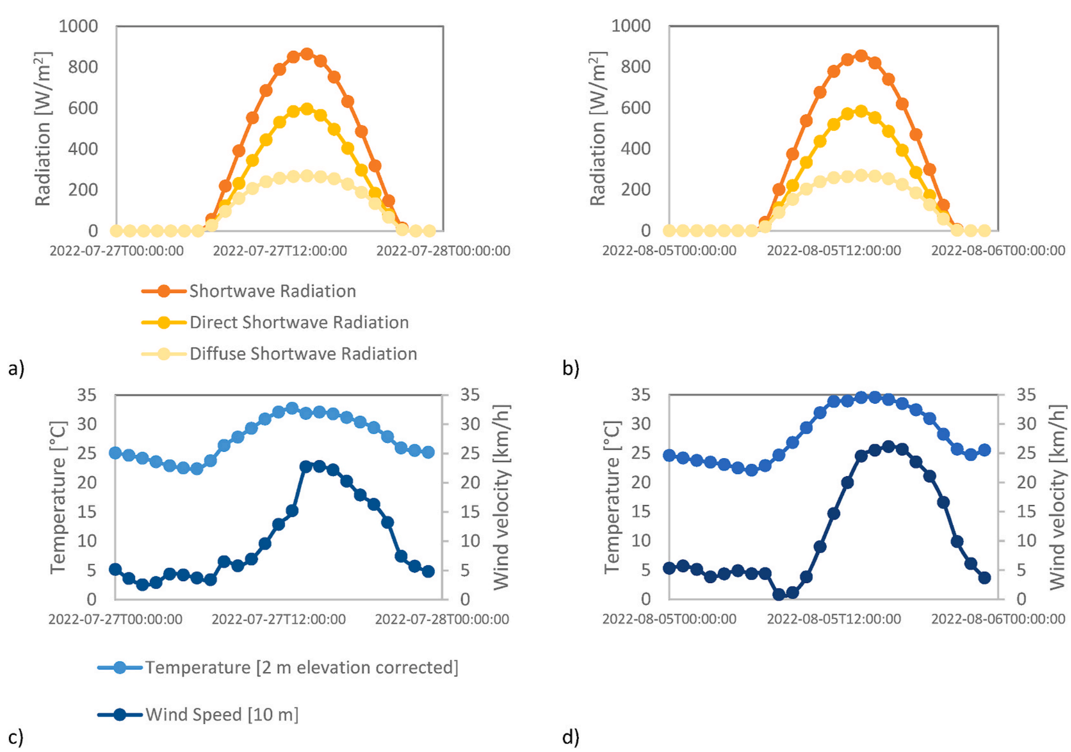


Fig. 7. Weather data of Roma-Urbe Airport during the two examined days: a),b) solar radiation; c),d) air temperature, and wind velocity.

Table 3
Model inputs.

Inputs	Unit	Data source
Inlet fluid temperature	°C	Measurements
Fluid mass flow rate	kg/h	Measurements
Ambient temperature	°C	Weather Data [70]
Incident radiation	kJ/h.m^2	Weather Data [70]
Windspeed	m/s	Weather Data [70]
Cell Efficiency at reference conditions	–	Module datasheet

compared. Fig. 8 shows the trends over time of the measured and simulated quantities. The average percentage error is 0.8 % for temperatures and 9.5 % for powers.

3.4. Water source heat pump

As per the calculations previously conducted, the Oilon RE56 water source heat pump was selected to be installed on the demo site in Palombara Sabina, Italy. Oilon's technical data sheet and dimensioning tool allow to define the characteristic curves of the machine (Fig. 9). Specifically, Fig. 9c illustrates the variation of the COP by changing temperatures at evaporator and condenser inputs; in Fig. 9a the pattern of the HP's thermal capacity and in Fig. 9b the pattern of the electricity consumption of the compressor are depicted, both related to the variations in the aforementioned temperatures.

Given the water temperature in the HP condenser $(T_{w,HP,c})$ and evaporator $(T_{w,HP,e})$, using the mappings from the heat pump technical data sheet, the COP and the thermal power required for the device to fulfill the building's demand are derived.

$$P_{th,rated} = f\left[MAP_{Pth,rated} = f\left(T_{w,HP,c}, T_{w,HP,e}\right)\right] \tag{16}$$

$$P_{th,HP,min} = P_{th,HP,rated}\ C_{f,min} \tag{17}$$

$$C_f = \frac{P_{th,HP,operating}}{P_{th,HP,rated}} \tag{18}$$

$$COP = f\left[MAP_{Pth,HP,rated} = f\left(T_{w,HP,c}, T_{w,HP,e}\right)\right] \tag{19}$$

$$P_{el,HP} = \frac{P_{th,HP,operating}}{COP} \tag{20}$$

Where C_f is the capacity factor, and $C_{f,min}$ represents the minimum modulation of the heat pump; MAP refers to values extracted from heat pump characteristic maps shown in Fig. 9.

In simulating winter operation of the system, to understand the operation of PVT as a thermal source in charge of replenish the energy grade of the cold well of the heat pump, it was necessary to quantify the refrigerating power exchanged between the evaporator and the cold well $(P_{cold,HP})$ as well as the temperature at the outlet of the evaporator $(T_{out,HP,e})$..

$$P_{cold,HP} = P_{th,HP,operating} - P_{el,HP} \tag{21}$$

$$T_{out,HP,e} = T_{in,HP,e} - \frac{P_{th,HP,e}}{\dot{m}_{w,HP,e} C_{p,w}} \tag{22}$$

Therefore, a range of operating temperatures for the heat pump was set in order to harness synergy with PVT and to maximize the COP:

$$T_{in,HP,e} = \begin{cases} T_{in,HP,e,min} \le T_{top} \le T_{in,HP,e,max} & \rightarrow T_{in,HP,e} = T_{top} \\ T_{top} > T_{in,HP,e,max} & \rightarrow T_{in,HP,e} = T_{in,HP,e,max} \\ T_{top} < T_{in,HP,e,min} & \rightarrow T_{in,HP,e} = T_{top} \end{cases} \tag{23}$$

Where T_{top} is the water temperature at the uppermost part of the TES, therefore the one that enters the HP and exchange with the evaporator (number 3 in Fig. 4a).

Using the OILON software, four different load side temperatures and six different source side temperatures were tested, and a COP curve for the RE 56 heat pump was created. After preparing the actual data, the heat pump model was created. The quantities assumed for the heat pump model are specified in Table 4. COP's from actual data and model's results are compared in Fig. 10a for the cooling mode and in Fig. 11a for the heating mode. The average error rate for the COP estimation by the model stands at 0.36 % (cooling mode) and 0.59 % (heating mode). The comparisons in terms of heat pump's cooling and heating capacity are outlined in Figs. 10b and 11b, respectively. The average percentage error for electric power usage is 0.73 % (cooling mode) and 0.34 % (heating mode).

3.5. Dry cooler

As for the cooling interval, it starts on May 1st and ends on September 31st, operating not continuously but according to external temperatures [71]. The plant consists of the same heat pump, whose condenser cooling system is guaranteed by a dry cooler. Therefore in the summer case the performance of the plant will be strongly conditioned by the sizing and operation of the DC. Its sizes are based on HP's maximum power requirements of 85 kW (work temperatures 35–40 °C; 20-15 °C). Fig. 12a depicts the operating curves of the considered DC, specifically thermal capacity and electrical consumption, as a function of the speed of the fans.

Since the heat exchange depends on the external air temperature, its trend during the period considered is reported in Fig. 12b: measurements vary between 35 and 10 °C. As the set-point temperature increases, at the same ambient temperature, the speed of the dry cooler decreases since the load to be disposed of decreases, thus also decreasing the power required (Fig. 12a).

4. Results and discussion

To comprehend the incorporation of the RESHeat system into the study building in Italy, an analysis was conducted on monthly and annual scales, taking into account thermal energy consumed and generated, as well as electricity demanded and produced. The energy profiles of the heat pump and cooled solar panels, along with those of the downstream and upstream tanks of the heat pump, serve as reference quantities. Additionally, the system's efficiency, particularly the average seasonal and monthly COP of the heat pump, is considered. Furthermore, to express the penetration of renewables, the achieved solar fractions are presented. Table 5 reports the annual summary of the prime energy aspects under consideration.

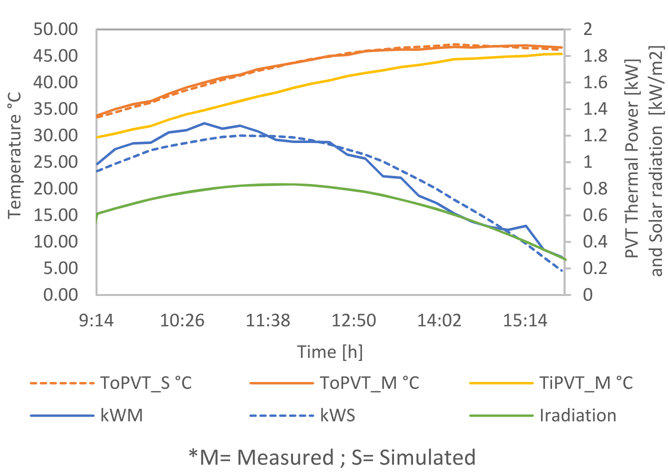


Fig. 8. Comparison of results.

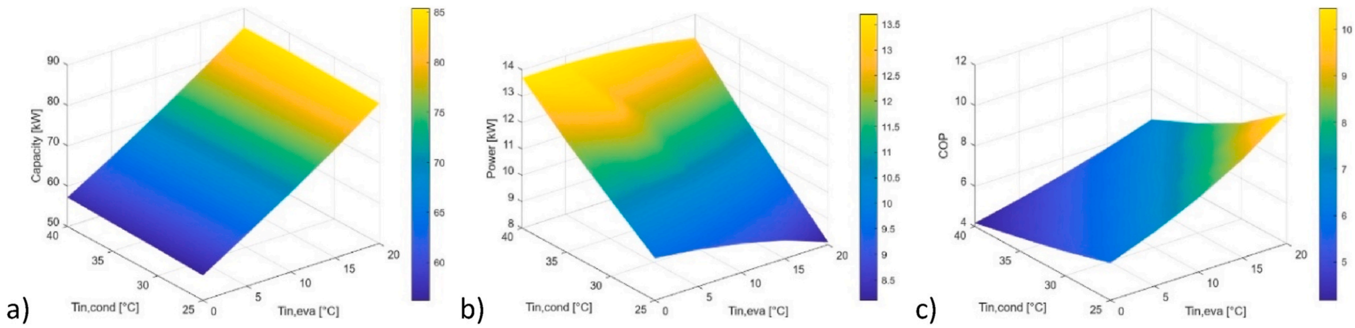


Fig. 9. Heat pump characteristics varying evaporator (Tin,eva = $T_{w,HP,e}$) and condenser (Tin,cond = $(T_{w,HP,c})$ inlet temperature. a) thermal capacity; b) electrical power; c) COP [70].

Table 4
Model parameter of the RE 56.

Parameters	Value
Source fluid specific heat (kJ/kg.K)	3.82
Load fluid specific heat (kJ/kg.K)	4.19
Source fluid density (kg/m^3)	1024.33
Load fluid density (kg/m^3)	1000.00
Rated heating capacity per heat pump (kW)	85.4
Rated cooling capacity per heat pump (kW)	74.0
Rated heating power per heat pump (kW)	11.3
Rated source flow rate per heat pump (l/s)	3.8
Rated load flow rate per heat pump (l/s)	4.1
Rated load flow rate per heat pump (l/s)	4.1

4.1. System efficiency

A crucial aspect of the system is the ability of guaranteeing a high level of efficiency, with the heat pump's COP consistently exceeding 5. The combined operation of the heat pump and the PVT panels is essential for optimizing system performance. During the winter, the panel cooling circuit, supplied by the HP's cold source, exchanges heat with the thermal storage, maintaining an average temperature inside it above 8 °C. Based on simulations, the heat pump achieve an annual average COP of 6. Specifically, the seasonal heating performance (sCOPh) stands at 5.4, and the seasonal cooling performance (EER/sCOPc) is 6.9 (Fig. 13).

In summer, according to the characteristics of the HP, raising the DC set point temperature, the COPc of the HP increases. When the temperature of set point is 25 °C, the average input temperature of the HP is maintained at 26.37 °C and its seasonal average COP results of 6.99.

4.2. Thermal energy

Another crucial aspect of the proposed system is the integration of the PVT array. Specifically, during the winter months, the low-temperature heat produced by the panels is harnessed to replenish the heat pump's cold well, ensuring the high-performance levels discussed earlier. In contrast, during non-winter months, when the panels can provide heat at higher temperatures, they are coupled with the system for domestic water heating. The thermal generation through the work of the panels is hence analyzed in relation to these two different needs.

In Fig. 14a, the thermal energy generated by the collectors and saved in the buffer tank $(E_{th,PVT,st})$, subsequently used by the HP is depicted, indicating as $E_{th,HP,e}$ the thermal energy required by the cold side of the heat pump. Additionally, the solar factor $(f_{sol,th})$ is provided for each month. During the winter period, the useful heat production by the panels amounts to 7.64 MWh, while the thermal demand by the HP's evaporator is 15.9 MWh. In this specific case, taking in account only the winter season, the solar thermal fraction $(f_{sol,th,H})$ is 0.54.

During the months outside the heating season, the heat produced by the PVT panels is allocated for domestic hot water production (Fig. 14b). From April to October the domestic hot water thermal demand $(E_{th,DHW})$ is equal to 25.18 MWh. The theoretical total thermal energy production by the PVT panels could reach 32.6 MWh, but the thermal energy actually available is given by the storage capacity of the DHW tank (number 6 in Fig. 4d). According to UNI TS 9182 [72] and to the DHW demand previously indicated, it is considered a volume of 1500 l. Since the heat source is of a variable nature, the actual storage capacity of the tank must be checked by dynamic simulation.

If the volume is of 1500 l the thermal energy provided by the PVT and retained in the buffer tank is 23.65 MWh, with a thermal energy coverage by RES equal to 94 %.

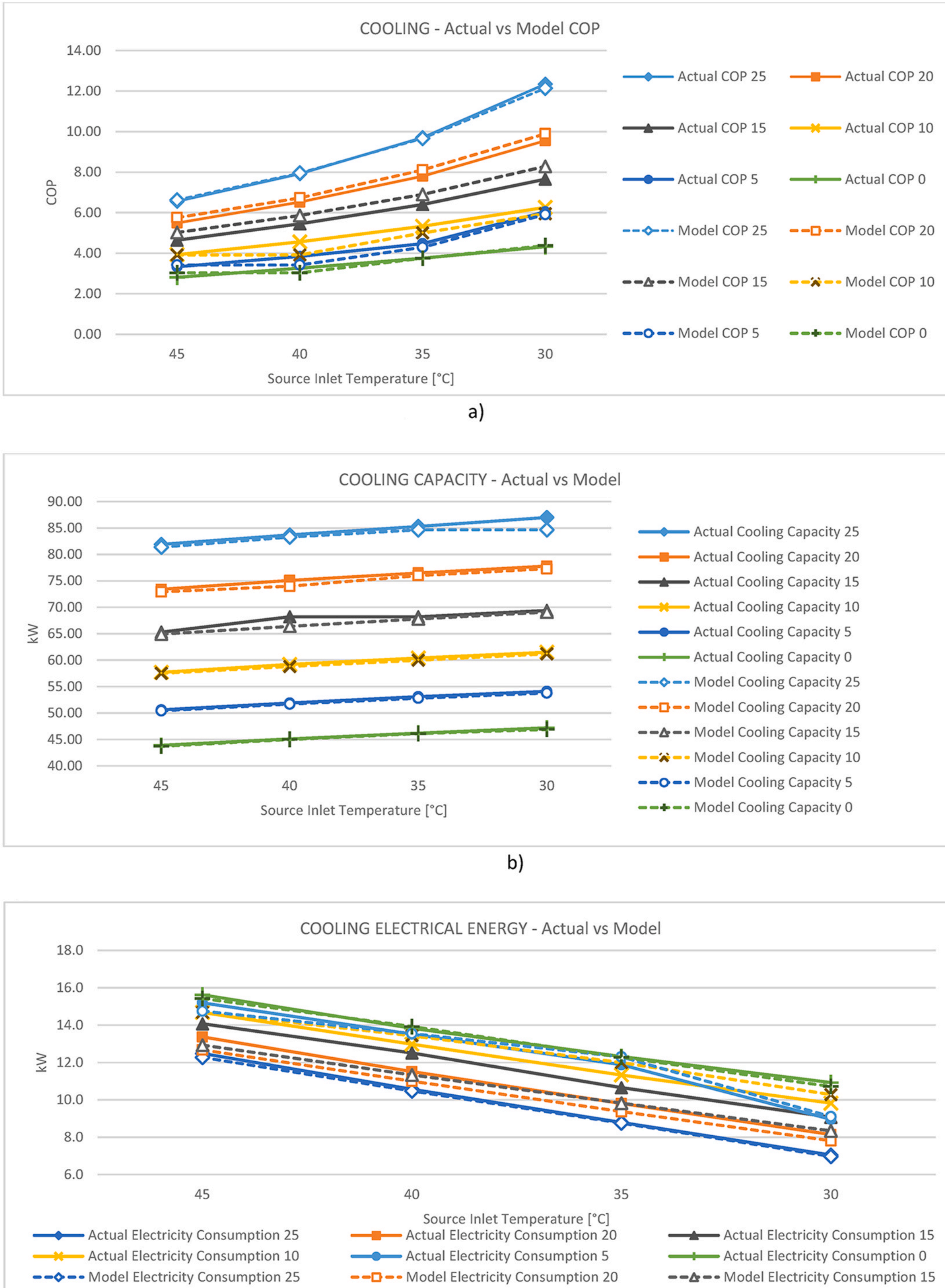
Directing heat deriving from panels' cooling, which otherwise should be dissipated by a dry cooler, to meet the summer load of domestic hot water, is an effective strategy in order to avoid dispersing heat and the electrical load of the dry cooler possibly attached to this end, at once rising the share of renewable coverage of the building, thus reducing current consumption from fossil sources.

4.3. Electrical analysis

Fig. 15 illustrates the monthly electricity generation and consumption.

The PVT system yearly generates 30 MWh/y. From simulation the electricity consumed by the heat pump over the annual operational period results equal to 9.28 MWh/y. The post-intervention estimated electricity consumption is calculated based on simulations (MWh) and increased by 10 % to account for the consumption of auxiliary electrical and electronic devices. To this, the current electricity consumption related to condominium use not connected to the heating system is added, augmented by 15 % to consider future additional condominium expenses. Resulting an Electrical Energy Consumption of 23 MWh/y, it is possible to state that the annual production ensures a positive balance between consumption and production.

The annual net solar electric fraction is equal to 1.27 (Fig. 16). In all months except the winter months, December, January and February, the electricity production exceeds the need with a $f_{,sol,el,net}$ more than 1. Specifically, there is a minimum $f_{sol,el,net}$ of 0.22 in December. On the contrary, as mentioned in the previous section (4.2 Thermal Energy), the annual solar thermal factor is 0.67 with a minimum in January of 0.25 and a maximum of more than 0.95 in June and July. Given the solar thermal and electrical factors, by Eq. (4) the global solar fraction was calculated, and the annual value results 0.98. In the months when the thermal and electrical demand is greater, but there is little production, the solar source needs an auxiliary support to ensure the thermal and electrical demand, reaching the minimum in January and December of 0.29, while in months with higher production and lower needs $f_{sol,gl}$ exceeds 1 with the maximum in the month of lower electricity and thermal consumption, April, equal to 2.



c)

Fig. 10. Cooling Validation results, comparison between HP datasheet (Actual) and model simulation (Model). a) COP; b) Cooling Capacity; c) Electrical Energy.

4.4. Primary energy

Taking into account the self-consumed and grid-supplied electrical energy, Primary Energy required by the current heating plant (PE_{NGB}) and by the RESHeat layout (PE_{HP}) were evaluated and compared (Fig. 17).

For the first one a primary energy conversion fraction equal to 1.05 (Natural gas factor) was used; for the second one two factors were assumed: $f_{PE} = 1$ if the HP is feed by the PVT electricity and $f_{PE} = 2.42$ if the HP is feed by the electricity take from the grid. In Fig. 17, the orange part of the bars represents PE,*nREN* and the green one PE,*REN* for the RESHeat scenario (*S1*). Black lines are for the current *PEnREN* amount (scenario S0). With a total (H + C + DHW) annual primary energy demand of 95.22 MWh/year, of which 39.5 MWh/year is non-renewable (PE,*nREN*) and 55.73 MWh/year is renewable (PE,*REN*), this represents a significant reduction from the initial (H + DHW) energy demand of 148.25 MWh/year, with 131.15 MWh/year being non-renewable (PE, *nREN*) and 17.1 MWh/year being renewable (PE,*REN*). The result is achieving non-renewable primary energy savings (PES) of 44 %, while also providing additional benefits to the tenants, such as increased

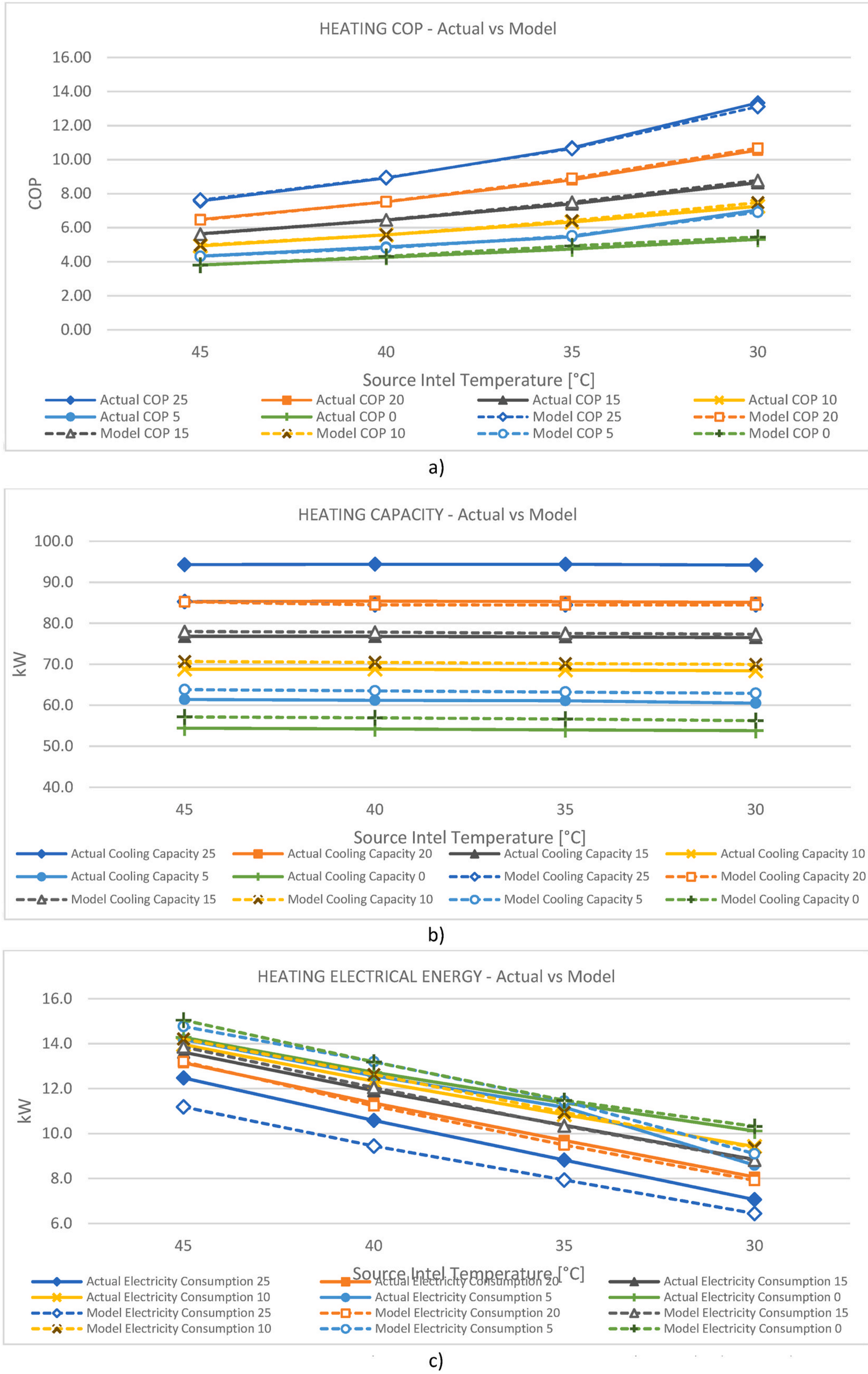


Fig. 11. Heating Validation results, comparison between HP datasheet (Actual) and model simulation (Model). a) COP; b) Heating Capacity; c) Electrical Energy.

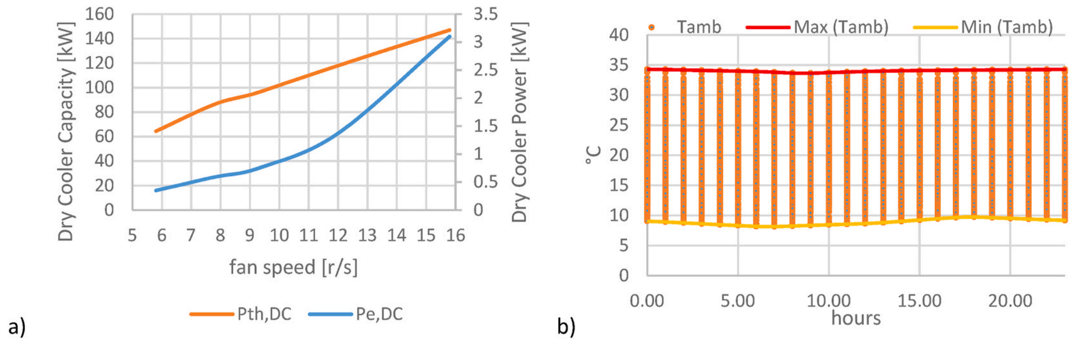


Fig. 12. a) Dry cooler thermal capacity and electrical power related to the fan speed. b) Outlet air temperature.

Table 5
Summary of annual energy analysis.

$E_{th,PVT,st}$	$E_{th,HP,e}$	$E_{th,DHW}$	$E_{el,PVT}$	$E_{el,demand}$	*PE, nREN*	*PES*	*fsol*	*fsc*	*sCOP*
31 MWh/y	16 MWh/y	25 Mwh/y	30 Mwh/y	28 MWh/y	56 MWh/y	36 %	98 %	15 %	6

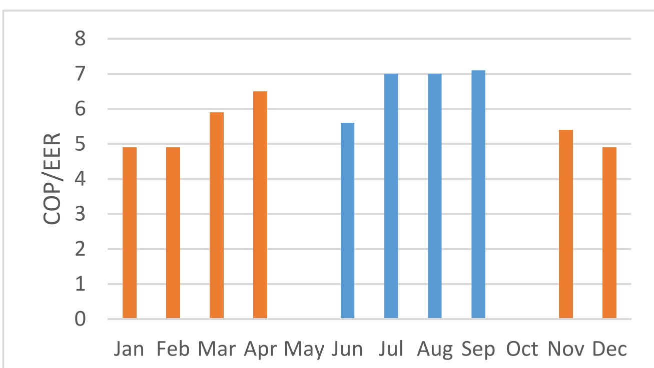


Fig. 13. Monthly performance: a) heating COP (orange); b) cooling EER (blue)

comfort due to summer cooling.

Looking only at the heating service (Table 6), this transition results in a reduction of total primary energy consumption from 60 MWh associated with the natural gas boiler to 34 MWh with the heat pump, translating to a 43 % decrease. When considering only the non-renewable portion, there is a reduction of 56 %.

If the focus is moved to domestic hot water, replacing independent electric generators with the centralized NGB system integrated with PVT for which the boiler works as a backup during summer, there is a 72 % reduction in non-renewable primary energy (Table 6).

A comparison between the present state and the RESHeat scenario indicates that the second one, leads to substantial savings in consumption. Considering the end energy use already installed in the building, heating and domestic hot water production, there is a primary energy reduction amounting to 98 MWh/year, equal to 55 % (Table 6). Even considering the additional consumption of summer cooling, a considerable decrease in primary energy of 48 % is achieved (87 MWh/y) (Table 6).

4.4.1. Carbon avoidance

For the purpose of evaluating the environmental impact and emissions associated with the operation of RESHeat heating system, the corresponding avoided tCO2eq emissions were calculated.

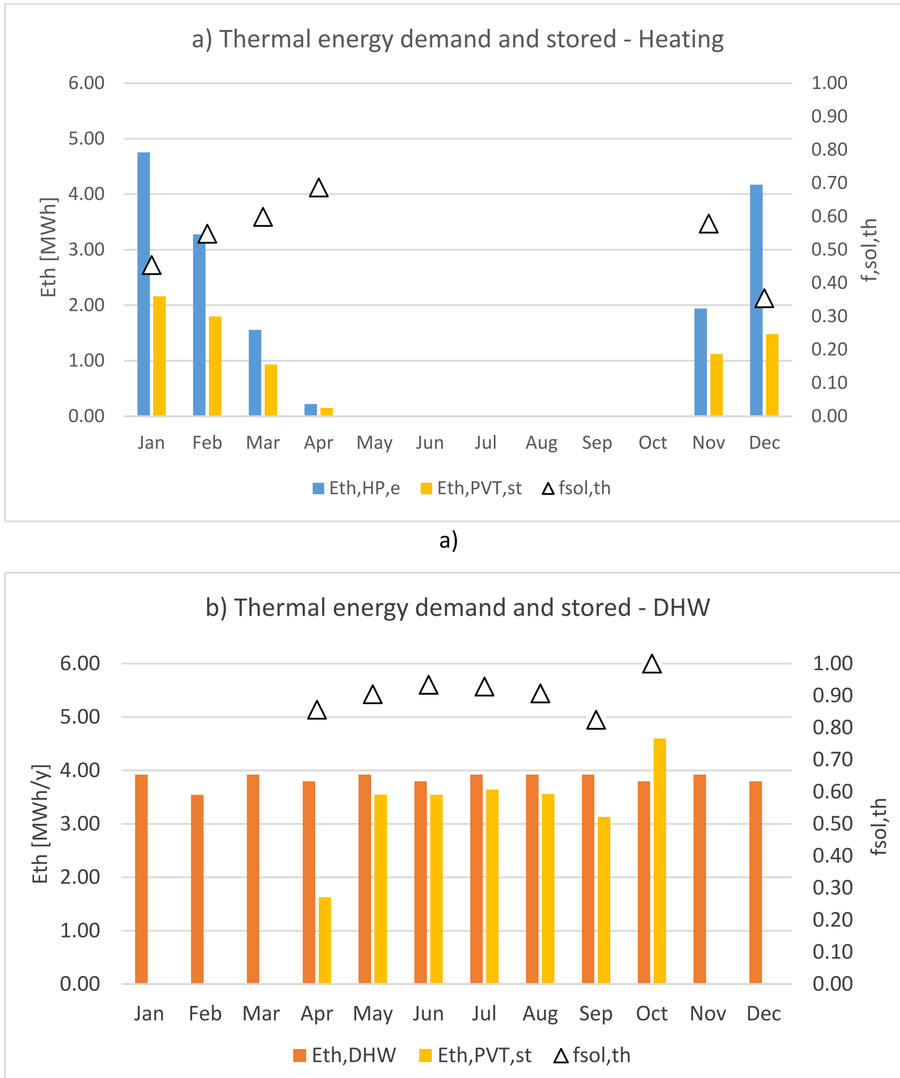
Specifically, consideration was given to the CO2 emitted by the new system for each final use: heat, cool and domestic hot water generation. The calculation involved the subtraction of CO2eq not emitted thanks to electric self-consumption from photovoltaic production ($tCO2_{el,PVT,sc}$), the CO2 avoided through the replacement of the methane boiler with the heat pump ($tCO2_{ng,NGB,H}$), and the CO2 avoided through the replacement of electric boilers ($tCO2_{el,EB,DHW}$), along with the integration of thermal energy from photovoltaic-thermal panels. When the production of the latter isn't sufficient to meet the needs of DWH a gas boiler is employed as a back-up generator.

As calculated by Eq. (8), an annual saving in emissions equivalent to 62.5 tCO2 is achievable, despite the increase in end uses, how it is visible from lower levels of CO2 avoided during the period in which cooling is introduced, and the enhanced comfort provided to the tenants (Fig. 18).

This analysis reveals the significant reduction in overall carbon dioxide equivalent emissions attributable to the implementation of the RESHeat system. It not only provides insights into the specific environmental advantages of RESHeat but also contributes valuable data for assessing the broader sustainability implications of innovative heating systems in residential buildings.

4.5. Economic assessment

In order to conduct a detailed cost evaluation of the intervention, it is necessary to consider maintenance activities for the proper functioning of the system and to maintain the guaranteed efficiency at the time of installation. Firstly, regular maintenance activities such as panel cleaning and component integrity checks should be scheduled, alongside long-term revamping or repowering actions aimed at improving overall system capabilities and performance. To counteract efficiency degradation affecting the photovoltaic field and potentially impacting self-consumption, it is essential to monitor various components of the system, including panels, the photovoltaic generator, and inverters [73]. Several studies indicate that accumulated dirt on photovoltaic modules leads to performance decrease of from 7 to 98.13 % [74]. In the analyzed case, with panels not subjected to unfavourable environmental conditions such as maritime zones, high pollution areas, or proximity to large trees, a reduced efficiency degradation over time is expected. Singular events may necessitate extraordinary maintenance interventions, such as repairing panel damages, especially after intense weather events that may cause cable or inverter damage and their subsequent replacement, as well as battery status checks. Furthermore, it is crucial to monitor system production levels and efficiency to identify any issues or malfunctions and intervene accordingly. Therefore, ensuring anomaly-free operation of the monitoring system is also essential. The thermal aspect of PVT systems entails specific checks, such as verifying the state and composition of the heat transfer fluid, especially in cases where the thermal solar system is equipped with a water and antifreeze mixture, an



b)

Fig. 14. Thermal energy produced and stored by PVTs($E_{th,PVT,st}$) and thermal solar fraction ($f_{sol,th}$) related to thermal energy consumed by different services: a) HP; b) DHW.

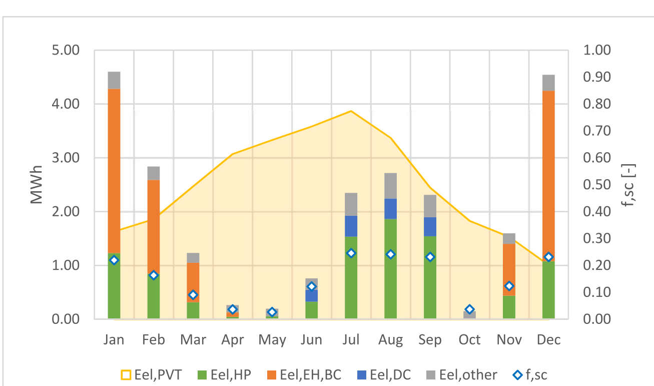


Fig. 15. Electrical production and consumption.

increasingly common solution: if the pH drops below 6.6, it could become corrosive. Other specialized interventions include checking the expansion vessel membrane and the venting and safety valves. As regards heat pumps [75] addresses the impact of soft faults, like refrigerant leakage and heat exchanger fouling, on their performance. Soft faults, if undetected, lead to significant performance degradation over time. A 50 % performance drop in cooling mode without planned maintenance was demonstrated that could be reached. For air-to-air heat pumps in heating mode, results show a 40 % condenser fouling and 30 % refrigerant leakage causing 16 % and 12 % performance degradation, respectively. Evaporator fouling has a lesser impact. Overlapping faults exacerbate degradation. Surprisingly, none of the maintenance strategies significantly reduce fault penalized scenarios, suggesting the need for automatic fault detection, diagnosis, and evaluation systems (FDDE).

The investments effectiveness of the intervention was evaluated in terms of payback period (PBP).

As first thing it has been calculated the initial cost of the system like sum of the costs of every single component brought back in Table 7.

To determine the NPV the saving cost of the n-th year (Cs_n) were calculated following Equation (23) and expressed in €/yr:

$$Cs_n = C_{el,ev,n} + C_{ng,ev,n} - C_{O\&M,n} - C_{re,n} \tag{24}$$

In this context, $C_{el,ev}$ and $C_{ng,ev}$ represent the economic gains linked to the saving of electricity and natural gas respectively and evaluated ac-

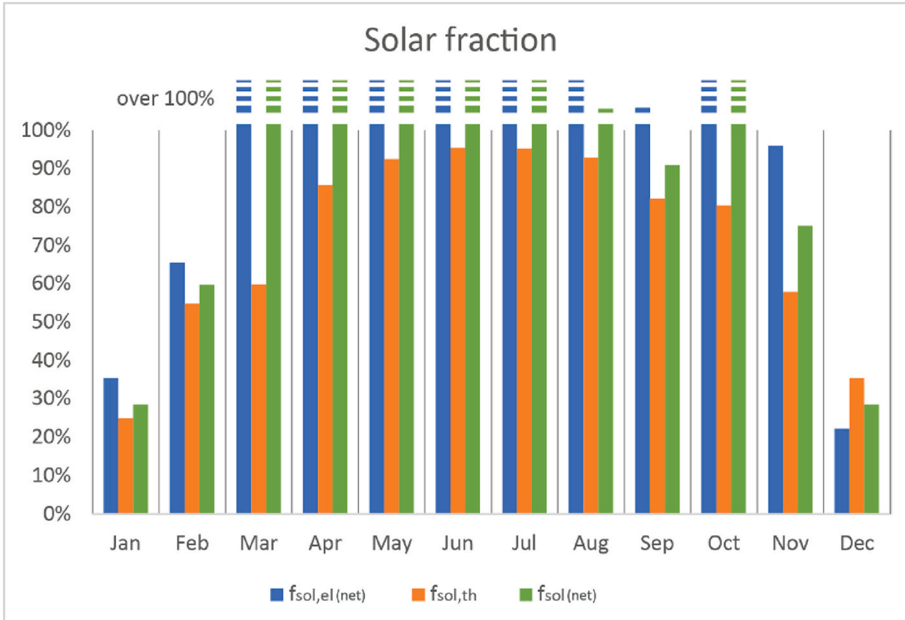


Fig. 16. Electrical, thermal and global solar fraction; (net) indicates that the considered electricity is the whole produced, including the self-consumed and the share fed into the grid.

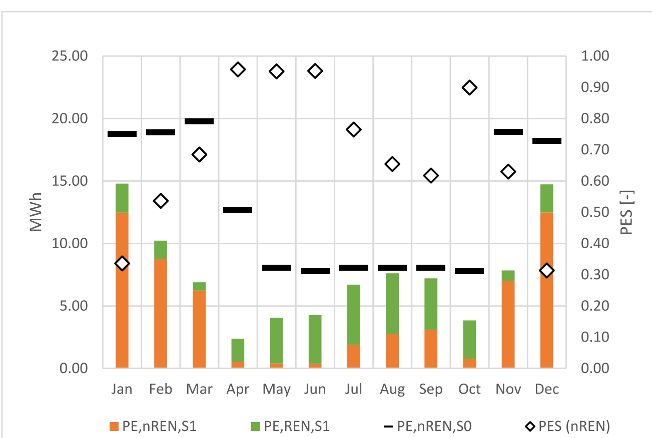


Fig. 17. Monthly Primary Energy demand for S0 and S1 scenarios, considering the whole energy consumption (heating, cooling and DHW), and expected PES.

Table 6
Annual primary energy consumptions.

PE end use	Total	nREN	REN	Units
Initial scenario/current situation				
S0, Heating, NGB	60.2	60.2	0	MWh/y
S0, DHW, Electrical Boiler	117.7	94.8	22.9	MWh/y
S0, H + DHW	177.9	155.1	22.9	MWh/y
RESHeat system				
S1, H	34.0	26.3	7.7	MWh/y
S1, DHW	46.2	23.6	22.6	MWh/y
S1, H + DHW	80.3	50.0	30.3	MWh/y
S1, H + C + DHW	90.5	56.8	33.8	MWh/y

cording to equations (24) and (25), $C_{O\&M}$ denotes operational and maintenance expenses (€/yr) calculated according to Table 8 and C_{re} denotes the revamping cost cording with the service time of the specific component (Table 8), it has been calculated as a tantum in correspondence of the service time.

$$C_{el,ev,n} = \left(E_{el,so} + E_{el,s1}\, f_d{}^n\right) C_{el} \tag{25}$$

$$C_{ng,ev,n} = \left(V_{ng,so} + V_{ng,s1}\ \ f_d{}^n\right) C_{ng} \tag{26}$$

Where E_{el} and V_{ng} represent the electricity consumption expressed in kWh and natural gas expressed in m3, for scenarios s0 and s1. While f_d represents a factor of decay of the productivity of the system applied annually and equal to 1 %. C_{el} and C_{ng} denote respectively the cost of the electrical energy and natural gas. As cost of individual energy carriers' reference was made to the regulatory authority for energy, networks and environment [76]. Fig. 19 show the cost of electricity (a) and methane (b) from 2016 to 2024, from which three different scenarios were examined considering the current cost of the specific energy carrier, the maximum value over the time considered and the average value.

Finally, NPV is then calculated as the difference between the sum of the discounted annual cost saving less the initial investment considering a investment interest rate, i (%) equal to 2.7 [77].

$$NPV = -IC + \sum_{n=0}^{25} \frac{C_s}{(1-i)^n} \tag{27}$$

Fig. 20 shows the time trends of the NPV for the three selected price scenarios. Getting three different payback period (PBP) equal to 4 years considering a cost equal to the average cost from 2016 to today, to 2.5 years considering the current price of energy and just 1 year considering the maximum cost.

4.6. Weaknessess and limitations of the system

The RESHeat system, which combines a water heat pump with a cooled photovoltaic system, offers significant advantages in terms of energy efficiency and emission reduction. However, its adoption and effectiveness in real-world contexts may be limited by several weaknesses that need to be considered. This study discusses the initial costs, end-user acceptance, adaptability to different climatic conditions, and potential solutions through the addition of electrical storage related to the RESHeat system.

Initial costs and payback period.

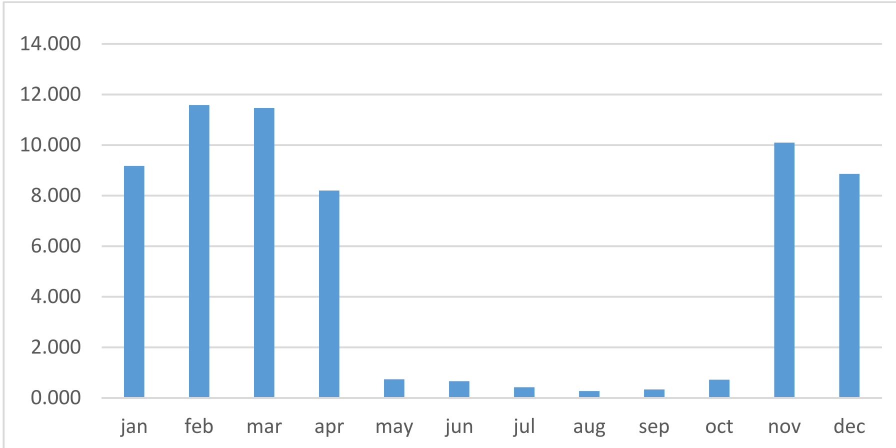


Fig. 18. Tons of CO2 avoided.

Table 7
Initial cost of the system components.

	Cost (euro)
Solar PVT panels	39400
Heat pump	30000
Termal energy storage	7500
Dry cooler	6500
Inverter	2000
Automation and control	6000
Fancoil units	12500
Circulation Pumps	5000
Piping	7000
DHW System	29800
Other cost	17500
Total	**163200**

Table 8
operational and maintenance expenses as function of initial investment.

	O&M cost/IC	Service time
	% of IC	Years
PVT	1.6 %	25
HP	5.8 %	20
TES	0.7 %	25
DC	5.8 %	10
FC	0.7 %	10
Other	1.5 %	20

- the installation of the RESHeat system may require significant initial investments, which are not always sustainable for all building owners or entities involved;
- some owners may be discouraged from investing in the technology due to the long time required to amortize the initial costs.

Adaptability to different climatic conditions.

- the RESHeat system is optimized for use in specific climatic conditions, such as those found in the Italian location under study, which limits its applicability on a wider scale. However, challenges may arise in adapting the system to different climatic and environmental conditions, such as those found in other regions or countries.

Addition of Electrical Storage.

- electrical storage would enable increased self-consumption of energy produced by photovoltaic panels, reducing dependence on external power grids and maximizing economic benefits for building owners.
- it could also be used to manage electricity demand during peak periods, reducing costs associated with higher electricity tariffs.
- the RESHeat system could be made more flexible to better respond to variations in solar energy production and the building's energy needs. This would improve the system's overall reliability and optimize the use of available energy resources.
- it could serve as a backup system during blackouts, ensuring a continuous power supply for critical services within the building.

However, it is important to consider the potential disadvantages and challenges of adding electrical storage with lithium batteries. These

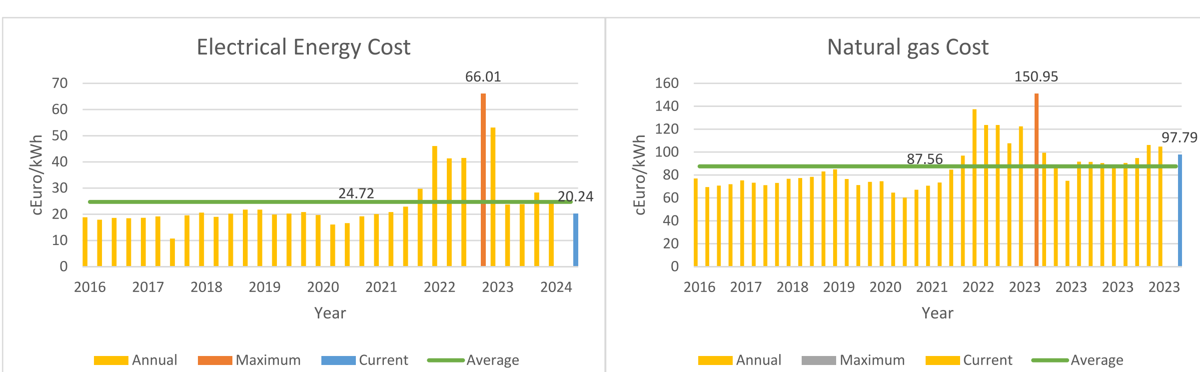


Fig. 19. Costs of electricity (a) and methane (b) from 2016 to 2024 [76].

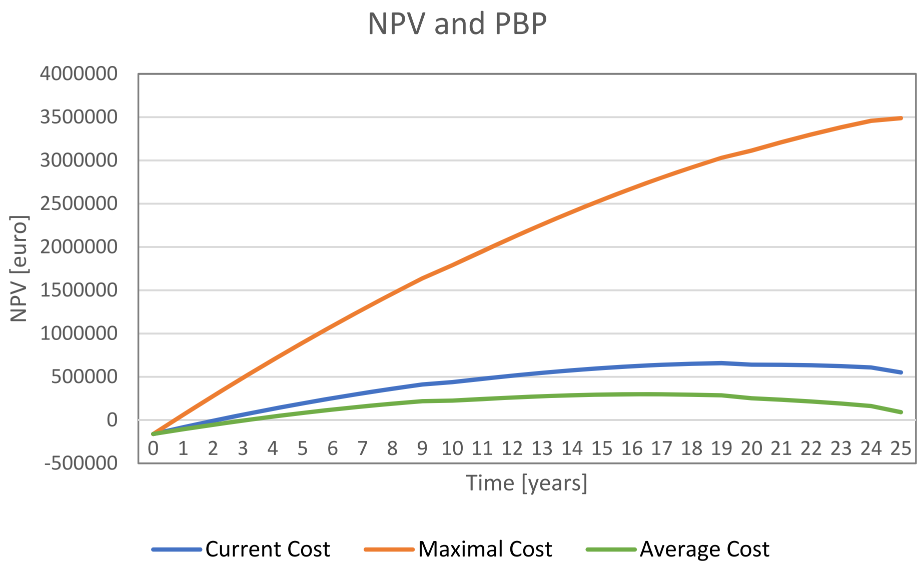


Fig. 20. NPV and PBP for the three different cost splinters considered, (current, maximum and average).

include the additional costs of purchasing, installing, and maintaining the storage unit, as well as the need for additional space to accommodate it. In addition, it is important to ensure that the electrical storage is compatible with the other components of the RESHeat system and is correctly configured to maximize the overall benefits of the system.

Space limitations.

- The installation of a RESHeat system requires a suitable and appropriately oriented surface area for the photovoltaic panels needed to meet the heat pump's thermal load.
- Additionally, there must be enough space to accommodate the thermal storage systems, which can be quite large depending on the building's energy needs and required storage capacity due to the limitation of available space.
- Limited space may hinder system implementation, particularly in buildings with restricted areas for photovoltaic panel installation or limited space for thermal storage units.

Development of a Digital Twin (DT) [78] of the system.

- implementation of a real-time virtual representation of the building-plant system would enhance its management by enabling efficient and accurate monitoring of its performance.
- DT can identify and resolve operational problems or inefficiencies in the RESHeat system in a timely manner by simulating and analyzing real-time data.
- RESHeat system parameters can be automatically adjusted to maximize performance and reduce energy consumption using real-time data and optimization algorithms.
- maintenance activities can be more effectively planned by predicting the future performance of the RESHeat system based on historical data and weather forecasts.

However, implementing a DT system may result in added expenses for infrastructure and software, as well as difficulties in collecting and integrating data from various sources. It is crucial to prioritize the security and protection of sensitive data used by the DT to prevent privacy breaches or cybersecurity vulnerabilities.

5. Review and comparison with the literature

A comparison of the results with other works in the literature is difficult because each case has its peculiarities. However, the different systems studied in the literature were analyzed and compared.

The comparison therefore concerned in general the type of plant, the intended use, the size of the building analyzed, the final uses satisfied by the plant. There where possible for similitude of climatic data, plant type, the KPIs used, we have passed to a comparison of the results obtained. Finally, highlighting the differences, strengths and innovative compared to the works in the literature.

Studies on plant systems whose main components are HP, PVT and TES are widely spread in the literature, what distinguishes the different jobs mainly is the operation of HP and the control system of the entire plant (Table 9). Several studies have focused on solar assisted HP (SAHP), ground source HP (GSHP) or dual source air-ground HP (DSHP) with the aim of increasing the seasonal efficiency of the system by exploiting the source of ground heat, air and thermal energy produced by PVT or SC (solar collector) [79–85].

Specifically, from the analysis carried out by the authors, with these components the most studied plant type is of the type PVT-GSHP-TES (Table 9, reference: [79,80,82,95,91]). In these systems the heat pump exploits the soil temperature, more stable than the air temperature, as a low temperature heat source [82]. However, the continuous operation of the GSHP, particularly in regions with very cold climates where there is an imbalance between winter and summer load in favor of the former, leads to a gradual decrease in soil temperature over the years. This decrease has a negative impact on the system COP [96]. In order to replenish the energy levels of the soil, several works propose a GSHP coupling with PVT, to exploit the heat produced at low temperature by the panels to compensate for the heat extracted by HP, ensuring a maintenance of performance. In Guadong et all we highlight how the combination of GSHP and PVT can improve soil temperature, as well as lead to an optimization in the sizing of the geothermal heat exchanger, indicating an optimal correspondence between the area of the PVT collector and the total length of the underground pipes such as not to create problems of accumulation of heat in the soil with increases in the COP of 10 % [96]. In Li et all [97] the coupled system PVT-GSHP reaches an average COP of 3,99 with a maximum of 4,61 and a minimum of 3,59 during the heating period, while in the cooling period the EER reached 4,59, the minimum value was 3,59 and the average value of the cooling COP was 3.96, thanks to the optimization of the control strategies of the heat accumulation.

Alternatives to the most widespread geothermal heat pumps in the literature consist of dual or multi-source heat pumps solar-air or only source HP, where with solar source we mean the direct connection between HP and PVT, without the interposition of a TES, also known as

Table 9
Annual primary energy consumptions.

Reference	Year	Location	Building use	HP (Typology)	PV/PVT	TES LOAD	TED SOURCE	DHW TES	HEATING	COOLING	DHW	Power	Energy	Economical	Environmental
[79]	2024	Shenyang, Cina	RS	GSHP	PVT	Y	N	N	Y	Y	N	Y?	Y	Y	N
[86]	2024	Shangai, Cina	RD	SADEHP	PVT/ evaporator	N	N	Y	N	N	Y		Y	Y	Y
[87]	**2022**	**Zaragoza, Spagna.**	**RM**	**WSHP**	**PVT**	**N**	**Y**	**Y**	**Y**	**N**	**Y**	**Y**	**Y**	**N**	**Y**
[80]	2024	Tianjin, in Cina	R	GSHP	PVT	N	Y	N	Y	Y	N	Y	Y	N	N
[81]	2023	–	–	MSHP Air/solar/ground	PV and SC	N	TES-PCM	N	Y	N	N		Y	Y	N
[82]	2023	–	–	GSHP	PVT	N	Y		Y	Y	N		Y	Y	
[88]	2022	Shanghai, Cina	R	WSHP	PVT	N	Y	Y	N	N	Y	N	Y	Y	Y
[83]	2023	Shenyang, Cina	RS	DSHP air-ground	PVT curtain wall	N	Y	N	Y	Y	N	N	Y	Y	N
[84]	2022	Zibo City, China	OF	DSHP air/solar assisted HP	PVT	Y	Y	N	Y	Y	N	N	Y	Y	X
[89]	2021	Palermo (Italy)	–	AWHP	PV/PVT/SC	N	N	N	N	N	Y	N	Y	N	N
[84]	2021	Innsbruck, Austria.	RM	GSHP	PV/PVT	Y	N	Y	Y	N	Y	N	Y	N	N
[90]	2020	Zaragoza, Spagna.	ED	WSHP	PV and PVT	N	Y	Y	Y	N	Y	Y	Y	Y	Y
[91]	2020	Belluno, Italy	ED	AHU and GSHP	PV and PVT	Y	Y	Y	Y	Y	Y	Y	Y	Y	N
[92]	**2022**	**Irlanda**	**RS**	**WSHP**	**PVT**	**Y**	**Y**	**Y**	**N**	**N**	**Y**	**Y**	**Y**	**Y**	**Y**
[93]	**2020**	**Denmark**	**RS**	**WSHP**	**PVT**	**N**	**Y**	**Y**	**N**	**N**	**Y**	**N**	**Y**	**N**	**N**
[94]	2023	Ferrara, in Italia	–	MSHP air, solar, ground	PVT	Y	Y	N	Y	Y	N	N	Y	N	N

direct expansion solar SDHHP.

In the first case the heat pump exploits multiple sources based on the energy levels of each of them optimizing their use and keeping them constant over time [81,84,94]. Whereas, in the second case, photovoltaic panels are used as evaporators in the thermodynamic cycle of the HP [86]. As in Nasouri et al. [98] the COP is maximized by connecting the HP to solar collectors, from an average COP of 3–7 for the production of DHW.

A further evolution of the latter type of plant consists in interposing a thermal tank between the PVT and the HP (source side) [99,100].

There are still few works dealing with solar-assisted water source heat pump plant systems that take advantage of the thermal inertia of TESs to optimize the performance of the system itself and meet the diverse energy, electrical, and thermal demands of residential buildings. Most articles, to the authors' knowledge, focus on the combination of PVT and GSHP to restore energy levels in the ground and maintain high performance over time [80,82–84,86]. Similarly, the use of these plant systems to produce heat for winter heating is focused more [19,80,82–84,86,87] or on DHW production [32,33,86,87], it is difficult to find an analysis that takes into account all types of energy consumption of a building by taking advantage of the combined production of heat, cold, (DHW) and electrical production of HP and PVT. The proposed system aims to cover all end uses of residential buildings by harnessing solar renewable energy with a minimum coverage of 70 % reaching, through the optimization reported in this paper, 100 % coverage. The work also complements the literature on the analysis of such plant systems applied to multifamily and multi-story buildings that has been poorly addressed compared to single-family dwellings [33,83,86].

In a comparison with similar work in the literature [87,92] and in agreement with these, it is shown that the proposed plant is a viable way forward in decarbonization and optimization of traditional plant systems. In Pintanel et all [87] a system composed of 90 photovoltaic-thermal hybrid panels (PVT) with a 100 m^3 seasonal storage tank coupled with a high-efficiency heat pump is analyzed to partially cover the heat demand of a social housing building located in Zaragoza, Spain, with an annual solar radiation 1796 kWh/m^2y.

The social housing building considered has a thermal load for winter heating of 26.5 kWh/m^2y and a load for DHW of 7.1 kWh/m^2y. With an electrical output of 56Mwh/y and thermal output of 80.8 MWh/y [87] it achieves 79.8 % solar coverage for DHW and 26.7 % for heating with an annual self-consumption of 43.2 %. Comparing, as far as possible given the differences between the two works, in Ref. [87] there is a lower number of PVTs per m2 of building than in the present work, but a significantly higher volume of TES given the seasonal function. The higher number of PVTs leads to increased solar thermal and overall solar coverage, but also to excess electrical generation and reduced self-consumption. However, leading overall to high system performance with COP of 6.

In contrast, Obalanlege et al. [92] discuss a similar system, consisting of cooled PV panels connected via TES to a WSHP that in turn serves a DHW tank for domestic consumption, located in Belfast, Northern Ireland. The plant system is applied to a small 100 m^2 building for DHW production alone of 25.5 kWh/m^2y and electricity consumption of 38.1 kWh/m^2y. With the installation of 12 PVTs [comp7] it achieves a solar thermal coverage of 80 %. Electric of 33 % and a self-consumption of 31 %.

Finally, Vallati et al. [54] present a PVT-HP-TES coupled system for a small office located in three different European cities: Rome, Milan and Krakow. The best results are achieved in the city of Rome with 70 % solar coverage, compared to 47 % obtained in the case of Krakow.

The comparison is made to emphasize how the proposed system is adaptable and applicable not only in the purely Italian setting, but in general there where climatic conditions involve a balance between winter and summer heat load and adequate solar radiation [87,101]. While looking at Obalanlege et all [92] with a ratio of m^2 of PVT per m^2 of building of 0.16 (compared to 0.11 in the present work) and the results obtained by Refs. [54,101] it is plausible to assume, within certain limits, an extendibility of the system while maintaining high performance, there where there is a harsher winter climate and less solar radiation, but with a reduction in performance, in such cases a specific analysis is therefore crucial to understand its actual energy and economic advantage over other plant solutions.

The work focused on a residential building as one of the most energy-intensive compartments in the civil sector. A comparison from literature with other building types is not easy given the scarcity of such work. In reference to Vallati et al. [54] as mentioned a small office building is analyzed obtaining a solar coverage, in the Rome location, of 70 % for winter heating with a COP of c.a. 5. The substantial difference between the different uses, from the energy point of view, lies in the different load, which is more centralized on the cooling and heating part and minor compared to DHW. A different load curve may lead to different numerical results, but remaining in the civil sector, the plant system properly scaled for the specific load is applicable to other uses while maintaining high performance.

Ultimately, the proposed PVT-TES-WSHP-TES-LOAD plant system was compared with other systems studied for the same building in Vallati et al. [56]. Three different plant systems are analyzed in the article with additional sub-differences for a total of 8 different scenarios. The comparison will consider the scenarios with air source heat pump only (s2.1), which appears to be the most prevalent HP plant system in the geographical area to date, and the hybrid HP-NGB system (s3.1). Among the various KPIs analyzed, an increase in plant performance (compared to scenario 0 similar to the one in this paper) of 12 % with the simple inclusion of an HP (s1.1) to 54 % (s3.1) with the inclusion of the HHP system and a PES of 0.22 and 0.28 for s.2.1 and s3.1, respectively, are highlighted. In none of the above scenarios is the coupling with PVT considered, leaving the comparison partial. Since they are applied to the same building, however, it is interesting to see how with the system proposed in this paper, extremely higher performance can be achieved by going from a maximum COP in Ref. [56] of 3.58 to an average annual COP of 6.

In any case, for all the different considerations made above, more in-depth work is needed, with an adequate sensitivity analysis to be able to make quantitative considerations and not only qualitative ones, as well as to understand the cost-effectiveness of these considerations in relation to the costs required to maintain the benefits. In this Work, it has been chosen not to go into further detail, but to devote a specific work to it that will allow for an adequate investigation of the topic.

6. Conclusions

Energy efficiency actions directed at residential buildings are essential to the achieve European targets aimed at minimizing greenhouse gases release and to make buildings more resilient to climate change. These buildings are at the core of this collective effort, as they represent a significant part of Italy's built environment. In this scenario, the proposed research takes centre stage, exploring the complex context of a typical multi-storey building dating back to the 1980s, located in Rome. The analysis of its structure aims to effectively understand the architecture of construction, but also to gain insights applicable to global energy retrofit strategies.

This research contributes to the European RESHeat project, which aims to implement an innovative heating system in various residential buildings. The project involves optimizing and increasing the Technology Readiness Level (TRL) of a plant which synergizes a water-source heat pump (WSHP), a field of cooled photovoltaic-thermal panels (PVT), a dry cooler for heat dissipation in summer and the potential transformation of WSHP into a dual source. In addition, thermal storage units, specifically non-underground and of reduced capacity in the Italian demo site, were utilized, while underground thermal storage units were employed in the Polish case studies.

This article focuses on the Italian demo site, chosen for its representativeness of an extensive part of the urban environment in Mediterranean area, since the study will serve as a foundational step for future extension of findings to the entire building stock of the aforementioned climate zone. The purpose is to devise effective preservation approaches that can be standardized for social housing, representing a noteworthy progression towards a sustainable and climate-resilient built environment.

The methodology began with a detailed survey of building, installed systems, and tenant habits [56]. Subsequently, mathematical models for the building and for the different components involved in the current and the designed energy systems were developed, calibrated and validated. The building model was created using SketchUp software and imported into tool of TRNSYS software named TRNBuild, which added gains, losses, heating and infiltration for each housing unit. After the existing building model being completed, the RESHeat system was implemented.

As expected an overall annual load increase was achieved, attributable to the introduction of cooling. Apart from that, simulations demonstrated that the combined use of HP-PVT-TES results in an Coefficient of Performance (COP) averaged over a year of 6.1, with a summer Seasonal COP (sCOP) of 7. The high COP, along with the combined production of thermal and electrical energy from PVT, led to a Primary Energy Saving (PES) of 36 % and a solar renewable energy coverage of 96 %. Considering the electricity produced by PVTs and self-consumed, as well as the cubic meters of methane not consumed by the boiler during the heating period, a reduction in emissions of 62 tCO2eq was achieved. In conclusion, the application of the proposed scheme will improve heating system's effectiveness and also boost the general wellbeing of inhabitants by the inclusion of cooling during the summer season.

At present the installation of the new RESHeat system has been completed. It is expected to provide data that will be used to automatically update the dynamic model calibrations. This process, along with creating the system's Digital Twin for building management, establishes the foundation for reproducing the scenario at different scales in the social housing landscape. In future developments, the research will encompass a broader outlook, indicating a uniform climate control system for the analyzed building typology. Such an application would allow comprehensive forecasts and detailed design solutions in the planning phase and management solutions in the operation through the Digital Twin.

CRediT authorship contribution statement

Andrea Vallati: Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Miriam Di Matteo:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Data curation. **Mukund Sundararajan:** Supervision, Methodology, Conceptualization. **Francesco Muzi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Investigation, Data curation. **Costanza Vittoria Fiorini:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The research was supported by European Commission and is a part of the HORIZON 2020 project RESHeat. This project received funding from the European Union's Horizon 2020 program in the field of research and innovation on the basis of grant agreement No. 956255.

References

[1] Perera JL, Nick LTD, Scartezzini VM. Impacts of extreme climate conditions due to climate change on the energy system design and operation. Energy Proc 2019;159:358–63. https://doi.org/10.1016/j.egypro.2019.01.002.

[2] European Commission. Communication from the commission to the European parliament, the European council, the council, the European economic and social committee and the committee of the regions. The European Green Deal; 2019. Available online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF. [Accessed 23 November 2022].

[3] EU agenda. 2023. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_it. [Accessed 11 February 2023].

[4] Annibaldi A, Cucchiella F, De Bernardinis P, Gastaldi M, Rotilio M. An integrated sustainable and profitable approach of energy efficiency in heritage buildings. J Clean Prod 2020;251:119516. https://doi.org/10.1016/j.jclepro.2019.119516.

[5] Galatioto A, Ciulla G, Ricciu R. An overview of energy retrofit actions feasibility on Italian historical buildings. Energy 2017;137:991–1000. https://doi.org/10.1016/j.energy.2016.12.103.

[6] European Commission. JRC Science for Policy Report. EU challenges for reducing fossil fuels use in buildings. The role of building insulation and low-carbon heating systems in 2030 and 2050. 2021.

[7] Treichel C, Cruickshank CA. Greenhouse gas emissions analysis of heat pump water heaters coupled with air-based solar thermal collectors in Canada and the United States. Energy Build 2021;231:110594. https://doi.org/10.1016/j.enbuild.2020.110594.

[8] Claußˆ J, Stinner S, Sartori I, Georges L. Predictive rule-based control to activate the energy flexibility of Norwegian residential buildings: case of an air-source heat pump and direct electric heating. Appl Energy 2019;237:500–18. https://doi.org/10.1016/j.apenergy.2018.12.074.

[9] Østergaard PA, Andersen AN. Economic feasibility of booster heat pumps in heat pump-based district heating systems. Energy 2018;155:921–9. https://doi.org/10.1016/j.energy.2018.05.076.

[10] Sarbu I, Sebarchievici C. General review of ground-source heat pump systems for heating and cooling of buildings. Energy Build 2014;70:441–54. https://doi.org/10.1016/j.enbuild.2013.11.068.

[11] Desideri U, Sorbi N, Arcioni L, Leonardi D. Feasibility study and numerical simulation of a ground source heat pump plant, applied to a residential building. Appl Therm Eng 2011;31:3500–11. https://doi.org/10.1016/j.applthermaleng.2011.07.003.

[12] Chaturvedi SK, Gagrani VD, Abdel-Salam TM. Solar-assisted heat pump – a sustainable system for low-temperature water heating applications. Energy Convers Manag 2014;77:550–7. https://doi.org/10.1016/j.rser.2015.10.157.

[13] Han Z, Qu L, Ma X, Song X, Ma C. Simulation of a multi-source hybrid heat pump system with seasonal thermal storage in cold regions. Appl Therm Eng 2017;116:292–302. https://doi.org/10.1016/j.applthermaleng.2017.01.057.

[14] Wang Q, Zhang X, Zhang H, Ma Y, Zhao S. Optimization of solar-assisted GWHP system based on the Trnsys model in cold regions. Renew Energy 2022;196:1406–17. https://doi.org/10.1016/j.renene.2022.07.072.

[15] Nouri G, Noorollahi Y, Yousefi H. Solar assisted ground source heat pump systems – a review. Appl Therm Eng 2019;163:114351. https://doi.org/10.1016/j.applthermaleng.2019.114351.

[16] Bakirci K, Ozyurt O, Comakli K, Comakli O. Energy analysis of a solar-ground source heat pump system with vertical closed-loop for heating applications. Energy 2011;36:3224–32. https://doi.org/10.1016/j.energy.2011.03.011.

[17] Trillat-Berdal V, Souyri B, Fraisse G. Experimental study of a ground-coupled heat pump combined with solar thermal collectors. Energy Build 2006;38:1477–84. https://doi.org/10.1016/j.enbuild.2006.04.005.

[18] Li Tao, Wang Xing, Li Guannan, Liu Yajiao, Liu Qingxia, Gong Yanfeng, Shi Lei, Hu Zhigao, Mao Qianjun. Thermal performance and energy flow analysis of a PV/T coupled ground source heat pump system. Appl Therm Eng 2024;240:122265. https://doi.org/10.1016/j.applthermaleng.2023.122265. ISSN 1359-4311.

[19] Si Q, Okumiya M, Zhang XS. Performance evaluation and optimization of a novel solar-ground source heat pump system. Energy Build 2014;70:237–45. https://doi.org/10.1016/j.enbuild.2013.11.065.

[20] Pardo N, Montero A, Martos J, Urchueguía JF. Optimization of hybrid-ground coupled and air source-heat pump systems in combination with thermal storage. Appl Therm Eng 2010;30:1073–7. https://doi.org/10.1016/j.applthermaleng.2010.01.015.

[21] Ho Shin H, Kim K, Lee M, Han C, Kim Y. Maximized thermal energy utilization of surface water-source heat pumps using heat source compensation strategies under low water temperature conditions. Energy 2023:129700. https://doi.org/10.1016/j.energy.2023.129700.

[22] Zhou F, Song Y, Ma G. Load characteristics analysis of the water source heat pump heating system using data center waste heat. Energy Convers Manag 2023;296:117679. https://doi.org/10.1016/j.enconman.2023.117679.

[23] Huang C, Wei W, Sun Y, Wang W, Li Z, Wang S, Deng S. Energy saving and peak load shifting performance of tail water source heat pump integrated with large-scale thermal storage pool space heating system in technology park. Energy Convers Manag 2023;287:117032. https://doi.org/10.1016/j.enconman.2023.117032.

[24] Ma Y, Xi J, Cai J, Gu Z. TRNSYS simulation study of the operational energy characteristics of a hot water supply system for the integrated design of solar coupled air source heat pumps. Chemosphere 2023;338:139453. https://doi.org/10.1016/j.chemosphere.2023.139453.

[25] Federation of European Heating. Ventilation and air conditioning associations. REHVA report 8-2023. Replacement of gas boilers with heat pumps, district heating. Hybrid solutions: report on the shift away from natural gas in buildings. 2023.

[26] Bagarella G, Lazzarin R, Lamanna B. Cycling losses in refrigeration equipment: an experimental evaluation. Int J Refrig 2013;36:2111–8. https://doi.org/10.1016/j.ijrefrig.2013.07.020.

[27] Schreurs T, Madani H, Zottl A, Sommerfeldt N, Zucker G. Techno-economic analysis of combined heat pump and solar PV system for multi-family houses: an Austrian case study. Energy Strategy Rev 2021;36:100666. https://doi.org/10.1016/j.esr.2021.100666.

[28] Bergamini Riccardo, Jensen Jonas Kjær, Elmegaard Brian. Thermodynamic competitiveness of high temperature vapor compression heat pumps for boiler substitution. Energy 2019;182:110–21. https://doi.org/10.1016/j.energy.2019.05.187.

[29] Li Z, Ma T, Zhao J, Song A, Cheng Y. Experimental study and performance analysis on solar photovoltaic panel integrated with phase change material. Energy 2019;178:471–86. https://doi.org/10.1016/j.energy.2019.04.166.

[30] Kuczynski Waldemar, Chliszcz Katarzyna. Energy and exergy analysis of photovoltaic panels in northern Poland. Renew Sustain Energy Rev 2023;174:113138. https://doi.org/10.1016/j.rser.2022.113138. ISSN 1364-0321.

[31] Chow TT. A review on photovoltaic/thermal hybrid solar technology. Renew Energy 2020;87(2):365–79. https://doi.org/10.1016/j.apenergy.2009.06.037.

[32] Zhou JZ, Zhao XD, Yuan YP, Li J, Yu M, Fan Y. Operational performance of a novel heat pump coupled with mini-channel PVT and thermal panel in low solar radiation. Energy Built Environ 2020;1:50–9. https://doi.org/10.1016/j.enbenv.2019.08.001.

[33] Dai N, Xu X, Li S, Zhang Z. Simulation of hybrid photovoltaic solar assisted loop heat pipe/heat pump system. Appl Sci 2017;7(2):197. https://doi.org/10.3390/app7020197.

[34] Alhuyi Nazari M, Rungamornrat J, Prokop L, Blazek V, Misak S, Al-Bahrani M, Hossein Ahmadi M. An updated review on integration of solar photovoltaic modules and heat pumps towards decarbonization of buildings. Energy for Sustainable Development 2023;72:230–42. https://doi.org/10.1016/j.esd.2022.12.018.

[35] Zisopoulos G, Nesiadis A, Atsonios K, Nikolopoulos N, Stitou D, Coca-Ortegón A. Conceptual design and dynamic simulation of an integrated solar driven thermal system with thermochemical energy storage for heating and cooling. J Energy Storage 2021;41:102870. https://doi.org/10.1016/j.est.2021.102870.

[36] Romanchenko D, Nyholm E, Odenberger M, Johnsson F. Impacts of demand response from buildings and centralized thermal energy storage on district heating systems. Sustain Cities Soc 2021;64:102510. https://doi.org/10.1016/j.scs.2020.102510.

[37] Calise F, Cappiello FL, d'Accadia MD, Petrakopoulou F, Vicidomini M. A solar-driven 5th generation district heating and cooling network with ground-source heat pumps: a hermos-economic analysis. Sustain Cities Soc 2022;76:103438. https://doi.org/10.1016/j.scs.2021.103438.

[38] Todorov O, Alanne K, Virtanen M, Kosonen R. A method and analysis of aquifer thermal energy storage (ATES) system for district heating and cooling: a case study in Finland. Sustain Cities Soc 2020;53:101977. https://doi.org/10.1016/j.scs.2019.101977.

[39] Calama-González CM, Symonds P, León-Rodríguez ÁL, Suárez R. Optimal retrofit solutions considering thermal comfort and intervention costs for the Mediterranean social housing stock. Energy Build 2022;259:111915. https://doi.org/10.1016/j.enbuild.2022.111915.

[40] Hernández H, Molina C. Analyzing energy poverty and carbon emissions in a social housing complex due to changes in thermal standards. Energy for Sustainable Development 2023;77:101347. https://doi.org/10.1016/j.esd.2023.101347.

[41] Mauri L, Vallati A, Ocłoń P. Low impact energy saving strategies for individual heating systems in a modern residential building: a case study in Rome. J Clean Prod 2019;2014:791–802. https://doi.org/10.1016/j.jclepro.2018.12.320.

[42] Vollaro ADL, Galli G, Vallati A, Romagnoli R. Analysis of thermal field within an urban canyon with variable thermophysical characteristics of the building's walls. J Phys Conf 2015;655:012056. https://doi.org/10.1088/1742-6596/655/1/012056.

[43] Gaglia AG, Dialynas EN, Argiriou AA, Kostopoulou E, Tsiamitros D, Stimoniaris D, Laskos KM. Energy performance of European residential buildings: energy use, technical and environmental characteristics of the Greek residential sector – energy conservation and CO_2 reduction. Energy Build 2019;183:86–104. https://doi.org/10.1016/j.enbuild.2018.10.042.

[44] Kampelis N, Gobakis K, Vagias V, Kolokotsa D, Standardi L, Isidori D, Cristalli C, Montagnino FM, Paredes F, Muratore P, Venezia L, Kyprianou Dracou M, Montenon A, Pyrgou A, Karlessi Theoni. Mat Santamouris, Evaluation of the performance gap in industrial, residential & tertiary near-Zero energy buildings. Energy Build 2017;148:58–73. https://doi.org/10.1016/j.enbuild.2017.03.057.

[45] Vallati A, Morganti M, Causone F, Mannucci S, Fiorini CV, Di Matteo M, Muzi F. Building archetype characterization for mass-housing energy efficiency through a UBEM approach. J Phys Conf 2023;2600:082030. https://doi.org/10.1088/1742-6596/2600/8/082030. 2600, Optimization at building & urban scale.
[46] Hernandez-Cruz P, Giraldo-Soto C, Escudero-Revilla C, Hidalgo-Betanzos JM, Flores-Abascal I. Energy efficiency and energy performance gap in centralized social housing buildings of the Basque Country. Energy Build 2023;298:113534. https://doi.org/10.1016/j.enbuild.2023.113534.
[47] Zanetti E, Bordignon S, Conte R, Bisi A, Azzolin M, Zarrella A. Experimental and numerical analysis of a CO2 dual-source heat pump with PVT evaporators for residential heating applications. Appl Therm Eng 2023;233:121165. https://doi.org/10.1016/j.applthermaleng.2023.121165.
[48] Bisengimana E, Zhou J, Binama M, Nyiranzeyimana G, Yuan Y. Numerical investigation of PVT coverage on an integrated building-solar-heat pump system: technical and economic study. Sol Energy 2023;249:507–20. https://doi.org/10.1016/j.solener.2022.12.005.
[49] Bordignon S, Spitler JD, Zarrella A. Simplified water-source heat pump models for predicting heat extraction and rejection. Renew Energy 2023:119701. https://doi.org/10.1016/j.renene.2023.119701.
[50] Jonas D, Lämmle M, Theis D, Schneider S, Frey G. Performance modeling of PVT collectors: implementation, validation and parameter identification approach using TRNSYS. Sol Energy 2019;193:51–64.
[51] Latorre-Biel Juan-Ignacio, Jimémez Esther, García Jorge L, Martínez Eduardo. Emilio Jiménez, Julio Blanco, Replacement of electric resistive space heating by an air-source heat pump in a residential application. Environmental amortization. Build Environ 2018;141:193–205. https://doi.org/10.1016/j.buildenv.2018.05.060.
[52] Jin Luo, Xue Wei, Shao Haibing. Thermo-economic comparison of coal-fired boiler-based and groundwater-heat-pump based heating and cooling solution – a case study on a greenhouse in Hubei, China. Energy Build 2020;223:110214. https://doi.org/10.1016/j.enbuild.2020.110214.
[53] RESHeat – Renewable Energy System For Residential Building Heating And Electricity Production, https://resheat.eu/en/home.
[54] Vallati A, Ocłoń P, Colucci C, Mauri L, Vollaro RDL, Taler J. Energy analysis of a thermal system composed by a heat pump coupled with a PVT solar collector. Energy 2019;174:91–6. https://doi.org/10.1016/j.energy.2019.02.152.
[55] Ocłoń P, Ławryńczuk M, Czamara M. A new solar assisted heat pump system with underground energy storage: modelling and optimization. Energies 2021;14:16. https://doi.org/10.3390/en14165137.
[56] Vallati A, Fiorini CV, Grignaffini S, Ocłon′ P, Di Matteo M, Kobylarczyk J. Energy retrofit optimization for social building in temperate climate zone. Energy Build 2023;282:112771. https://doi.org/10.2139/ssrn.4240479.
[57] Grant agreement number 956255, renewable energy system for residential building heating and electricity production (RESHeat). https://cordis.europa.eu/project/id/956255/it. [Accessed 10 October 2023].
[58] UNI 10200 – Impianti termici centralizzati di climatizzazione invernale e produzione di acqua calda sanitaria – Criteri di ripartizione delle spese di climatizzazione invernale ed acqua calda sanitaria.
[59] Manuale degli impianti idrico sanitari, Bearzi Vittorio. Tecniche nuove. second ed. 1999.
[60] D.P.R 412/93 – Decreto del Presidente della Repubblica del 26 agosto. 1993. p. 412.
[61] Zenhäusern D. Key performance Indicators for PVT systems SHC task 60/report D1. nov 2020. https://doi.org/10.18777/ieashc-task60-2020-0007.
[62] UNI TS 11300-2. Energy performance of buildings – part2: valuation of primary energy need and of system efficiencies for space heating, domestic hot water production, ventilation and lighting for non-residential buildings..
[63] ISPRA. Indicatori di efficienza e decarbonizzazione del sistema energetico nazionale e del settore elettrico. 2022. p. 363.
[64] Trnsys 17 – a TraNsient system simulation program, user manual. Volume 5: multizone building modeling with type 56 and TRNBuild. Version 17.1, solar energy laboratory. Madison, USA: University of Wisconsin; 2012.
[65] ISO 6946:2017 - Building components and building elements — Thermal resistance and thermal transmittance — Calculation methods.
[66] UNI 10351 – Materiali da costruzione – Proprietà termoigrometriche – Procedura per la scelta dei valori di progetto.
[67] ISO 9869-1 – Isolamento termico – Elementi per l'edilizia – Misurazione in situ della resistenza termica e della trasmittanza termica – Parte 1: Metodo del termoflussimetro.
[68] Sun Vat, Asanakham Attakorn, Deethayat Thoranis, Kiatsiriroat Tanongkiat. A new method for evaluating nominal operating cell temperature (NOCT) of unglazed photovoltaic thermal module. Energy Rep 2020;6:1029–42. https://doi.org/10.1016/j.egyr.2020.04.026. ISSN 2352-4847.
[69] Znshinesolar 5BB bifacial double glass mono PV module datasheet.
[70] Meteoblue weather archive, https://www.meteoblue.com/it/tempo/historyclimate/weatherarchive (accessed on 22/October/2023).
[71] UNI TS 9182 – hot and cold water supply and distribution installations – design, installation and testing..
[72] Oilon, Installation and operation manual RE 28-48, RE 56-96 3 august 2022.
[73] Abdulla Hind, Sleptchenko Andrei, Nayfeh Ammar. Photovoltaic systems operation and maintenance: a review and future directions. Renew Sustain Energy Rev 2024;195:114342. https://doi.org/10.1016/j.rser.2024.114342.
[74] Wan Letao, Zhao Liqian, Xu Wensheng, Guo Feihong, Jiang Xiaoxiang. Dust deposition on the photovoltaic panel: a comprehensive survey on mechanisms, effects, mathematical modeling, cleaning methods, and monitoring systems. Sol Energy 2024;268:112300. https://doi.org/10.1016/j.solener.2023.112300.
[75] Mauro Alfonso William, Pelella Francesco, Viscito Luca. Performance degradation of air source heat pumps under faulty conditions. Case Stud Therm Eng 2023;45:103010. https://doi.org/10.1016/j.csite.2023.103010.
[76] ARERA https://www.arera.it/dati-e-statistiche.
[77] ARER. framework for built environment: a review of key enablers. Energies 2024.
[78] Piras G, Agostinelli S, Muzi F. Digital Twin framework for built environment: a review of key enablers. Energies 2024;17:436. https://doi.org/10.3390/en17020436.
[79] Yu Shui, Liu Xueyan, Li Ruizhe, Yin Zekai, Chen Zhijie, Han Fuhong, Li Siyao. Demand side management full season optimal operation potential analysis for coupled hybrid photovoltaic/thermal, heat pump, and thermal energy storage systems. J Energy Storage 2024;80:110375. https://doi.org/10.1016/j.est.2023.110375. ISSN 2352-152X.
[80] Li Tao, Wang Xing, Li Guannan, Liu Yajiao, Liu Qingxia, Gong Yanfeng, Shi Lei, Hu Zhigao, Mao Qianjun. Thermal performance and energy flow analysis of a PV/T coupled ground source heat pump system. Appl Therm Eng 2024;240:122265. https://doi.org/10.1016/j.applthermaleng.2023.122265. ISSN 1359-4311.
[81] Pelella Francesco, Zsembinszki Gabriel, Viscito Luca, Mauro Alfonso William, Cabeza Luisa F. Thermo-economic optimization of a multi-source (air/sun/ground) residential heat pump with a water/PCM thermal storage. Appl Energy 2023;331:120398. https://doi.org/10.1016/j.apenergy.2022.120398. ISSN 0306-2619.
[82] Qiu Guodong, Li Kuangfu, Cai Weihua, Yu Shipeng. Optimization of an integrated system including a photovoltaic/thermal system and a ground source heat pump system for building energy supply in cold areas. Appl Energy 2023;349:121698. https://doi.org/10.1016/j.apenergy.2023.121698. ISSN 0306-2619.
[83] Chang Shasha, Feng Guohui, Zhang Lei, Huang Kailiang, Li Ainong. Multi-objective optimization of a photovoltaic thermal curtain wall assisted dual-source heat pump system. Appl Therm Eng 2023;222:119845. https://doi.org/10.1016/j.applthermaleng.2022.119845. ISSN 1359-4311.
[84] Wang Yubo, Quan Zhenhua, Zhao Yaohua, Wang Lincheng, Liu Zichu. Performance and optimization of a novel solar-air source heat pump building energy supply system with energy storage. Appl Energy 2022;324:119706. https://doi.org/10.1016/j.apenergy.2022.119706. ISSN 0306-2619.
[85] Corberán José M, Cazorla-Marín Antonio, Marchante-Avellaneda Javier, Montagud Carla. Dual source heat pump, a high efficiency and cost-effective alternative for heating, cooling and DHW production. Int J Low Carbon Technol June 2018;13(2):161–76. https://doi.org/10.1093/ijlct/cty008.
[86] Liu Lei, Liu Wenjie, Yao Jian, Jia Teng, Zhao Yao, Dai Yanjun. Life cycle energy, economic, and environmental analysis for the direct-expansion photovoltaic-thermal heat pump system in China. J Clean Prod 2024;434:139730. https://doi.org/10.1016/j.jclepro.2023.139730. ISSN 0959-6526.
[87] Pintanel MT, Martínez-Gracia A, Uche J, del Amo A, Bayod-Rújula ÁA, Usón S, Arauzo I. Energy and environmental benefits of an integrated solar photovoltaic and thermal hybrid, seasonal storage and heat pump system for social housing. Appl Therm Eng 2022;213:118662. https://doi.org/10.1016/j.applthermaleng.2022.118662.
[88] Qu Minglu, Yan Xufeng, Wang Haiyang, Hei Yingxiao, Liu Hongzhi, Zhao Li. Energy, exergy, economic and environmental analysis of photovoltaic/thermal integrated water source heat pump water heater. Renew Energy 2022;194:1084–97. https://doi.org/10.1016/j.renene.2022.06.010.
[89] Martorana Francesca, Bonomolo Marina, Leone Giuliana, Monteleone Francesco, Zizzo Gaetano, Beccali Marco. Solar-assisted heat pumps systems for domestic hot water production in small energy communities. Sol Energy 2021;217:113–33. https://doi.org/10.1016/j.solener.2021.01.020. ISSN 0038-092X.
[90] Del Amo A, Martínez-Gracia A, Pintanel T, Bayod-Rújula AA, Torné S. Analysis and optimization of a heat pump system coupled to an installation of PVT panels and a seasonal storage tank on an educational building. Energy Build 2020;226:110373. https://doi.org/10.1016/j.enbuild.2020.110373. ISSN 0378-7788.
[91] Lazzarin Renato, Noro Marco. Photovoltaic/Thermal (PV/T)/ground dual source heat pump: optimum energy and economic sizing based on performance analysis. Energy Build 2020;211:109800. https://doi.org/10.1016/j.enbuild.2020.109800. ISSN 0378-7788.
[92] Obalanlege Mustapha A, Xu Jingyuan, Markides Christos N, Mahmoudi Yasser. Techno-economic analysis of a hybrid photovoltaic-thermal solar-assisted heat pump system for domestic hot water and power generation. Renew Energy 2022;196:720–36. https://doi.org/10.1016/j.renene.2022.07.044. ISSN 0960-1481.
[93] Dannemand Mark, Sifnaios Ioannis, Tian Zhiyong, Furbo Simon. Simulation and optimization of a hybrid unglazed solar photovoltaic-thermal collector and heat pump system with two storage tanks. Energy Convers Manag 2020;206:112429. https://doi.org/10.1016/j.enconman.2019.112429. ISSN 0196-8904.
[94] Jelić Marko, Batić Marko, Krstić Aleksandra, Bottarelli Michele, Mainardi Elena. Comparative analysis of metaheuristic optimization approaches for multisource heat pump operation. Renew Sustain Energy Rev 2023;188:113871. https://doi.org/10.1016/j.rser.2023.113871. ISSN 1364-0321.
[95] Dermentzis Georgios, Ochs Fabian, Franzoi Nicola. Four years monitoring of heat pump, solar thermal and PV system in two net-zero energy multi-family buildings. J Build Eng 2021;43:103199. https://doi.org/10.1016/j.jobe.2021.103199. ISSN 2352-7102.
[96] Masson-DelmotteP V, Zhai HO, Pörtner D, Roberts J, Skea PR, Shukla T, Waterfield. Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of, 1.5; 2018.
[97] Franzoi N, Prada A, Verones S, Baggio P. Enhancing PV self-consumption through energy communities in heating-dominated climates. Energies 2021;14(14):4165.
[98] Nasouri Masoud, Bidhendi Gholamreza Nabi, Amiri Mohammad Javad, Delgarm Navid, Delgarm Saeed, Azarbad Khadijeh. Performance-based Pareto

optimization and multi-attribute decision making of an actual indirect-expansion solar-assisted heat pump system. J Build Eng 2021;42:103053. https://doi.org/10.1016/j.jobe.2021.103053. ISSN 2352-7102.

[99] Fang Guiyin, Hu Hainan, Liu Xu. Experimental investigation on the photovoltaic–thermal solar heat pump air-conditioning system on water-heating mode. Exp Therm Fluid Sci 2010;34(6):736–43. https://doi.org/10.1016/j.expthermflusci.2010.01.002. ISSN 0894-1777.

[100] Ji Jie, Pei Gang, Chow Tin-tai, Liu Keliang, He Hanfeng, Lu Jianping, Han Chongwei. Experimental study of photovoltaic solar assisted heat pump system. Sol Energy 2008;82(1):43–52. https://doi.org/10.1016/j.solener.2007.04.006. ISSN 0038-092X.

[101] Ramos Alba, Chatzopoulou Maria Anna, Guarracino Ilaria, Freeman James, Markides Christos N. Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban nvironment. Energy Convers Manag 2017;150:838–50. https://doi.org/10.1016/j.enconman.2017.03.024. ISSN 0196-8904.