



FuturHist

HVAC system and management solutions for demo cases



Project Overview

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Executive Summary

This report presents a series of active system solutions that can be applied to Historic Buildings, in particular to those Historic Buildings typologies defined in task 1.2 and reported in deliverable 1.2, which are representative of the project demo buildings. The active systems considered are meant to cover the heating, cooling and Domestic Hot Water demand of the buildings, possibly exploiting locally produced renewable energy.

These active system solutions range from more complete air/water heat pump systems, which can deliver space heating, cooling, and Domestic Hot Water to users, to other systems, such as mechanical ventilation with heat recovery. In addition, the third active system solution taken into account considers the connection to a District Heating Network for covering the building's space heating and Domestic Hot Water demand. The last active system considered is a water-loop heat pump system, a heat pump-based solution which, however, presents some characteristics that could be of particular interest for its application in Historic Buildings.

The first three active system solutions, developed initially targeting the building typologies of the five demonstration buildings, are those that will be implemented in the five demonstration buildings of the project after the planned renovations. On this regard, the active system solutions and their control presented in this document constitute the starting point for the development of the solutions that will be implemented in the demonstration buildings within WP5, with some adjustments related to the specificities of each demonstration site. As the building typologies identified in task 1.2 are representative of many Historic Buildings in the specific countries, the active system solutions presented in this document can be considered applicable to a large number of Historic Buildings.

In addition to the general description of the solutions and the used control logic, their performance is assessed through dynamic simulations and using mainly the Performance Indicators defined in task 1.6.

The active system solutions developed are meant to be modular, with the possibility to scale them to respond to Historic Buildings of different sizes and, in general, with different thermal demands. Moreover, the dynamic simulations are performed using both present and future climatic conditions of the demo locations. This is to verify that the considered active system solutions are appropriate and able to ensure the covering of buildings' thermal demands also in a future climatic scenario.

Overall, the main objectives of this document are:

- To develop and document a series of active system solutions suitable for Historic Buildings;
- To analyse their performance from dynamic simulation;
- To define a starting point for the development of the active system solutions to be deployed in the project demonstration buildings.

In comparison to the systems currently installed, the main advantages of the developed ones are the possibility to cover the building's thermal needs with a higher efficiency (i.e. with lower energy consumption), and the improved indoor environmental quality. These advantages are achieved while respecting the buildings' heritage value.

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Abbreviations and definitions

Archetype building	Theoretically defined building based on the typical or average census values of the overall characteristics of the building type
Active system	In this context, any system used to cover buildings' thermal needs. More specifically, any system used to cover heating, cooling, domestic hot water and ventilation demand of a building.
AHU	Air Handling Unit
AWHP	Air/Water Heat Pump
Building envelope	The "skin" of a building, consisting of exterior facing walls, roof, windows, and lower floor slab.
Building typology	A set of buildings with common properties (e.g., age of construction, geometry, thermo-physical properties, and energy performance) (IEE Project TABULA, 2012).
COP	Coefficient Of Performance
D	Project Deliverable
DCW	Domestic Cold Water, i.e., the cold water entering the building from the aqueduct
Demonstrator building	A real building belonging to a typology which is used to demonstrate retrofitting solutions (also referred to as "demo case" - DC).
DHN	District Heating Network
DHNC	District Heating Network Connection
DHW	Domestic Hot Water, i.e., heating water for domestic or commercial purposes other than space heating and process requirements (ASHRAE, 2024).
DSO	Distributor System Operator
Ed	In the tables, Energy demand
EER	Energy Efficiency Ratio
Ef	In the tables, Final Energy consumption
el	In the tables, used as an abbreviation for "electric" or "electrical"
Energy consumption for heating and cooling	Energy input required to satisfy the heating and cooling demand of a building. This quantity considers also efficiency and losses of systems and user behaviour (Hotmaps, 2020).
Energy demand for heating and cooling	Calculated amount of energy required to cover heating and cooling of a building (Hotmaps, 2020)
Energy retrofit	A general concept for all types of renovations where reduced energy consumption is the main goal for the renovation (Eriksson, 2021). It is used for the entire renovation process, from planning to evaluation, and is closely related to sustainable renovation (Thuvander et al., 2012). Sustainable renovation of existing buildings is a way of extending the lifespan of a building and improving its living and working conditions, which includes lowering the energy used for those purposes (Asdrubali and Desideri, 2018, chapter 9).
Ep (ren, nren, tot)	In the tables, Primary energy consumption (renewable, non-renewable, total)
EU	European Union
fGHG	Greenhouse Gas emission factor
fp (ren, nren, tot)	Primary energy factor (renewable, non-renewable, total)
GHG	Greenhouse Gas (emissions)
Heritage value	Aspect of importance that individuals or society assign(s) to a building (EN 16883:2017). Note 1 to entry: Heritage values can be of aesthetic, historic, scientific, cultural, social or spiritual nature. These types of heritage values include

Historic Building

various aspects, for example: architectural, artistic, economic, symbolic, technological, use, etc.

Note 2 to entry: The heritage assigned value can change according to circumstance, e.g., how the judgement is made, the context and the moment in time. Value should always be indicated by its qualifying type.

Building of heritage significance (EN 16883:2011)

Note 1 to entry: A historic building does not necessarily have to be statutorily designated as cultural heritage.

Note 2 to entry: Historic buildings are a specific form of objects, as defined in EN 15898:2011, 3.1.3.

HP

Heat Pump

HR

Heat Recovery

HVAC

Heating, Ventilation and Air Conditioning system

HX

Heat Exchanger

IEQ

Indoor Environmental Quality

Joule effect

It stands for the transformation of electrical energy into thermal energy in an emission unit. One example is an electric radiator, where an electrical resistance is used as the heating element.

KPI

Key Performance Indicator

LCA

Life Cycle Assessment

mHPs

Micro Heat Pumps (a different name to call the WAHPs used in some graphs)

MVHR

Mechanical Ventilation with Heat Recovery system

Multi-split

Air-Air heat pump system featuring one outdoor unit connected to more than one indoor unit.

P&ID

Piping and Instrumentation Diagram

PI

Performance Indicator

PV

Photovoltaic system

QH&C_XF

Thermal energy delivered for Heating and Cooling to the dwelling XF

RES

Renewable Energy System

RH

Relative Humidity

SC

Space Cooling

SH

Space Heating

SoC

State of Charge (Battery)

SRI

Smart Readiness Indicator

T

Project Task

th

In the tables, used as an abbreviation for "thermal"

WAHP

Water/Air Heat Pump

WLHP

Water Loop Heat Pump system

WP

Project Work Package

WWHP

Water/Water Heat Pump

1. Introduction

1.1. Background

FuturHist addresses a major challenge in Europe's path to climate neutrality: the energy retrofitting of historic buildings. Representing a significant share of European building stock, many of these buildings remain in active use as homes, offices, cultural institutions, and public facilities. Despite their cultural and architectural value, they often have poor energy performance due to outdated construction, limited thermal efficiency, and other economic, technical and legislative constraints. FuturHist aims to demonstrate that energy efficiency and heritage preservation are not mutually exclusive but can be successfully combined through the application of well-adapted retrofit strategies.

Reducing the energy demand of historic buildings can be approached from two complementary directions. On one hand, improvements to passive systems—such as better insulation of the building envelope, including walls, roofs, basements, and windows—can significantly reduce heat loss and improve indoor comfort. On the other hand, optimising or implementing active systems such as heating, ventilation, and air conditioning (HVAC) can further enhance energy performance, particularly when these systems are designed to work efficiently within the constraints of heritage buildings.

The principal goal of FuturHist is to facilitate the mass renovation of historic buildings across Europe, regardless of whether they fall under strict conservation regulations or not, always respecting the building's heritage value. While there are already many examples of successful retrofitting projects in historic buildings, these are often site-specific and rely heavily on expert knowledge and bespoke solutions. This makes it difficult to scale such interventions or to develop broadly applicable guidelines. FuturHist addresses this challenge by developing a methodology based on building typologies—groups of buildings that share common features such as construction period, climatic conditions, size, and architectural values (materials, geometry).

By focusing on typologies, the project aims to create tailored intervention strategies that can be applied more systematically, while still respecting the unique character of each building. This typology-based approach makes it possible to recommend retrofit solutions that are both effective and compatible with heritage values, thus bridging the gap between energy performance and conservation.

Ultimately, FuturHist contributes to the broader goal of the sustainable transformation of Europe's existing building stock. Its outcomes are designed to support practitioners (such as architects and engineers), building owners, as well as policymakers, including planners and heritage authorities, in making informed decisions about energy retrofits. Researchers will also

benefit from the databases and tools made available by the project to facilitate effective and sensitive renovation strategies for historic buildings across Europe.

1.2. Objectives

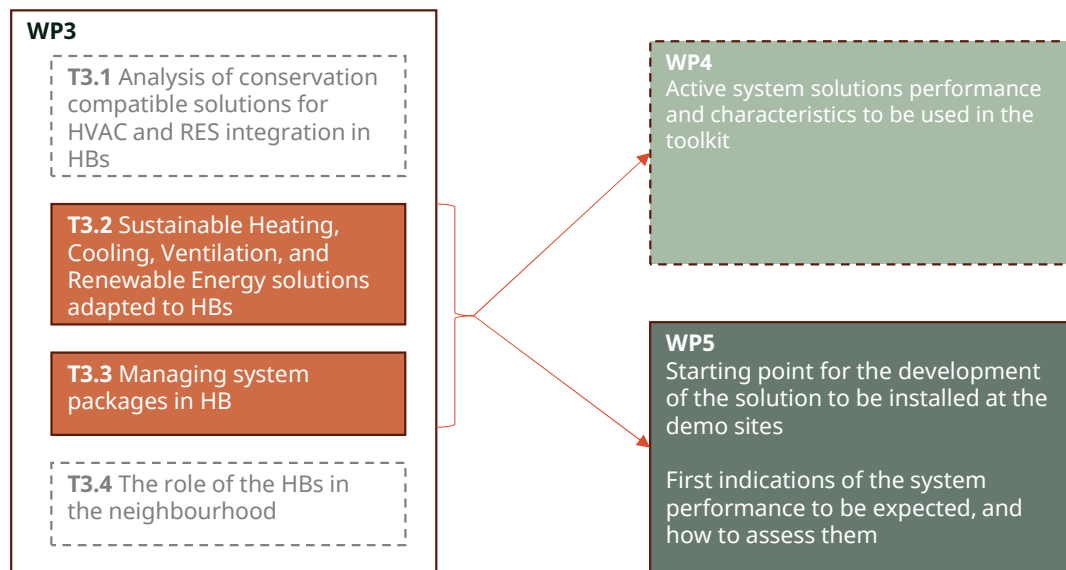
The scope of tasks 3.2 and 3.3 that is documented in this deliverable D3.4 is the development of 3-5 active system solutions (with active system solutions mainly referring to solutions to cover heating, cooling, ventilation and Domestic Hot Water thermal demands, with the eventual integration of Renewable Energy Systems) adapted to Historic Buildings (task 3.2), and the related system control (task 3.3). Solutions which can be modular, hence scalable, are developed. This allows for the integration of solutions in Historic Buildings of different sizes and, more generally, with varying thermal demands, making the solutions applicable to a large number of Historic Buildings. The building used as targets will be the building typologies identified in T1.2 and reported in D1.2, to which the five project demo cases belong. In this way, the active system solutions developed are (and will be) used as a starting point for developing the active system solutions to be applied to the demo cases. Some adaptations will be necessary to translate the design of the active system solution for the building typology into the real implementation at the demo and are expected to account for the specificities of each demo case. To clarify the similarities and the differences between the active system solutions developed, modelled and simulated within tasks 3.2 and 3.3, and the real implementation at the demonstration sites, a dedicated section with the title *"Relation with the future system in the XX demo"* is reported at the end of the description of each active system solution.

Within tasks 3.2 and 3.3, the active system solutions identified are modelled and simulated using dynamic simulation software. The simulations account not only for the actual climatic conditions of the four demo locations but also for future conditions. This aims to assess the evolution of the buildings' thermal demands under the considered climatic scenario and the ability of the developed active system solutions to meet these demands in a future climatic scenario.

Regarding the system control, the objectives are: to define the main characteristics a proper control for the considered systems should have; to develop rule-based control strategies that allow for optimally managing the system and, where possible, to exploit positive synergies with a local renewable energy system (e.g., PV system).

For performance assessment, the indicators defined in T1.6 and reported in D1.6 will be used, with eventual additions to assess specific aspects of the considered systems where needed.

In addition to being used as a starting point for the development of active system solutions in the demo cases, this work will be used in the toolkit under development (WP4) to assess different active system solutions. The following figure shows the main connections with other project activities.



1.3. Organisation of the report

The report is organised as follows:

Chapter 2 describes the simulation software used, the boundary conditions assumed, the building typologies considered, the active system solutions developed, and their control logic. A dedicated section titled *“Relation with the future system in the XX demo”* is included at the end of the sections describing the different active system solutions to identify similarities and differences between the developed, modelled and simulated active system solutions and the one that will be implemented at the demonstration sites. Moreover, this chapter concludes with a section detailing the system control characteristics and the main sensors to be used to properly monitor and control the developed active system solutions, and one reporting the methodology followed to assess the Smart Readiness Indicator for the same active systems.

Chapter 3 provides an analysis of the simulation results, dividing it into four main subsections. First, the thermal energy demand for space heating, cooling and Domestic Hot Water is identified for all considered building typologies using current and future climate scenarios. Second, the active systems' operation and consumption are presented for both a single representative week and a yearly time horizon. Third, an assessment of the ability of the considered systems, sized for the current climatic conditions, to cover (where possible) cooling demand in a future climatic scenario is reported. Fourth, the Smart Readiness Indicator is assessed for all the developed active system solutions.

Chapter 4 offers conclusions and an outlook on future work.

The Annexes report first a detailed analysis of the present and selected future climatic conditions for the four cities where the demonstration buildings are located. Second, detailed Piping and Instrumentation Diagrams of the active system solutions developed that can be used as a starting point for the adaptation of these solutions for the implementation in the various demonstration

cases. Third, the input values used for the Smart Readiness Indicator calculation are reported. Fourth, primary energy factors and Greenhouse gas emission factors, relative to the different countries considered and used in the calculation, are presented.

2. Methodology

This section reports the building typologies considered as a target for the developed active system solutions, a description of the active system solutions and the related system control. Moreover, this section includes the description of the simulation software used and of the simulation boundary conditions accounted for.

2.1. Simulation software used and boundary conditions assumed

This section reports the simulation software used to model, simulate and analyse building and related Heating, Ventilation and Air Conditioning (HVAC) system performance, and the boundary conditions assumed in the definition and development of the active system solutions.

In this context, boundary conditions refer to the building typologies considered as target buildings for the application of the developed active system solutions, as well as the climatic conditions accounted for in the dynamic simulations.

Regarding the building typologies, these are those identified in task (T) 1.2 and reported in Deliverable (D) 1.2 [1].

Regarding the climatic conditions, they are representative of present and future climatic conditions of the four cities where the five demo buildings of the project are located.

As in this work, in some cases, more than one software has been used “in cascade” to analyse the performance of a building and its HVAC system, section 2.1.1.1 reports the reasons and the methodology followed for this part.

2.1.1. Simulation software used

The buildings and related active systems are modelled using different dynamic simulation software. More specifically, the Spanish Historic Building typology n. 1 (similar to the Spanish demo building located in Cordoba) and the related heat pump (HP) system developed are modelled and simulated using TRNSYS 18 [2] (also called simply TRNSYS in the following).

The Polish Historic Building typology n. 1 (similar to the Polish demo building located in Krakow) and the related connection to the local District Heating Network (DHN) are modelled and simulated using DesignBuilder [3] and TRNSYS. Similarly, the Swedish Historic Building typology n. 1 (similar to the Swedish demo building located in Linköping) and the related connection to

the local DHN and to the Water Loop Heat Pump (WLHP) system are modelled and simulated using IDA ICE [4] and TRNSYS.

The Scottish Historic Building typology n. 2 (similar to the Scottish demo building 1 located in Edinburgh) and the related mechanical ventilation system with heat recovery (MVHR) are modelled and simulated using ESP-r [5].

2.1.1.1. Simulation software used “in cascade”

As reported in the section 2.1.1, the Polish and Swedish Historic Building typologies considered in this work have been modelled using more than one software. More specifically, DesignBuilder and IDA ICE have been used to first model the building and assess its thermal demand (space heating and, eventually, Domestic Hot Water (DHW)) with an hourly time resolution over the entire year.

The resulting hourly thermal demand time series have been used as input in a TRNSYS model, which simulated the HVAC system part, its control and operation, to cover the given building thermal demand. From the TRNSYS model simulations, the overall system performance is calculated and presented in section 3.

This choice aims to use the same simulation software used in other project tasks (mainly within WP5) and those that the different partners are more familiar with. However, different simulation software presents a different level of detail in terms of the modelling of the active system part and the related control. In this sense, the use of TRNSYS allows for a detailed model of the active system part and its control and, overall, this methodology ensures a proper assessment of building and related system behaviour and performance.

Figure 1 shows the process, starting from the modelling of the building, detailing the objective, the software used and the results. Then, the building model simulation results are used as input in the TRNSYS model, where the objective is the simulation and assessment of the system performance.

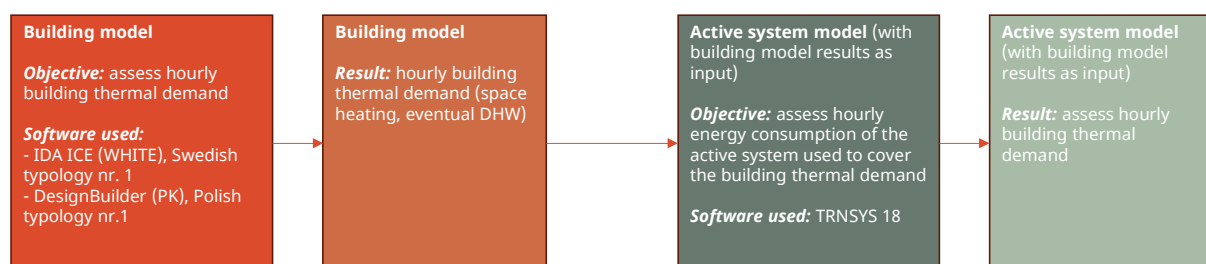


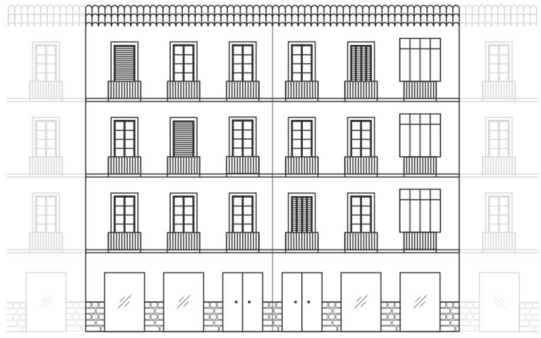
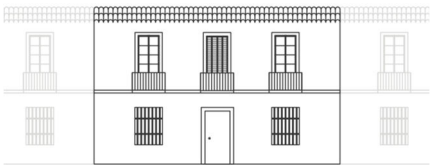
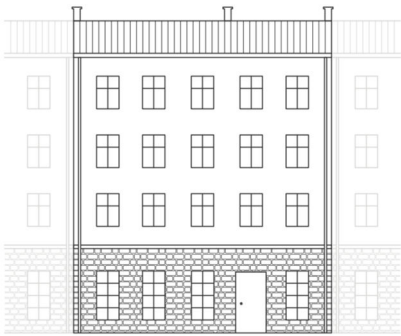
Figure 1 Methodology followed in those cases where more than one simulation software is used to obtain building and related system performance, highlighting the building and active system models, their objectives, the software used and the related results

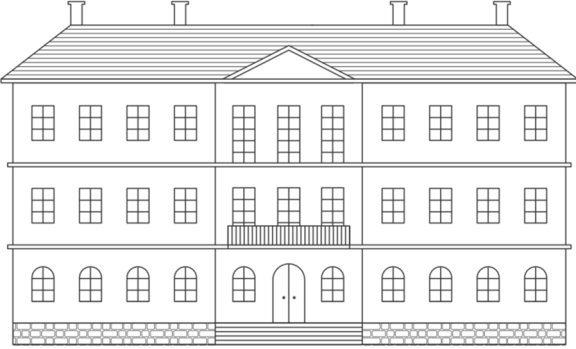
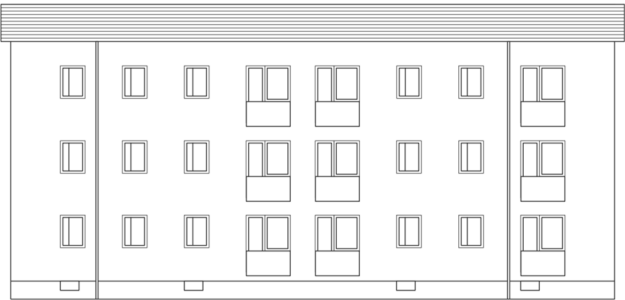
2.1.2. Building typologies considered

The development of an active system solution should always start by identifying the building (or building typology) that constitutes the target and the thermal demand(s) to be met.

In T1.2, nine building typologies have been identified. For each country, one building typology is defined as the one representative of the demo site (except for Scotland, which has two demo sites; therefore, two typologies are defined). Moreover, an additional building typology is defined for each country, resulting in a total of nine building typologies. The Table 1, taken from D1.2, presents the nine building typologies.

Table 1 Icons and names of the nine typologies defined in T1.2 and reported in D1.2

Icon	Typology
	Casa de pisos Spanish terraced tenement building (1600-1920)
	Patio de vecinos Spanish terraced courtyard tenement building (1600-1920)
	Kamienica Polish terraced tenement building (1750-1945)

	<i>Willa miejska</i> <i>Polish garden-city/urban villa</i> <i>(1900-1945)</i>
	<i>Monumentalbyggnad</i> <i>Swedish monumental public building</i> <i>(1850-1920)</i>
	<i>Flerbostadshus funktionalism</i> <i>Swedish functionalist multi-family housing block</i> <i>(1920-1945)</i>
	<i>Georgian cottage</i> <i>Scottish Georgian detached cottage</i> <i>(1750-1850)</i>

	<i>Georgian tenement</i> <i>Scottish Georgian terraced tenement building</i> <i>(1750-1850)</i>
	<i>Victorian terraced house</i> <i>Scottish Victorian terraced house</i> <i>(1850-1920)</i>

The active system solutions developed in T3.2 focus on the building typologies to which the demo buildings belong. Therefore, based on the previous Table 1, typologies nos. 1, 3, 5 and 8 are considered.

2.1.2.1. Indoor temperature set point considered

The indoor temperature set point considered in the simulations depends on a case-by-case basis. Although this approach limits eventual comparison between the simulation results of the different buildings and related active systems, it has been chosen to be aligned with the indoor temperature set point fixed in general by the different national regulations.

On the other side, some analysis performed needs a constant indoor set point temperature. This is valid for the Spanish simulations of the building and an ideal space heating and cooling system that was performed initially to extrapolate the peak building thermal loads in space heating (SH) and cooling (SC) mode to be used in the AWP system sizing.

Moreover, also the analysis regarding the optimisation of the system control in the DHN connection case is done with a constant indoor set point temperature and the same is valid also for the analysis of the case featuring the Water Loop Heat Pump system.

The Table 2 summarises the indoor temperature set point used for all the considered cases.

Table 2 Indoor temperature set points considered for the different simulations with different building typologies and active systems. In red: indoor temperature set points used in combination with an ideal space heating and cooling system to assess the peak building thermal demands, which are then used to size the AWHP system

Building typology	Climatic variable	
	Winter	Summer
Spanish typology n. 1	17 °C (from 23:00 to 07:00) 20 °C (from 7:00 to 23:00) 20 °C (from 00:00 to 24:00)	27 °C (from 00:00 to 07:00) +inf ¹ °C (from 07:00 to 15:00) 25 °C (from 15:00 to 23:00) 27 °C (from 23:00 to 24:00) 26 °C (from 00:00 to 24:00)
Polish typology n. 1	21 °C (from 00:00 to 24:00)	-
Swedish typology n. 1	21 °C (from 00:00 to 24:00)	-
Scottish typology n. 1	21 °C (from 07:00 to 23:00 during weekend days and holidays) 21 °C (from 07:00 to 09:00 and from 17:00 to 23:00 during working days)	-

2.1.3. Climatic conditions considered

The climatic conditions of the four cities (Cordoba, Krakow, Linköping, Edinburgh) in which the demo buildings are located are taken from Meteonorm software version 8 [6]. Each climatic file contains the hourly values for an entire year of a series of climatic variables (e.g., ambient temperature, absolute and relative humidity).

As the scope of the work is to assess the behaviour and the capacity of the developed active system solutions to ensure the covering of buildings' thermal demand not only in the current climatic scenario but also in the future one, dynamic simulations are performed accounting for two different climates: the current one (marked as "Contemporary" in Meteonorm 8) and a future one. As a future climate scenario, the one defined by IPCC RCP 8.5 in the year 2070 is considered. The choice of which IPCC future climate scenario to consider is arbitrary. In this work, the RCP 8.5 scenario is considered as it is the worst among the four scenarios defined by the IPCC and, therefore, accounts for the most different climatic conditions in comparison to the current one. Moreover, the same future climatic scenario is also used in other activities (e.g., WP2) within the project.

Table 3 reports a brief analysis of the climatic conditions in the four considered locations in terms of yearly minimum, maximum and average temperature and cumulated solar irradiation on a horizontal surface. The values are reported for the "Contemporary" climate scenario in black and for the selected future scenario in brackets in red. Their difference is also reported in square

¹ In the Spanish regulation no indoor set point temperature are indicated for space cooling in the period 07:00-15:00. For this reason +infinite is used in this period to avoid SC system activation

brackets in orange. A more detailed analysis of the climatic conditions in the four considered locations is reported in section 6.1.

Table 3 Yearly minimum, maximum and average ambient temperature and cumulated solar irradiation on a horizontal surface for the four considered locations (Cordoba, Krakow, Linköping, Edinburgh) in the contemporary (black) and IPCC RCP 8.5, year 2070 (red, in brackets) scenarios and their difference (orange, in square brackets). Data taken from Meteonorm 8 [6]

Location	Climatic variable			
	Temperature [°C]			Solar Irradiation [kWh/m²/y]
	Min	Max	Average	
Cordoba	-0.9 (1.7) [+2.6]	42.7 (47.3) [+4.6]	18.6 (21.9) [+3.3]	1762 (1803) [+41]
Krakow	-13.1 (-9.3) [+3.8]	31.9 (36.3) [+4.3]	9.7 (13.3) [+3.6]	1100 (1164) [+64]
Linköping	-15.5 (-11.6) [+3.9]	29.9 (33.3) [+3.4]	7.7 (11.1) [+3.4]	1018 (1042) [+24]
Edinburgh	-1.0 (1.2) [+2.2]	24.9 (27.1) [+2.2]	9.5 (11.7) [+2.2]	860 (887) [+27]

2.2. Active system solutions developed

Four active system solutions are developed and simulated, and these can be divided into three categories, where the first, including heat pump systems in general, includes both a typical Air/Water Heat Pump (AWHP) system and a cascade heat pump system (also called Water Loop Heat Pump (WLHP) system).

Except for the WLHP, which won't be applied at any of the project demo sites, the other active system solutions presented will be tested in at least one demo building (with some adaptation to the specific building).

The Table 4 summarises the main characteristics of the four active system solutions, including the type of generation, distribution (if present), and emission system, highlighting the different possibilities where applicable.

Table 4 Active system solutions considered, with details on the generation, distribution and emissions system, and the relation with the demo building in which the considered active system solution will be installed

Solution Nr.	Generation system	Distribution system	Emission system	Related demo site
1	Heat pump system	YES, water (or refrigerant) pipes	Fan coil units (if an air-air system is considered, the emission unit is the indoor unit of the air-air split system). Possible alternatives: radiators, radiant floor/wall/ceiling system	Cordoba
2	Cascade heat pump system (also Water Loop Heat Pump system)	YES, water pipes	Water-Air heat pumps	-
3	Mechanical Ventilation with	YES, air ducts	Air emission units	Edinburgh

	heat recovery system				<i>(Krakow², Linköping²)</i>
4	District Heating Network	YES, pipes	water	<i>Radiators, possible alternatives: fan coils, radiant floor/wall/ceiling</i>	<i>Krakow², Linköping²</i>

In addition to the HVAC system, the presence of Renewable Energy Systems (RES) is also accounted for in some of the simulations. In this context, RES refers to Photovoltaic (PV) systems (eventually with an electric battery). More specifically, a PV and battery system is considered in the simulations of the active system solutions featuring an HP system (solutions n. 1 and 2 in Table 4), as these systems use electricity for their operation. These solutions (AWHP and WLHP systems) use, as reference building, the Spanish and Swedish typology n.1, respectively. On the other hand, the Polish typology n. 1 will not account for HP systems to cover its thermal needs; however, it will be the only demo case featuring a PV (and probably a battery) system installation. Therefore, a simulation of the PV + battery system is useful to have a first estimation of the PV contribution to the planned renovation.

2.2.1. Heat pump system

The first active system solution presented is an AWHP system. Figure 2 shows a schematic of the considered HP system solution. In this figure, a split AWHP is shown, with the hydronic module placed in the technical room on the ground floor, alongside a buffer tank. From the technical room, two sets of water pipes (supply and return) distribute thermal energy to the different dwellings. One set distributes hot water for the charging of the decentralised DHW tanks placed in the different dwellings (which finally deliver the DHW to the users), while the other set of supply and return pipes delivers hot or cold water for covering the SH and SC thermal demand of the flats.

² In both Krakow and Linköping demo cases, the connection to the local DHN ensures the covering of space heating and DHW thermal demand. On these buildings, in parallel, there is also a mechanical ventilation system with heat recovery. The presence of the mechanical ventilation system with heat recovery is considered in the simulations performed.

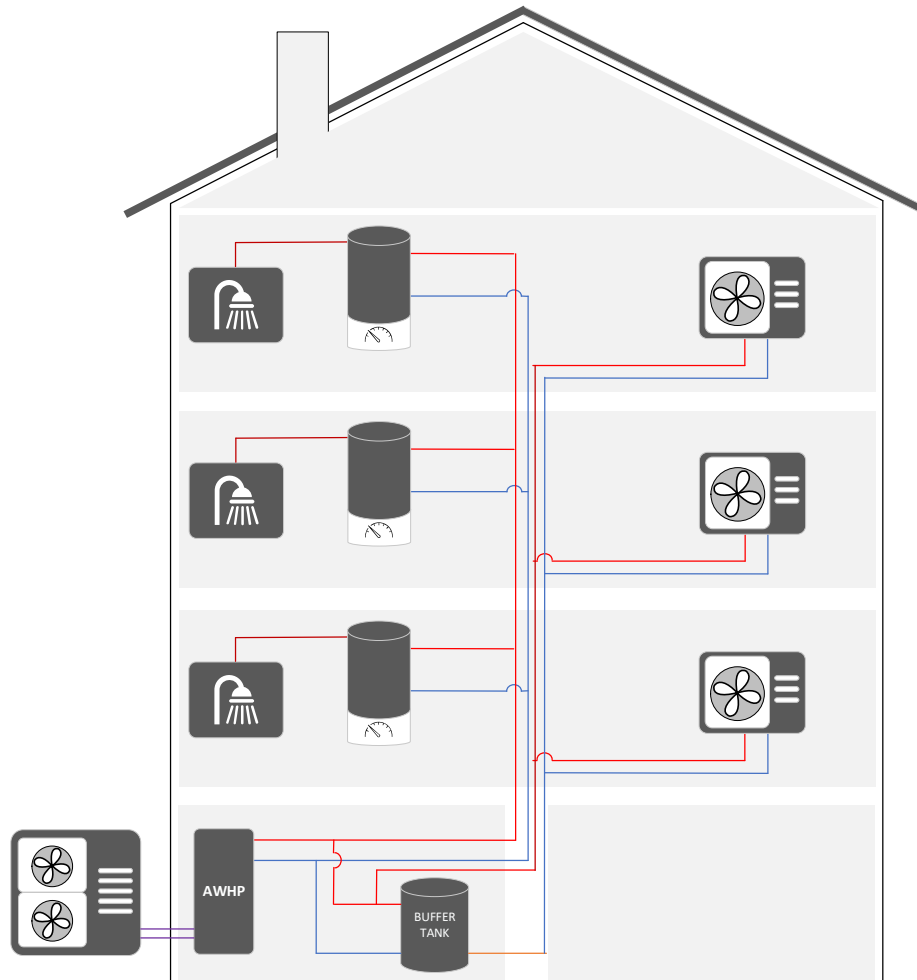


Figure 2 Schematic of the HP system with decentralised DHW tanks considered

Figure 3 shows a more detailed Piping and Instrumentation Diagram (P&ID) of the same AWHF system, including also the main hydraulic components, such as the circulating pumps, diverting and mixing valves and hydraulic collectors. This figure is used as a reference to explain in more detail the HP system and its components in the next paragraphs, subdividing them among generation, distribution and emission systems. This part ends with a subsection that presents the similarities and main differences between this active system solution and the solution that will be installed in the Cordoba demo case.

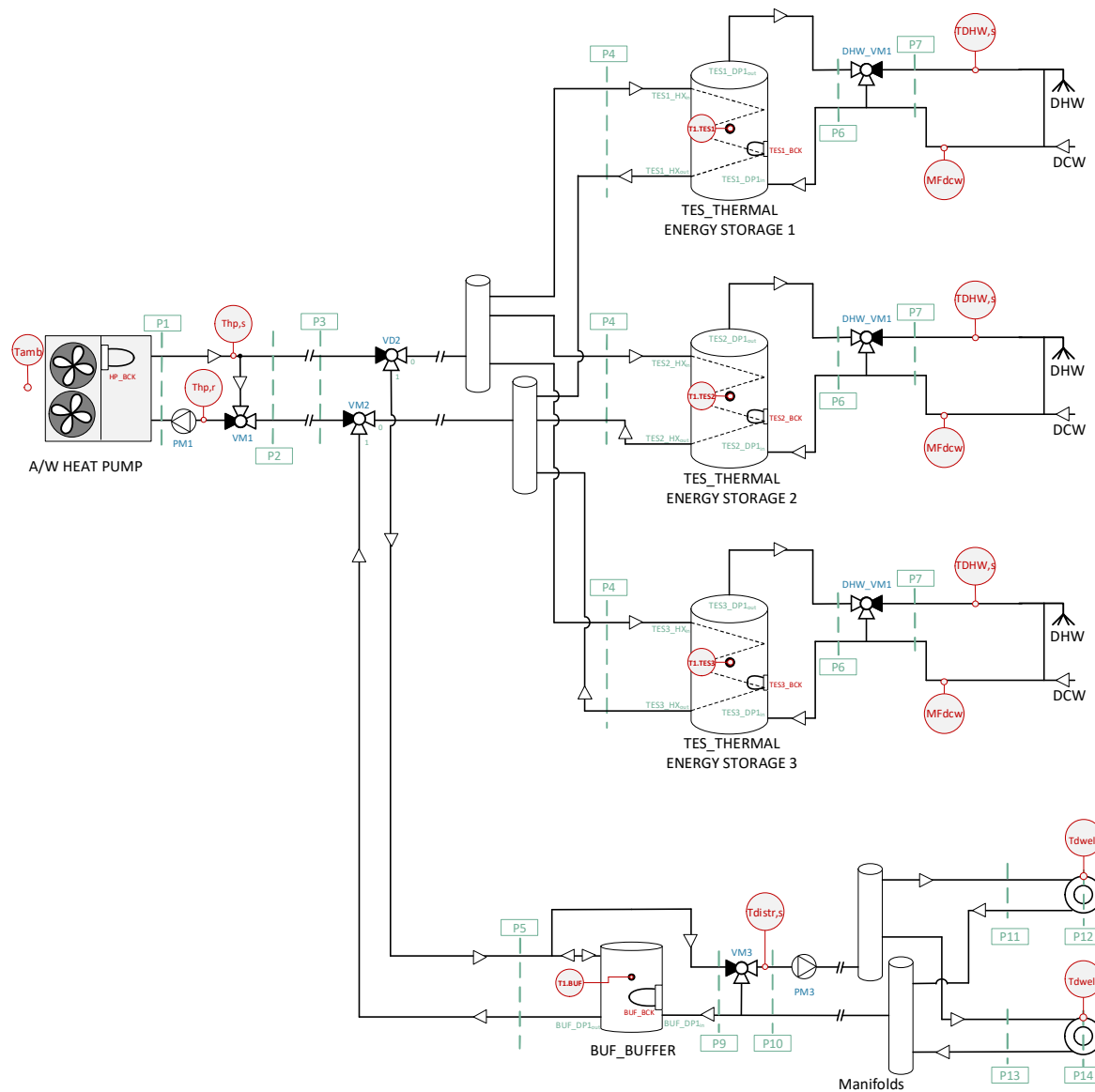


Figure 3 Simplified P&ID of the HP system with decentralised DHW tanks considered

2.2.1.1. Generation system

As already written above, an AWHp is considered a generation unit. Although in Figure 2 and Figure 3 only one AWHp is shown for the sake of simplicity; the system can be modular and composed of multiple (generally up to three) AWHps working in parallel. Moreover, although in Figure 2 a split AWHp is shown; also, other configurations (i.e., monobloc HP systems) can be considered, as the differences between different types of machines (monobloc vs. split AWHps) are minimal for the scope of this analysis.

The size, in terms of AWHp nominal thermal power, has been defined starting from the results of a dynamic simulation of the considered building, performed to assess the thermal demand of the building for SH and SC. Using dynamic simulations, based on specific simulation software (e.g., TRNSYS, Energy+), or on the simpler dynamic hourly calculation based on the standard EN-ISO 52016 [7], is particularly important to properly size the AWHp as these components, differently

from gas boilers, suffer more from an oversizing condition. In fact, an oversized HP system generally works with frequent activations and deactivations, with short operating time within each ON-OFF cycle. This type of operation is characterised by a higher electric consumption in comparison to a system working more continuously, with fewer ON/OFF cycles.

Based on the dynamic simulations performed with the ideal heating and cooling system, the building's peak thermal demand is for SH (although SH and SC peak thermal demand are similar), and this is in the range of 7 kW. In addition, the thermal power needed from the AWHP system to cover the users' DHW demand has been calculated. This is in the range of 4 kW, resulting in a total thermal demand (SH + DHW) in the range of 11 kW. This is also the thermal power in nominal conditions³ of the AWHP considered in the dynamic simulations with the AWHP system. For the sake of completeness, it is useful to report that the thermal power values just reported refer to the Spanish building typology n. 1, which accounts for three flats with a net floor area in the range of 50 – 60 m² each, distributed on three floors.

2.2.1.2. Distribution system

The water exiting the AWHP is delivered to the different dwellings through the distribution circuit. After a first common branch, in correspondence with valve VD2 in Figure 3, the distribution circuit is divided into two parts: the DHW distribution circuit and the SH/SC distribution circuit.

The first connects the AWHP to the decentralised DHW tanks (one per apartment, Thermal Energy Storage (TES) in Figure 3). As visible in Figure 3, there are two hydraulic collectors (one for the supply and one for the return line) from which three separate pipes supply hot water to the three considered decentralised DHW tanks for their charging. In these pipes, technical water is flowing and, to avoid mixing with and contamination of the DHW, the technical water flows in a coiled heat exchanger inside the tanks (black dashed line in the decentralised DHW tanks in Figure 3). The Domestic Cold Water (DCW) from the aqueduct enters the decentralised DHW tanks from the bottom and exits from the top. Before reaching the users, a tempering valve (DHW_VM1 in Figure 3) is considered to limit the supply water temperature exiting each DHW tank.

The SH/SC distribution part, instead, connects the AWHP to the fan coil units in the apartments, including also a three-port buffer tank. The three-port configuration allows, depending on the water flow rate of the AWHP and of the SH/SC distribution circuit (the latter defined by the PM3 in Figure 3) to use the buffer for storing or extracting thermal energy. In fact, the buffer tank is charged, with water entering the top-left port if the AWHP water flow rate is higher than the SH/SC distribution flow rate. Contrarily, the buffer tank is discharged, with water exiting the top-left port if the AWHP water flow rate is lower than the SH/SC distribution flow rate. Finally, this configuration allows bypassing the buffer tank if the water flow rate of the AWHP is equal to that

³ Nominal conditions for the AWHP in heating mode are defined as $T_{\text{air_source_in}} = 7 \text{ }^{\circ}\text{C}$, $T_{\text{water_load_in/out}} = 30/35 \text{ }^{\circ}\text{C}$

of the SH/SC distribution circuit, delivering the hot/cold water produced by the AWHP directly to the emission units.

2.2.1.3. Emission system

Fan coil units are considered as the emission system in this active system solution. The main advantage of fan coils is their ability to deliver both SH and SC from the same emission unit, with proper management of the water condensate in cooling mode. Also, radiant systems (i.e., radiant floor, wall, ceiling) can deliver space cooling, but they should work in connection with a separate system controlling the indoor humidity of the considered zone/flat.

2.2.1.4. Renewable Energy Systems

The considered AWHP system uses air as a thermal source and electricity to run the compressor to finally deliver thermal energy to the building. If air is accounted as a totally renewable energy source, the assessment of the renewable fraction of the electricity consumed depends on different factors, with the main one being the electrical grid energy mix of the country considered. For the objective of the work in these tasks (T3.2 and 3.3), it is considered sufficient to use the renewable fraction for electricity reported for the specific country considered. The most up-to-date yearly value made available will be used.

However, regardless of the country considered, the production of a PV system (and eventually also the presence of an electric battery system) is beneficial for improving the building's renewable energy consumption, as PV production is generally considered totally renewable.

HP systems and PV (with the eventual presence of a battery) are a set of technologies which allow for the exploitation of positive synergies, i.e., consuming locally produced renewable energy (and eventually temporarily stored if a battery is present) to run the HP system and cover the building's thermal demand.

On this basis, a PV system with a battery is considered in the simulation of the AWHP system in the Spanish typology 1. The sizing of the PV system is done considering the limited footprint of this building typology and, therefore, the limited space available on the roof. Based on this, a 2 kWp PV system is considered. Regarding the battery, a 3 kWh battery is considered for each apartment (for a total of 9 kWh). This is because, generally, a capacity of 2-3 kWh is the minimum value for most of the commercial systems available nowadays.

When an HP system is installed, it generally represents the highest electric consumption at the building level. For this reason, and also for the sake of simplicity, it is considered that the PV and battery system can cover only the electric consumption of the AWHP system (i.e., the electric consumption of the AWHPs and that of the circulation pumps).

2.2.1.5. System control

The system control implemented for the AWHP system aims to cover the SH, SC and DHW thermal demands, maximising both the instantaneous system performance in terms of AWHP Coefficient Of Performance (COP) and the use of renewable electricity produced on-site through the considered PV and battery system.

The AWHP can operate in DHW or SH/SC mode, with DHW mode (i.e., the DHW tanks' charging mode) prioritised over SH/SC mode by the system control.

More specifically, the AWHP is activated in DHW mode if the temperature measured by the sensor T1.TESX in Figure 3 (installed at 60 % of the tank's height starting from the bottom, and where the "X" indicates one of the three DHW tanks) in at least one DHW tank reaches 45 °C. The DHW tank's charging continues until the same temperature reaches 50 °C. When working in DHW mode, the temperature set point at the condenser side output of the AWHP is fixed and equal to 55 °C.

In principle the DHW tanks charging periods could be limited along the day and scheduled to be done just before the periods in which a high DHW users' demand is expected (with DHW users demand having generally a peak in the period 06:00-09:00 and 18:00-21:00) and, eventually, charge the single DHW tank if the temperature set point is not ensured through an electric resistance, that is in any case often present in these tanks, for the rest of the day. Although the use of electrical resistances increases the overall electric consumption (in fact, an electrical resistance can be seen as a sort of HP system with a COP around 1), this schedule has in principle the advantage of reducing the number of switches between heating and cooling operations for the AWHP in summer, with the machine working in heating mode only in the fixed periods along the day that are dedicated to the DHW tanks' charging, and operating in cooling mode for the rest of the time. The reduction of switches between heating and cooling operations can be beneficial for extending the technical life of the system. However, in the considered simulations, the system efficiency is prioritised, and, therefore, the DHW tanks can be charged over the entire 24 hours by the AWHP.

Regarding SH/SC operation, the SH/SC demand is identified by the signal of the thermostats that are present in the three dwellings. As in the building model of the Spanish building typology n.1 each dwelling is divided into two thermal zones, the indoor air temperature seen by the thermostat is the weighted average of the air temperatures of the two thermal zones, weighted based on the net floor area of each thermal zone.

If the indoor air temperature is below (in winter) or above (in summer) the considered set point, the PM3 in Figure 3 is activated. The valve VM3 in Figure 3 regulates the supply temperature to the fan coils according to a climatic curve in winter (reported in Table 5) and at a fixed set point (7 °C, typical value for fan coil systems in SC operation) in summer. In principle, the use of a climatic curve also in summer could lead to a better system efficiency (in terms of the AWHP COP). However, the use of a higher temperature for the water supplied to the fan coil would reduce the

dehumidification effect that, in summer, plays a crucial role. For this reason, in the considered simulations, in summer, the temperature of the water supplied to the fan coils is maintained constant and equal to 7 °C.

Table 5 Climatic curve considered in the AWHP system for the Spanish building typology n.1

Building considered	Tclimatic MAX	Tclimatic MIN
Spanish typology n.1	45 °C (at Tamb=-2 °C)	30 °C (at Tamb=20 °C)

The water supplied to the fan coils comes from the buffer tank and/or from the AWHP.

In winter, the buffer tank is used alone (and the AWHP is not activated in SH/SC mode) if the buffer tank temperature (measured by the sensor T1.BUF in Figure 3, located at 60 % of the tank's height starting from the bottom) measures a temperature equal to the considered set point temperature (based on the selected climatic curve), reduced by the considered hysteresis lower dead band (in the simulations, assumed equal to 3°C).

If the temperature measured by the sensor T1.BUF reaches the value of set point temperature minus the hysteresis lower dead band, the AWHP is activated and it remains active until the same sensor measures a temperature equal to the same set point increased by the hysteresis upper dead band (also set equal to 3 °C). To clarify this with an example, if the climatic curve set point is in the considered conditions equal to 40 °C, this means that the AWHP is activated in SH mode to charge the buffer tank when the temperature T1.BUF reaches $40-3=37$ °C, and remains active until the same sensor measures a temperature of $40+3=43$ °C.

During the buffer tank charging in winter, the AWHP is controlled to follow a variable set point equal to the climatic curve plus a small ΔT (3-5 °C) at the condenser outlet.

In SC mode, the system operation is similar, in the sense that the AWHP is activated to condition the buffer tank at the desired temperature. The main difference is the use of a constant set point temperature for the water supplied to the fan coils, for the buffer tank and also for the AWHP control as written above. To clarify with numbers, the set point temperature for the water supplied to the fan coils is equal to 7 °C, the buffer set point temperature is equal to 7 °C (with upper and lower hysteresis dead bands equal to + and - 3 °C), and the AWHP set point temperature at the condenser outlet is equal to 4 °C.

The use of a properly set climatic control in SH, not only at the distribution side (at the fan coil units), but also to manage the temperature in the buffer tank and the AWHP condenser outlet temperature set point, ensures covering the SH load, maximising the instantaneous AWHP COP. This is because, in general, in an AWHP system, at the same source inlet temperature (i.e., at the same ambient air temperature), the use of a lower set point temperature at the AWHP condenser outlet results in a reduced electric consumption and, therefore, a higher AWHP COP. Based on this, the AWHP condenser outlet temperature is minimised, checking that the used values are sufficient to cover the SH demand and ensure the desired indoor air temperature level.

Moreover, considering the presence of a PV system and an electric battery, the system control is developed to maximise the exploitation of the renewable electricity locally produced. More in detail, the PV production is used first to cover the HP system's electric consumption and, secondly, if there is a PV surplus, this is used to charge the battery. If there is still PV surplus and the battery is fully charged, before dumping the PV production to the grid, the building is used as a sort of "thermal storage". Practically, if there is PV surplus and the battery is already fully charged, the building's indoor air temperature set point is increased by a certain ΔT . This ΔT is considered equal to 1 °C, as this value is considered appropriate for this building to have better exploitation of the PV production, without impacting too much on the users' comfort.

In principle, the DHW tanks' set-point temperature could also be increased in periods in which there is PV dumped power. However, due to the limited volume of the DHW tanks considered (120 l for each dwelling), the additional thermal energy that can be stored by changing the DHW tanks' temperature set point by up to a few °C is considered limited and, for this reason, it is not accounted for in the performed simulations.

2.2.1.6. Relation with the future system in the Cordoba demo

The HP system described above constituted the basis for the development of the system that will be installed in the Cordoba demo.

The pre-renovation situation in the Cordoba demo in terms of HVAC system foresees punctual electric radiators connected to the standard electric plugs of the dwelling to deliver SH, and a decentralised DHW tank for each apartment (50-60 l) with an electrical resistance to heat the water in the tank through the Joule effect. There are only some dwellings with an SC system, represented by an air/air HP (split unit), that cover at least part of the SC demand and improve users' comfort in the hot season.

The system just described lacks a distribution system for both decentralised DHW tanks charging and for the SH/SC part.

The solution proposed is an innovative aerothermal system with a direct expansion multi-split system. The choice of a direct expansion system (air/air HP), instead of a more typical water-based HP solution as the one described above, is mainly due to the absence of a distribution system and the typically smaller diameter of the distribution pipes in which refrigerant flows in comparison to a typical system in which technical water flows.

For a series of advantages, among these, a wider system operative range and an easier accounting of the electric consumption by each of the three considered apartments, three separate systems, one per dwelling, are considered. Therefore, the system of each dwelling will be composed of one outdoor modulating (inverter) unit, which delivers the hot/cold refrigerant to three wall-mounted indoor units (two located in the living room and one in the bedroom) to cover the SH and SC demand of the considered dwelling. There will also be a refrigerant line delivering the hot refrigerant to the decentralised DHW tank. In this regard, a decentralised DHW

tank developed specifically for multi-split systems will be used. This DHW tank features a coiled tube heat exchanger through which the hot refrigerant transfers heat to the water in the tank. Figure 4 shows the simplified schematic of the active system solution for the Cordoba demo case under evaluation. The figure highlights the unique outdoor unit connected to the four (three for SH/SC and the DHW tank) indoor units, the sensors considered and the connections to the electric board. Moreover, Figure 4 shows the active system for one flat, with the same system that will be equally replicated for the three flats of the building.

Regarding RES, the Cordoba demo will not include the installation of either a PV system or a battery.

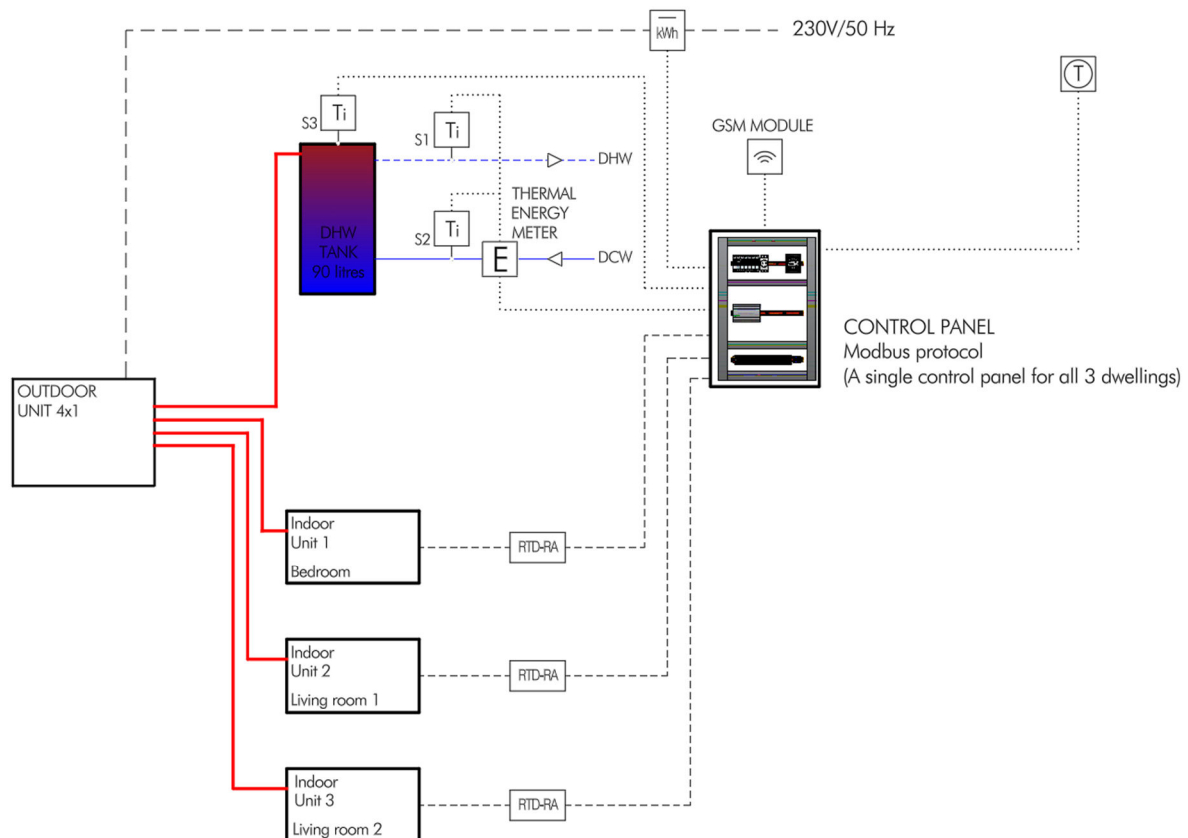


Figure 4 Simplified schematic of the active system solution under evaluation for the Cordoba demonstration site for one flat (the same system is replicated for all three flats)

2.2.2. Water Loop Heat Pump system

As reported in Table 4, in addition to the more conventional AWHP system solution presented in the section 2.2.1, this section presents a slightly different HP system. In this one, multiple HPs work in series (i.e., in cascade). Although this active system solution won't be installed in any project demo case, some features make it worth presenting, as it could represent a valid solution in some Historic Buildings.

The concept of the WLHP system is to use one or more centralised unit(s), in this case AWHP(s), to condition a buffer tank and a distribution system (this last also called water loop) in an almost neutral temperature range (around 20-35 °C), and to use other HPs, using the water loop as thermal source, to finally cover the users' SH, SC and DHW needs.

The first advantage of this system is the ability to cover the thermal load of buildings with poor thermal envelope performance and with high SH peak demand (up to 70-100 W/m²), a situation that can be common in Historic Buildings where insulation intervention options may be limited. This situation could require a typical AWHP system to operate for long periods at high temperatures (around 60 °C) with limited performance in terms of COP.

The second is the possibility of replacing the existing radiators with Water/Air HPs (WAHPs) with limited interventions and visual differences in comparison to the existing heat emission system.

The third advantage is associated with the use of a very low water loop temperature (20-35 °C), which drastically reduces the distribution system thermal losses. This is particularly important in those cases in which the distribution pipes are non-insulated and not accessible, a situation that can be common in Historic Buildings. In these buildings, a typical system using radiators as heat emission units would distribute the water at temperature levels generally in the range 50-70 °C, with high thermal losses in the distribution pipes.

The fourth is the possibility for this system to cover SH, SC and DHW thermal demand. In particular, the covering of SC demand is, in general, a request which is becoming increasingly common. Moreover, in summer, the Water/Water HP (WWHP), responsible for the DHW production, uses the water loop as a thermal source, extracting thermal energy from it, while the WAHPs, delivering SC to the dwellings, use the water loop as a thermal sink, rejecting thermal energy to it. These two operations tend to thermally balance themselves, resulting in an overall reduced system electric consumption in comparison to a situation in which two separate systems (or the same system working alternatively in SC and DHW mode) deliver SC and DHW to the users.

In principle, there could be different WLHP systems, with similar performance in terms of system efficiency and differences associated with the configuration of the HPs used to meet the building's thermal demand. One option is to have a series of WWHPs, one per dwelling, delivering SH, DHW and eventually SC to that dwelling. This system can deliver both SH and SC only if the emission units allow both (i.e., fan coil units, radiant system in combination with a mechanical ventilation system). This system, having one WWHP per apartment, can be called "WLHP system with apartment booster HPs". The second option is to have a unique WWHP, generally installed in the technical room to cover the DHW users' demand and a series of WAHPs installed in each apartment (typically one per room) for the covering of the SH and SC demand. This system, having HPs installed at the room level, can be called "WLHP system with room booster HPs". Both the apartment and room booster HP systems have been developed within the H2020 HAPPENING project [8], and a more extended description of these systems can be found in the HAPPENING D2.7 [9].

In this work, the WLHP with room booster HPs is modelled and simulated, considering the Swedish Historic Building typology n.1 as the target building. The choice of using this building as a target is because it presents the highest heated floor area among those identified within T1.2. The choice of this system, requiring in general more components and with a slightly higher initial cost in comparison to a typical AWHP system, can be more easily justified in the case of big buildings. Being the Swedish Historic Building typology n.1 a non-residential building, it does not have a relevant DHW demand. For this reason, the DHW demand is not accounted for in the simulations. However, for the sake of completeness, it is considered useful to present in the explanation of the WLHP system how this system covers the eventual DHW demand. The same is also valid for SC: no SC thermal demand is considered for the Swedish Historic Building typology n.1. However, for the sake of completeness, in the explanation of the WLHP system, it is presented how SC would be covered.

Figure 5 shows a schematic of the considered WLHP system. As in the AWHP system described in the section 2.2.1, there is one (or more) centralised AWHP(s). These machines are used to condition the temperature of a buffer tank, which is then connected to the water loop. After a first common part, the water loop is divided into two branches: one connecting the buffer tank to a WWHP responsible for the charging of a DHW tank (Thermal Storage in Figure 5) and, ultimately, for the delivery of DHW to the users; and one connecting the buffer tank to a series of WAHPs responsible for the delivery of SH and SC to the dwellings.

For the sake of completeness, Figure 6, similarly to Figure 5, shows the same schematic for the WLHP with apartment booster HPs to highlight the differences between the two WLHP systems' configurations. Moreover, Figure 7 presents two examples of WLHP solutions available on the market.

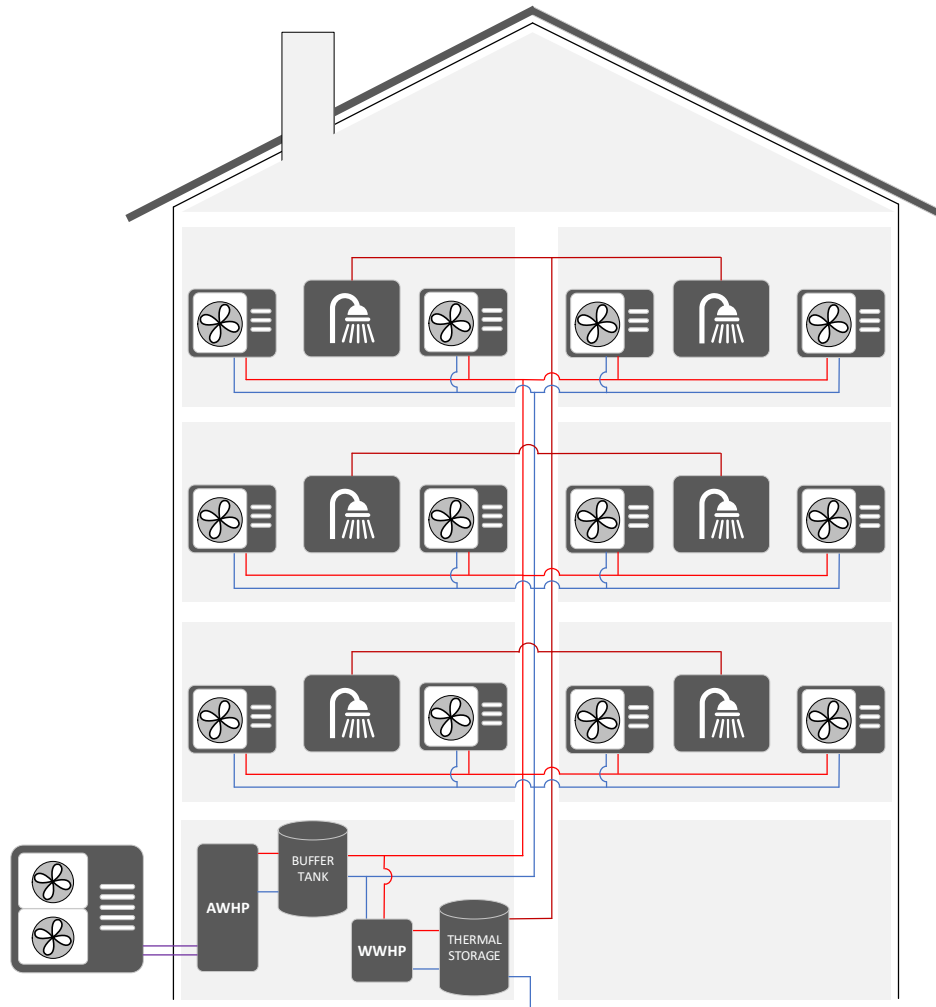


Figure 5 Schematic of the WLHP system with room booster HPs

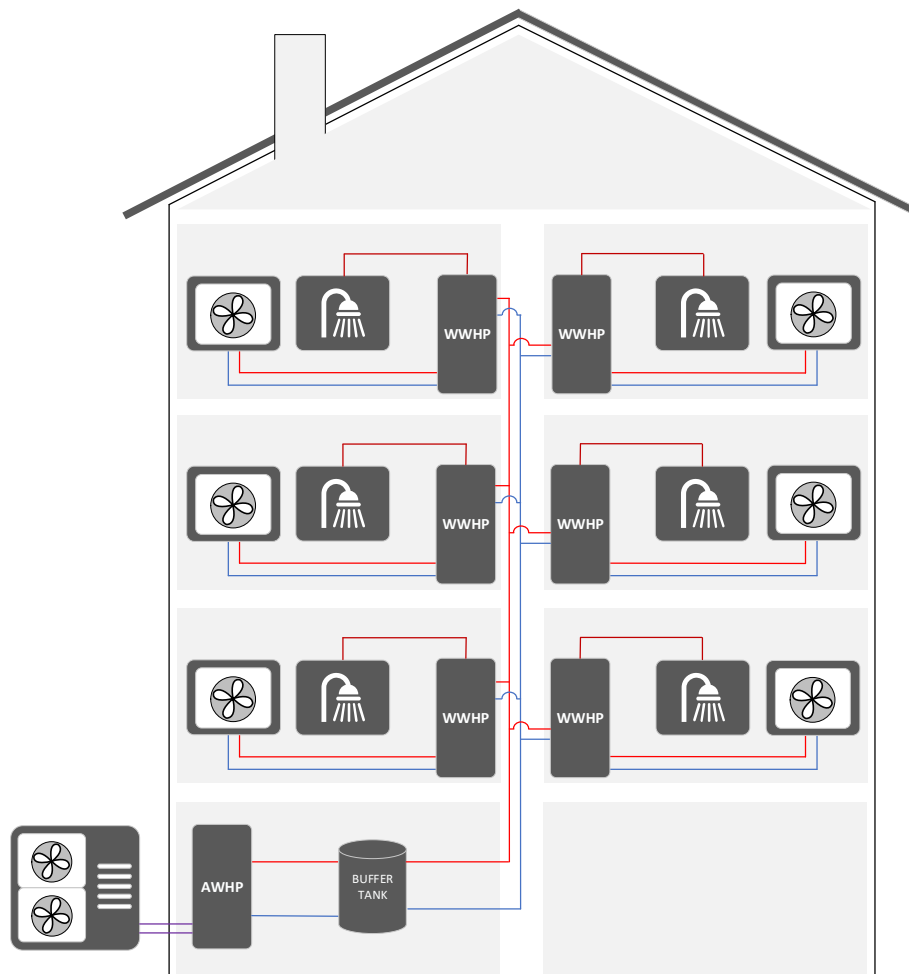


Figure 6 Schematic of the WLHP system with apartment booster HPs



Figure 7 Example of apartment booster HP (left figure, source: https://www.daikin.eu/en_us/solutions/collective-housing.html) and example of WAHP installation in the case of room booster HPs system (right figure, source: <https://www.innovaenergie.com/prodotti/terminali-in-pompa-di-calore-wlhp/wlhp/>)

Similar to the section 2.2.1, also here, Figure 8 presents a more detailed P&ID and is used in the next sections to describe the WLHP system in more detail.

Different from the categories used to describe the HP system in the section 2.2.1, the WLHP system is described by dividing it into the Centralised generation system (instead of Generation system), Distribution system and Terminal emission system (instead of Emission system). These differences are because all machines, including the WAHPs installed at the room level, can be considered generation units and, therefore, the use of the categories adopted in the section 2.2.1 could create confusion. Instead, the description considered aims to clearly distinguish between those components installed in the technical room, the distribution system, and the units installed at the room level.

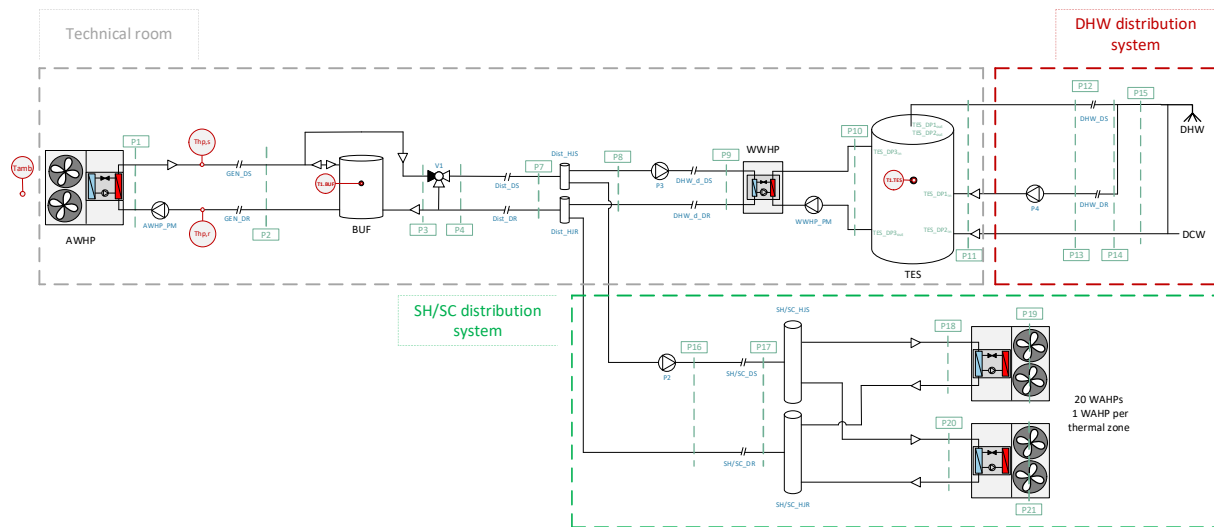


Figure 8 Simplified P&ID of the WLHP system

2.2.2.1. Centralised generation system

Similar to section 2.2.1.1, also in the WLHP system, AWHPs are used as centralised generation units. Figure 8 shows only one AWHP for the sake of simplicity. However, also in this case, the centralised generation system can be modular and composed of multiple AWHPs connected in parallel. Moreover, similar to the HP system, also in this case, there are no strict requirements in terms of refrigerant and/or system configuration (i.e., monobloc vs. split AWHPs).

As already stated above, the WLHP has been sized to be able to cover the peak SH demand of the Swedish building typology n. 1. This peak demand has been obtained from dynamic simulations performed in IDA ICE and is in the range of 52 kW. As the AWHP modelled in TRNSYS is based on laboratory test performance of a real AWHP developed for this application, and with a thermal power in nominal conditions³ of 15 kW, four AWHPs are considered in the TRNSYS model.

2.2.2.2. Distribution system

The AWHPs work to maintain a 2000 L buffer tank (BUF in Figure 8) in a temperature range defined by a climatic curve (see section 2.2.2.5 for more details about the definition of the considered climatic curve). This buffer tank serves to both limit the number of AWHPs' ON/OFF cycles and store thermal energy under conditions in which the AWHPs work with a high instantaneous COP.

After the buffer tank, the mixing valve V1 in Figure 8 is used to regulate the water loop temperature according to the climatic curve defined in section 2.2.2.5.

After a first common branch, the distribution circuit, in correspondence with the hydraulic collectors Dist_HJR and Dist_HJR in Figure 8, the water loop is divided into two separate circuits.

The first connects the water loop to the WWHP (having a thermal power in nominal conditions⁴ of around 9 kW), which extracts thermal energy from the water loop to charge the DHW tank (TES in Figure 8) in a temperature range (50-55 °C) that ensures the delivery to the users of DHW at the right temperature level (considered equal to 42 °C). The second distributes the almost neutral temperature water to the WAHPs, which use the water loop as a thermal source in winter and as a thermal sink in summer.

2.2.2.3. Terminal emission system

The terminal emission units of the WLHP system are a series of WAHPs responsible for covering the building's SH and SC thermal demand. These units are characterised by a thermal power in heating mode in nominal conditions⁵ generally in the range 2-5 kW and use the water loop as a thermal source in winter (extracting thermal energy from it) and as a thermal sink in summer (rejecting thermal energy to it). The number of WAHPs installed in each room depends on the size of the considered room, going from a minimum of one WAHP per room to some (often up to 3-5).

2.2.2.4. Renewable Energy Systems

Similar to what is already presented in the section 2.2.1.4 for the considered HP system, the WLHP system also uses electricity to run and cover the building's thermal demand, and, therefore, it is worth assessing the positive synergies that can be obtained by also installing a PV system and an electric battery installed on-site, which enable the possibility to consume the renewable energy locally produced and eventually temporarily stored.

The consideration of a PV and battery system is undertaken for various reasons, although the considered Swedish building typology n. 1 is representative of buildings generally subjected to the highest level of heritage protection.

First, there are PV system solutions nowadays that allow for PV installation with limited visual impact; therefore, they can also be considered in Historic Buildings under the highest level of heritage protection. In some cases, the PV elements are adapted to lower their visual impact (e.g., coloured PV panels, PV tiles), in others, the PV system is installed not on the building but, for example, in an available and appropriate space in the near vicinity. A series of examples of PV system integration in Historic Buildings is reported in D3.2 [10].

A PV system with a nominal power of 10 kWp is considered in the simulations, and this is complemented by the presence of a 19.3 kWh battery.

⁴ Nominal conditions for the WWHP are defined as $T_{\text{water_source_in/out}} = 10/7 \text{ °C}$, $T_{\text{water_load_in/out}} = 30/35 \text{ °C}$

⁵ Nominal conditions for the WAHP in heating mode are defined as $T_{\text{water_source_in}} = 20 \text{ °C}$, $T_{\text{air_load_in}} = 20 \text{ °C}$

Different from what is reported in the section 2.2.1.4, being the target building considered a non-residential one, it is possible to imagine that the PV + battery system can cover both the HVAC system and also the other building's electric consumption. However, it is useful to note that, in the case in which an HP system is used, it generally represents the highest electric consumption at the building level.

2.2.2.5. System control

The system control considered for the WLHP system aims, similarly to what has been done for the AWHP system, to maximise both the instantaneous WLHP system COP and the exploitation of the PV production.

However, in the case of the WLHP system, having multiple HPs operating simultaneously in cascade, each of them with a specific performance and variation of the performance based on the operative conditions, the optimisation is not straightforward as in an AWHP system.

In general, when two HPs work in cascade, the COP of this system has a maximum given by the following formula:

$$SYS_COP_{theo} = \frac{COP_1 \cdot COP_2}{(COP_1 + COP_2 - 1)}$$

Where:

- SYS_COP_{theo} is the theoretical system COP
- COP_1 and COP_2 are the instantaneous COPs of the two HPs working in series

This equation is maximised when COP_1 and COP_2 are equal. For this reason, the control of the various HPs should tend to obtain the same (or as similar as possible) COPs for all the HPs working in cascade.

The system control is done differently in winter and in summer.

In winter, the cascade AWHPs – WAHPs deliver SH to the building, while the cascade AWHPs – WWHP ensures the charging of the DHW tank. Therefore, all machines work in heating mode.

Except for the WWHP, which presents a relatively low COP due to the high condenser outlet temperature required for this machine, the HPs working with the lowest COP are often the AWHPs. Therefore, the considered system control tends to maximise the AWHPs COP to increase, as a consequence, also the system COP.

To do so, an inverse climatic curve (shown in orange in the Figure 9) is used to control the buffer tank temperature and also the temperature set point at the AWHP condenser inlet side. As visible in this figure, the buffer tank set point is equal to 20 °C at ambient temperature equal or lower than 0 °C, while it is limited to 30 °C at ambient temperature equal to or higher than 20 °C. At

ambient temperature between 0 and 20 °C, a linear interpolation between the just defined two points is considered.

The same figure shows, in addition to the buffer tank temperature set point considered (orange line) also the lower (blue line) and upper (red line) thresholds, which respectively activate and deactivate the AWHPs for the buffer tank charging. As visible in the figure, the considered range is quite large (10 °C). This value is used so that, when in operation, the AWHPs work for a relatively long time, avoiding ON/OFF operations that decrease both system performance (COP) and the technical life of these machines.

The use of a reduced set point temperature at the buffer tank and at the AWHP condenser side ensures a relatively high AWHP COP also on the coldest winter days. On the other hand, the considered control ensures that in conditions characterised by milder ambient temperatures, the buffer tank and AWHP temperature set points are increased, with thermal energy stored in the buffer tank, profiting from the possibility to have high AWHP COPs also with higher water temperature at the condenser outlet.

Moreover, although not visible in the Figure 9 for the sake of simplicity, the buffer tank set point temperature is further modified to better exploit the PV production. More specifically, the buffer tank temperature set point is increased by a ΔT (2 °C) if there is PV excess that is sent to the grid. In this way, thermal energy is stored in the buffer using electricity locally produced and can be used in a second moment when PV production is not or less available.

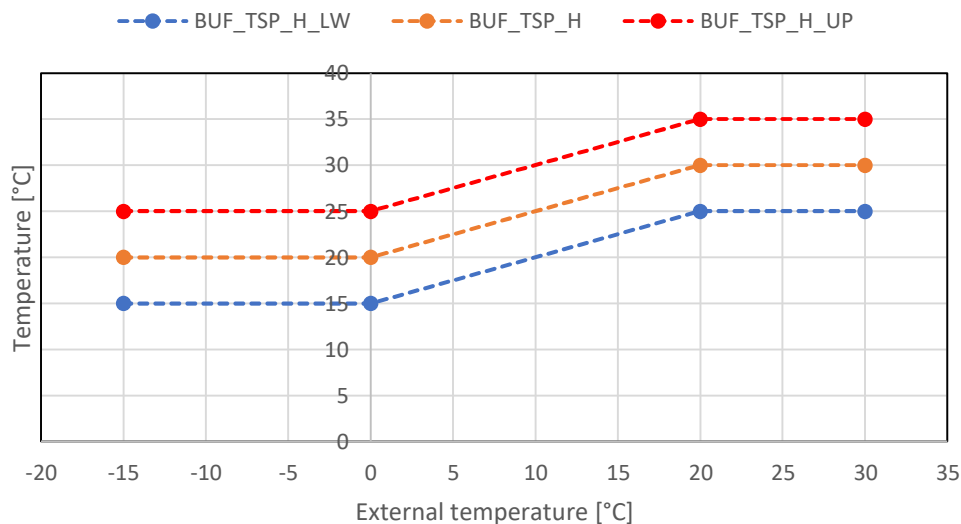


Figure 9 Buffer tank temperature set point (TSP) considered in the winter (heating (H)) season (orange), lower (blue) and upper (red) thresholds used to activate the AWHPs. The buffer tank set point is also equal to the AWHPs' temperature set point at the condenser inlet

In summer, instead, as already written above, the WWHP works in heating mode, while the WAHPs work in cooling mode. These two operation modes tend to thermally balance themselves.

To exploit as much as possible this thermal balance effect, the buffer tank temperature is allowed to vary in a wide range, with the AWHPs used in heating or cooling mode to avoid too low or too high temperatures in the buffer tank and in the water loop. Moreover, the hysteresis dead bands considered are reduced from ± 5 °C in winter to ± 2 °C in summer. This also aims to limit the AWHPs contribution and allow the WWHP and WAHPs operation to thermally balance themselves as much as possible.

More in detail, the AWHPs are activated in heating mode if the sensor T1.BUF in Figure 8 measures a temperature equal to 23 °C and remains active until the same temperature reaches 27 °C. The AWHPs are activated in cooling mode instead if the same sensor T1.BUF measures a temperature equal to 40 °C and remains active until the same temperature reaches 36 °C. Buffer tank temperatures lower than 23 °C and higher than 40 °C could result in non-optimal operation for the WWHP or for the WAHPs in cooling mode.

Regarding the control of the temperature in the water loop, Figure 10 shows the climatic control considered in the winter (red line) and summer season (blue line).

In winter, the control is similar to the one used for the buffer tank and the AWHPs set points. In general, a higher water loop temperature is beneficial in winter for the WWHP and the WAHPs, as all the machines work in heating mode using the water loop as a thermal source, and a higher source temperature ensures, in this case, higher performance in terms of the machines' COP.

In summer, instead, the water loop temperature control is done differently from the buffer tank and AWHPs temperature set point.

More specifically, the water loop temperature control in summer considers a high water loop temperature (35 °C) when the ambient air temperature is up to 20 °C, while the same temperature set point is linearly decreased up to 25 °C in correspondence with the ambient air temperature equal to 35 °C.

The use of a high water loop temperature on milder/colder summer days aims to optimise the operation of the cascade between the AWHPs and the WWHP as, using the water loop as a thermal source, the WWHP benefits from a high water loop temperature. On these days, SC demand is very limited or not present. On the contrary, on hot summer days, SC demand often becomes the main building thermal demand. In these conditions, the WAHPs work to cover the main building thermal load, and a low water loop temperature improves the performance (in terms of COP) of these machines in cooling mode.

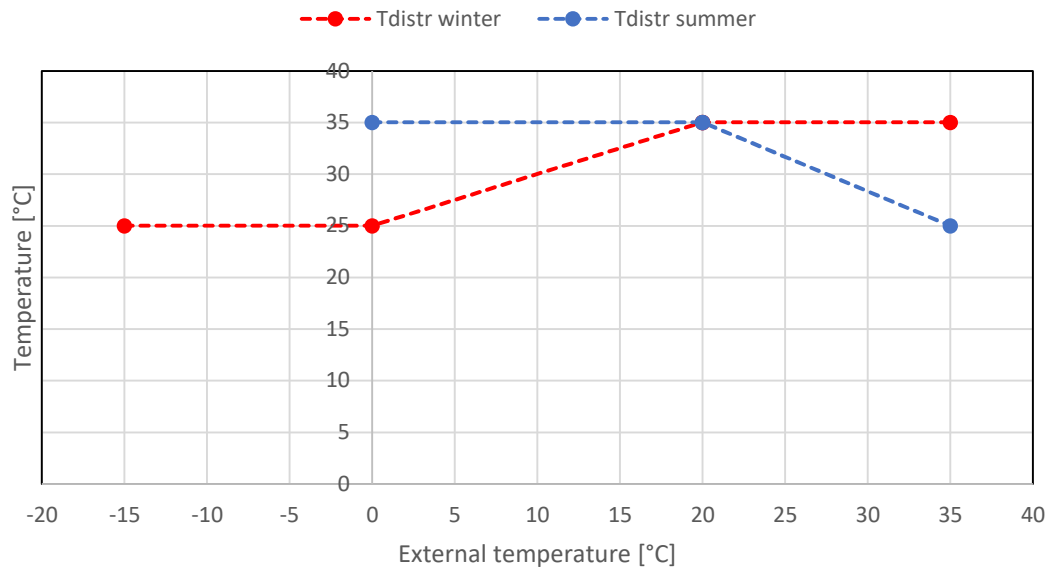


Figure 10 Distribution system (water loop) temperature set point considered in winter (red) and summer (blue)

2.2.2.6. Adaptation to the Swedish building typology considered?

As already written in the section 2.2.2, the Swedish building typology n.1 is considered as the target building to simulate the behaviour of the WLHP system and assess its performance.

However, the building thermal demand considered is solely SH, while DHW and SC are not accounted for in the analysis. Regarding the DHW, based on the usage of the building (non-residential, office building), the DHW can be considered negligible. Regarding SC, the dynamic simulations performed in IDA ICE show that SC is absent or very limited for this building typology.

These aspects imply that some features of the WLHP system (e.g., the thermal balance effect of WWHP and WAHPs in summer) cannot be verified in the performed simulations. Nevertheless, as the SH demand is by far the most important for this building typology, it is considered useful to document the simulation results with the main aim of giving a description of the performance and the advantages that can be obtained using this HP system.

2.2.3. Mechanical ventilation with heat recovery system

The MVHR system was modelled as a balanced, full-supply system based on the Zehnder ComfoAir Q350 unit. The unit provides equal supply to the four main habitable rooms and extracts from the kitchen and bathroom as visible in Figure 11 and Figure 12, with total flow rates of 40 L/s in boost mode and 20 L/s in background mode. A sensible heat-exchange efficiency of 90% and a specific fan power of 0.6 W/(L·s) were assumed and the fan electricity was calculated from $\text{airflow} \times \text{specific fan power}$. No auxiliary heating within the unit was modelled; only heat recovered from exhaust air was applied. This implies that a different system (not part of the MVHR

is considered to deliver SH to the building. In the considered case, SH demand is considered covered through electric radiators.

In ESP-r the MVHR was implemented as fixed flow boundary conditions within the airflow network, operating continuously and independently of real-time CO₂ levels. The envelope reflects the “improved” case, with secondary glazing and a 50 % reduction in window crack area so that the MVHR provides the dominant ventilation path. An overflow configuration was also tested in ESP-r where all supply air is delivered only to the hallway relying on transfer through door undercuts and natural pressure differences to move air into the bedrooms and living spaces, but air quality performance of that design was subpar to the full scale MVHR. In full scale MVHR, unlike the overflow configuration, supply air is delivered directly to each habitable room. This avoids reliance on transfer through the hallway and ensures more even distribution of fresh air and recovered heat.

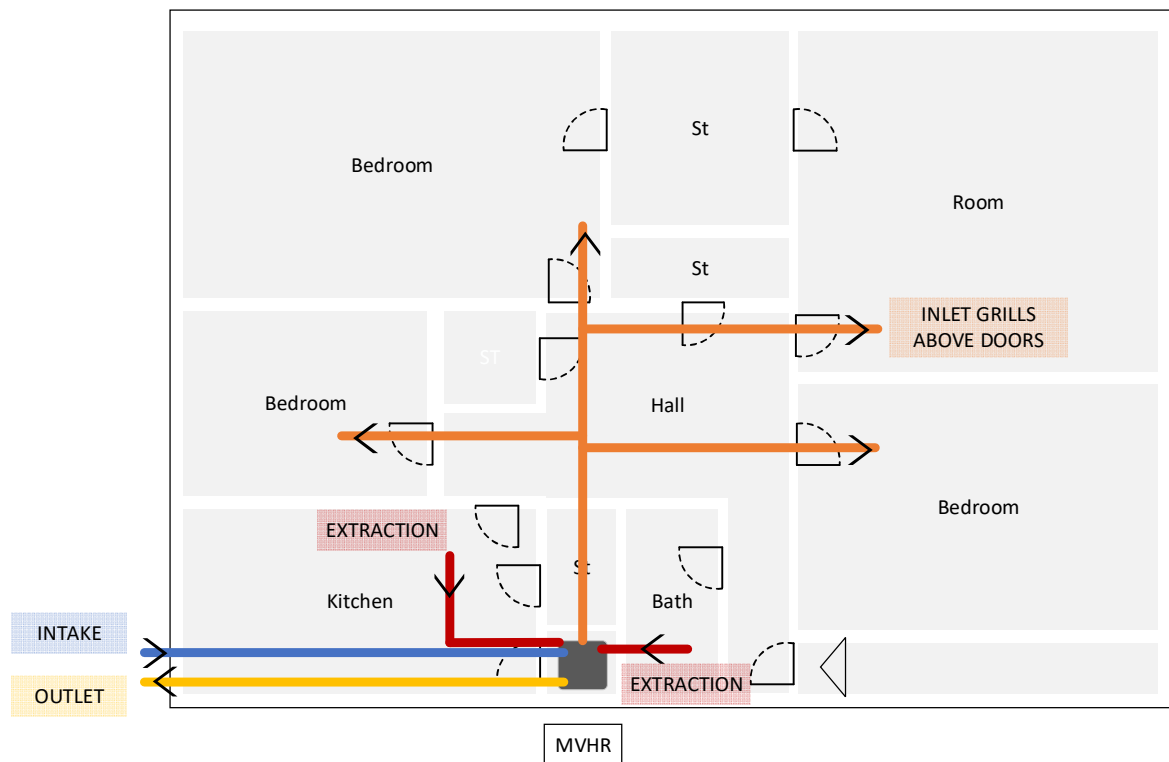


Figure 11 Simplified schematic of the MVHR system in the considered building (at dwelling level)

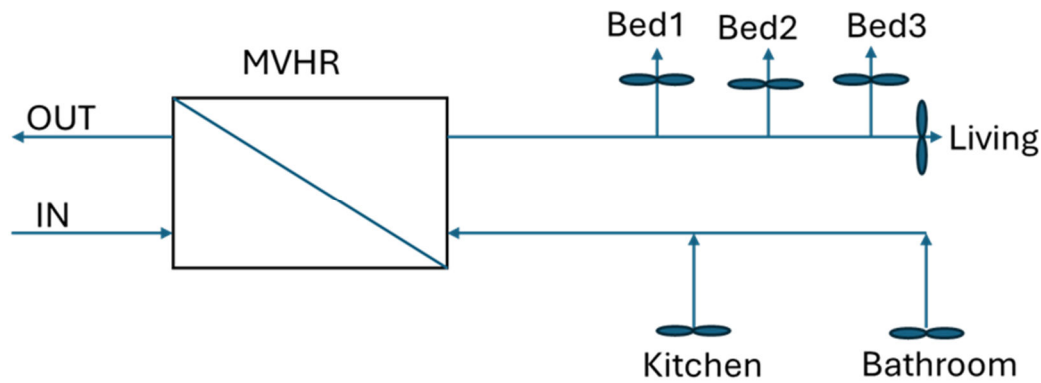


Figure 12 Schematic of the full scale MVHR system

2.2.3.1. System control

The MVHR can be controlled with a simple schedule function, with the system delivering different air mass flow rates in different periods. However, in the performed simulation, a constant air mass flow rate (40 L/s) is delivered by the system 24/7. The used control aims at reproducing how this system generally works in a real application, ensuring that a certain air change, in the range of 0.5 ach/h, is maintained 24/7, in alignment with general standards. In principle, it is possible to imagine for this system a smarter control, e.g., using the monitored CO₂ level inside the dwellings to modulate the MVHR system.

2.2.3.2. Relation with the future system in the Edinburgh demo

The demo case in Edinburgh will feature an MVHR system close to the one presented in the previous paragraphs, with minor adjustments in terms of sizing and positioning of the various components based on the specific needs of the installation at the demonstration site.

2.2.3.3. Relation with the future system in the Krakow demo

A centralised MVHR system will also be installed in the Krakow demo building.

The building will be equipped with an integrated mechanical supply and exhaust ventilation system featuring high-efficiency heat recovery. This ensures proper air exchange throughout the facility, including in basement rooms, ground floor commercial units and first floor residential units. The Air Handling Units (AHUs) will form the core of the system and will be responsible for air treatment and distribution. They will be placed in the attic, where the main supply and exhaust ducts will be routed to the various zones of the building. Each subsystem will be served by AHUs with counterflow heat exchangers, with an expected HR efficiency in the range of 90%, air filters and, in selected installations, modules for neutralising microbiological contaminants. Fresh air will be supplied through ducts in the attic and existing gravity shafts, while exhaust air will be removed through separate ducts. All ducts will be fitted with acoustic silencers and thermal insulation in accordance with design requirements. In systems serving commercial units, heating and cooling of the supply air is enabled by freon-based coil systems. In the residential units, the

supply air is preheated electrically, while waste heat from the district heating substation is utilised in the basement areas. It is planned to operate the AHUs continuously with variable airflow capacity, adjusted according to the current needs of the users. The automation system should be developed to optimise the utilisation of HR and to have full control over the system's operation.

2.2.3.4. Relation with the future system in the Linköping demo

The Linköping demo is already equipped with an MVHR system, which is, however, not working properly at present. For this reason, interventions are planned on the MVHR system, with the aim of having a situation similar to the Krakow demo, in which the MVHR will be the system mainly responsible for ensuring an adequate air quality inside the building for the users.

2.2.4. Connection to the District Heating Network

The last active system solution considered is the connection to a local DHN. Although this is a situation that could be quite peculiar and dependent on the specific context of the considered building and related heating system, this solution is considered as this is the current situation (and the same situation will remain in the future) for two out of five project demo cases.

With reference to the Polish typology n.1, the building is connected to the local DHN via a heat substation. This is designed as a compact, dual-function heat exchanger substation. It supplies SH and DHW to the building. On the DHN side, separate primary circuits for SH and DHW are connected in parallel. Figure 13 shows the schematic of the connection of the building to the DHN.

The installation side comprises flat plate heat exchangers (HX) for SH and DHW, as well as circulation and distribution pumps, an expansion vessel, shut-off and control fittings, a safety valve and a heat meter for each circuit. All these devices can be seen in the complete P&ID in the section 6.2.4, which shows the connection equipment installed in the technical room in the Krakow demo building. Figure 14 shows instead a simplified P&ID useful as a reference to explain the system and its operation.

The substation is operated by a weather-compensated controller, which regulates the supply temperature of the central heating installation and prioritises DHW preparation. The heating medium is supplied from the municipal DHN MPEC. The supply temperature is 135/55°C (for supply and return, respectively) in winter. In summer, the supply and return DHN temperatures are decreased to 70/30°C as the buildings' thermal load is lower in comparison to the winter period and is only related to the DHW needs of the users. The central heating system on the installation side (building or users' side) operates at approximately 70/50°C (weather-dependent) in a standard case, while the DHW system operates at 60°C and is stored in a 100 L buffer tank. The DHW tank serves as a dumper for moderating the eventual peaks in terms of thermal energy demand due to the users' requests.

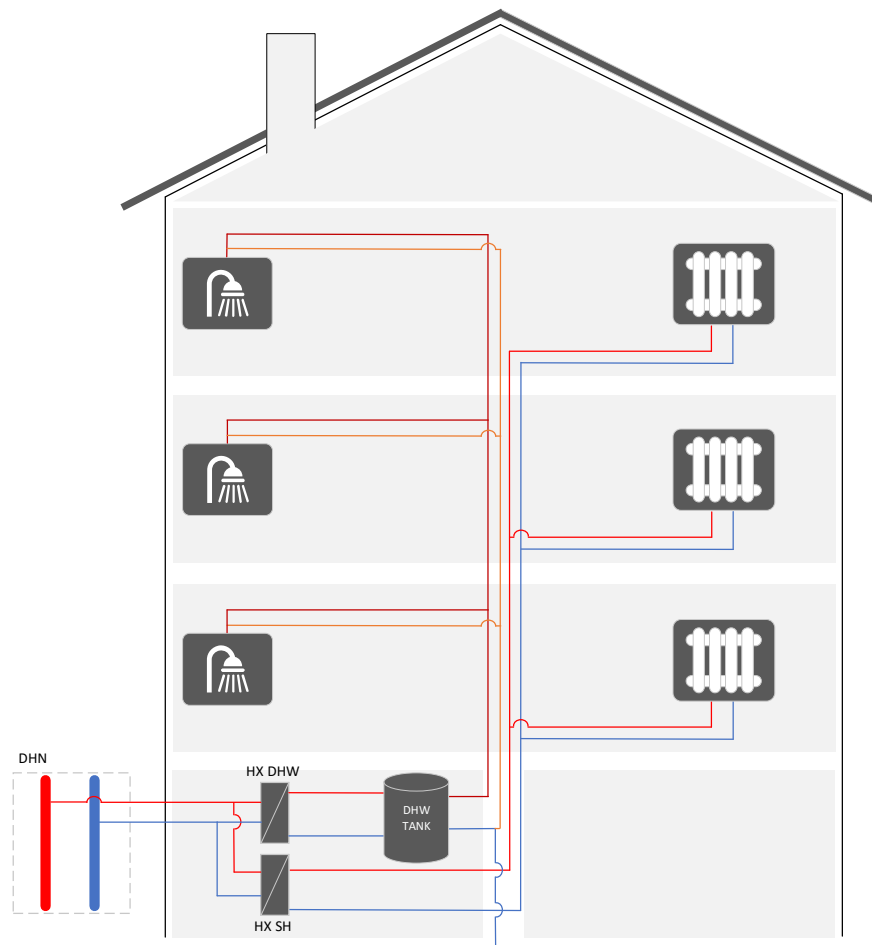


Figure 13 Schematic of the district heating network system with central individual heat node

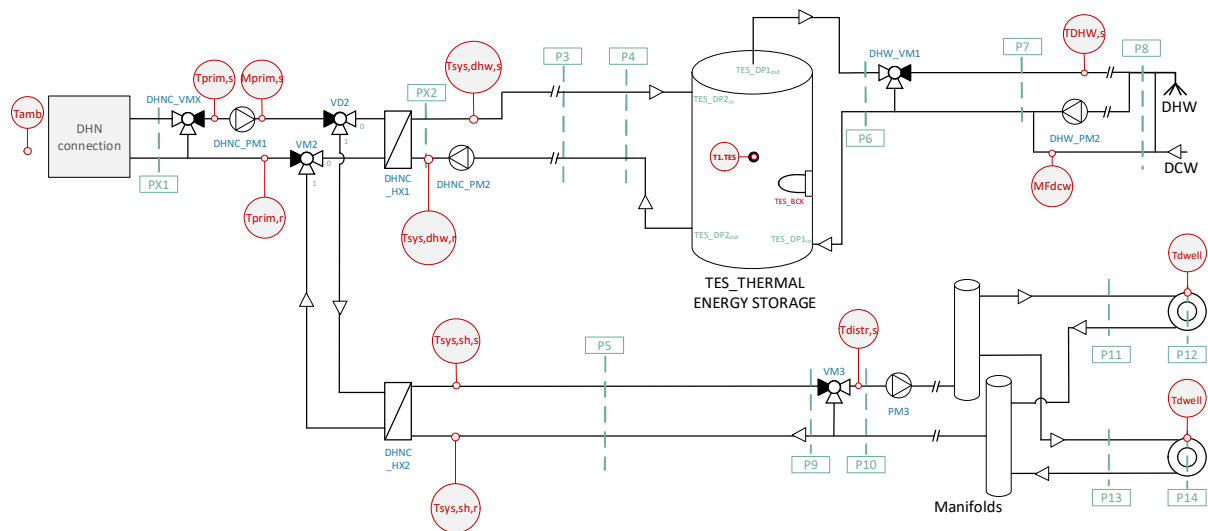


Figure 14 Simplified P&ID of an individual dual-function heat distribution node for supplying central heating and domestic hot water

2.2.4.1. Generation system

In the DHN system, the generation system is constituted by the heat substation (the complex including the counter-current flat plate HXs connecting the DHN to the user and all the related hydraulic components. In this case, and as common practice, two HXs, one for the SH and one for the DHW preparation, are connected in parallel to the DHN.

2.2.4.2. Distribution system

The SH distribution system connects the SH HX to the radiators present in the various building zones. The DHW HX, instead, delivers hot water to a DHW tank and to the users. To ensure the delivery of DHW at the right temperature level, in the considered building, a DHW recirculation circuit is considered.

2.2.4.3. Emission system

The distribution system delivers hot water to the radiators. In the dynamic simulations performed, the radiators present in the different building's thermal zones are sized to cover the peak SH load of the building in the baseline scenario; therefore, before considering any renovation of the thermal envelope. This approach aims to be aligned with a realistic case, in which, in the case of a building renovation that involves thermal envelope insulation interventions, thus reducing peak SH demand, and in which the emission system is untouched, it is possible, and the most common solution, to reduce the supply temperature to the radiators to cover the new (reduced) SH thermal load.

2.2.4.4. Renewable Energy Systems

The Krakow demo building will be the only project demo site with the installation of a PV + battery system (coloured PV panels installed on the roof) and, eventually, an electric battery. For this reason, in the performed simulations, it is considered the presence of a PV + battery system able to cover the HVAC system electric consumption (i.e., the MVHR electric consumption and the electric consumption of the circulation pumps). The installed PV nominal power and the battery capacity considered in the simulations are equal to 4 kWp and 9 kWh, respectively, which these values that are aligned with the sizes of the system that is expected to be installed in the Krakow demo building based on the current situation at the demo.

2.2.4.5. System control

The system control implemented in the dynamic simulations performed has two objectives.

The first is to reduce, as much as possible, the temperature of the water supplied to the radiators, ensuring, at the same time, that the SH thermal demand is covered, and, therefore, the indoor set point temperature is ensured. The reduction of the supply water temperature has the objective of minimising the thermal losses in the distribution circuit. To reach this scope, different climatic curves have been tested in the simulations, with the final ones reported in Table 6. As

visible in this table, two climatic curves are reported depending on whether the MVHR is considered or not. In fact, the MVHR system (with HR efficiency considered equal to 90 %) reduces the SH thermal demand, allowing the use of a lower supply temperature to the radiators. As shown in the table, the minimum supply temperature is always considered equal to 30 °C. This is because a supply temperature lower than 30 °C results in a very limited heat emission from the radiators, which does not motivate the water circulation in these conditions.

Table 6 Climatic curve considered in the DHNC case for the Polish building typology n. 1 with and without the MVHR system

Building considered	Tclimatic MAX	Tclimatic MIN
Without MVHR	55 °C (at Tamb=-13 °C)	30 °C (at Tamb=20 °C)
With MVHR	50 °C (at Tamb=-13 °C)	30 °C (at Tamb=20 °C)

It is important to note that the verification that the heat delivered by the radiators is enough to cover the SH thermal demand has been done not only at the entire building level, considering the entire building as a unique thermal zone, but also at the single thermal zone level. This check is important because, within the same building, different zones can present different specific (in terms of W/m²) SH demands. A supply water temperature level developed based on the overall SH demand could result, in principle, in having some zones of the building where the thermal demand is not covered and, therefore, the desired comfort conditions (in terms of indoor temperature) are not ensured. Instead, the methodology used guarantees that all the building's thermal zones receive the requested SH thermal energy from the radiators.

The second is to develop a control for the primary side of the DHN substation, slightly different from the most commonly used. To this aim, Figure 15, representing the main elements of the DHN substation, is used to explain the control logic used. For the sake of simplicity, only one HX is reported in this figure.

The DHN primary side is, in general, a part of the system designed and controlled by the DHN service supplier that uses a two-way valve to regulate the water flow rate at the primary side of the HXs to ensure the desired outlet water temperature at the HXs secondary side and, at the same time, lower as much as possible the return temperature to the DHN. This control, acting solely on reducing the HXs' primary side mass flow rate, works well, especially in winter, when both SH and DHW thermal demand are present. More specifically, generally, the DHN supplies water at the primary side of the flat plate HXs with a temperature that is not regulated and is equal to the water temperature supplied by the DHN.

However, in summer, or in general in cases with a very low building thermal demand, this control can have limitations in terms of modulation, and this can result in non-constant temperatures at the HXs' secondary side outlet and in a high return water temperature to the DHN (from the HXs' primary side outlet).

To limit this behaviour, the developed control logic controls both the HXs' primary side inlet temperature (through the mixing valve DHNC_VMX in Figure 15) and mass flow rate (through the circulating pump DHNC_PM1 in Figure 15).

The valve DHNC_VMX controls the temperature at the HXs' primary side inlet to the minimum temperature that ensures the reaching of the desired temperature at the HXs' secondary side outlet. The pump DHNC_PM1, instead, is controlled to maintain a fixed DT between the HXs' primary side inlet and outlet, to avoid high return temperature to the DHN, which is generally an undesired behaviour for DHN operators.

In this way, the control acts on both the HXs' primary side inlet temperature and mass flow rate and has more possibilities to ensure the desired HXs' secondary side outlet temperature, limiting at the same time the return water temperature to the DHN.

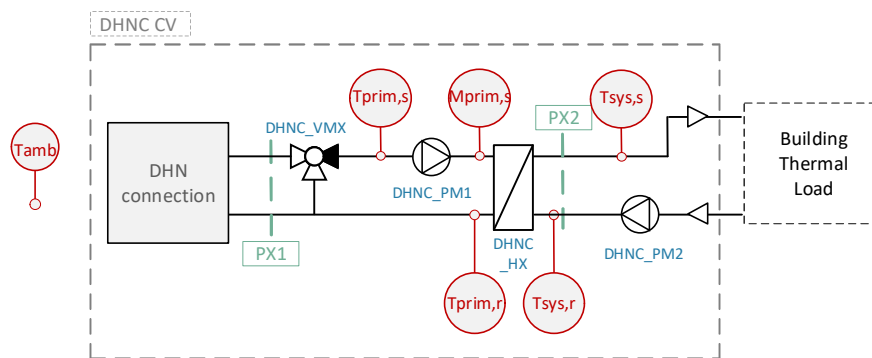


Figure 15 Simplified P&ID of the DHNC. The figures highlight the DHN and one HX, the mixing valve (DHNC_VMX) and the circulating pump (DHNC_PM1), both controlled in the considered control logic; the circulating pump present at the HX secondary side (DHNC_PM2) and a series of temperature (T) and mass flow rate (M) sensors used in the definition of the system control

2.2.4.6. Relation with the future system in the Krakow demo

The Krakow demo building has been recently (2024-2025) connected to the local DHN, in replacement of the old gas boiler, and this situation will remain in the future. Moreover, the building will feature an MVHR system. Therefore, in terms of the HVAC system, the demo situation will be close to that considered in the simulations of the Polish typology n. 1.

In terms of RES, the installation of a PV system on the roof (and eventually a battery) is planned. The sizing of this system, based on the information currently available, will be 4 kWp and a maximum of 10 kWh for the PV system and the battery, respectively.

2.2.4.7. Relation with the future system in the Linköping demo

The Linköping demo building is also already (and will remain) connected to the local DHN. In this demo, it is planned to implement an optimised control strategy, aiming at reducing the supply water temperature to the heat emission units (radiators), with the scope of reducing the distribution system thermal losses, ensuring at the same time the users' comfort in terms of

indoor temperature. The procedure described above and regarding the definition of the climatic curve used for the Polish building typology n.1 has been repeated also for the Swedish building typology n.1 (the one to which the Swedish demo case belongs) and the Table 7 reports the suggested climatic curve to be used to ensure the indoor temperature set point.

Table 7 Climatic curve considered in the DHNC case for the Swedish building typology n. 1 with the MVHR system

Building considered	Tclimatic MAX	Tclimatic MIN
With MVHR	60 °C (at Tamb=-15 °C)	30 °C (at Tamb=20 °C)

2.3. System control of the active system solutions (sensors and their features)

The control logic used to run the active system solutions considered above is already reported in sections 2.2.1.5, 2.2.2.5, 2.2.3.1, 2.2.4.5, respectively.

The aim of this section is instead to report a series of features that the sensors used, and in general the control and monitoring system, should have to allow the implementation, in a real application, of the control logic used in the simulations.

This section is complemented with a series of P&IDs that are developed specifically to highlight the sensors that are essential or optional for the considered control and their position. However, for better readability of the document, these P&IDs are reported in the section 6.2.

In general, all the used devices should support communication via standard and open protocols. The most used open protocols are Modbus or BACNet. Moreover, the system should allow for local and remote control; therefore, they should be equipped with Wifi or other types of remote connection. In terms of time resolution of the acquired measurements, in general, values with resolution in the order of 1-15 min should be used.

The tables in the following sections summarise the main sensors needed to properly control and monitor the operation of the active system solutions considered.

2.3.1. Heat pump system

Table 8 shows the main sensors needed to control and monitor the AWHP system operation. It should be noted that some of the measurements needed could be available directly from the AWHP, without the need for the installation of a dedicated sensor. This, in particular, is valid for the thermal energy delivered by the AWHP, its electric consumption and the temperatures and mass flow rates at both evaporator (ambient air temperature) and condenser inlet and outlet sides.

Table 8 Main sensors required to control and monitor the considered AWHP system

Characteristic	Sensor	Number of sensors
IEQ	Indoor temperature sensor (thermostat)	At least one per dwelling; optional one per zone
	Indoor humidity sensor	At least one per dwelling, optional one per zone (optional if the system does not deliver SC)
	CO ₂ sensor	At least one per dwelling (optional if the system does not control CO ₂)
	VOCs sensor	Optional
System operation and energy flows	Temperature sensors	At least supply and return water temperature from/to the AWHP, temperature in the DHW tanks, Ambient air temperature, temperature delivered to the SH system
	Mass flow rate sensors	At least in the three main system branches: AWHP, DHW and SH parts.
	Thermal energy meter	At least one thermal energy meter to monitor the thermal energy flow delivered by the AWHP, entering the single DHW tanks and delivered to the single dwellings.
	Electric energy meter	At least one electric energy meter to monitor the AWHP el. Consumption. If possible, measurement of the electric consumption of other auxiliary elements (e.g., circulating pumps)

2.3.2. Water loop heat pump system

Table 9 shows the main sensors required to control and monitor the WLHP. As reported for the AWHP system, it should be noted that some measurements could be available directly from the HPs without the need for the installation of dedicated sensors. This, in particular, could be the case for the evaporator and condenser inlet and outlet temperatures and mass flow rate, the thermal energy delivered by each HP and its electric consumption.

Table 9 Main sensors required to control and monitor the considered WLHP system

Characteristic	Sensor	Number of sensors
IEQ	Indoor temperature sensor (thermostat)	At least one per zone
	Indoor humidity sensor	At least one per zone (optional if the system does not deliver SC)
	CO ₂ sensor	At least one per dwelling (optional if the system does not control CO ₂)
	VOCs sensor	Optional
System operation and energy flows	Temperature sensors	At least supply and return water temperature from/to all the HPs, temperature in the buffer and DHW tank, ambient air temperature, temperature delivered to the water loop
	Mass flow rate sensors	At least in all the HPs sides using water, an optional mass flow rate at the user side for DHW usage
	Thermal energy meter	At least thermal energy meters to monitor the thermal energy flow used and delivered by all the HPs

	Electric energy meter	At least electric energy meters to monitor all the HPs el. Consumption. If possible, measurement of the electric consumption of other auxiliary elements (e.g., circulating pumps). Moreover, if a PV + battery system is considered, the PV production, energy to/from the battery and energy to/from the grid are also parameters that should be available for both monitoring and controlling the overall system.
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2.3.3. Mechanical ventilation with heat recovery system

Table 10 reports the main sensors to be used to control and monitor the MVHR system. As the focus for this system is on the indoor users' comfort and not on the delivery of the needed SH thermal energy, the main sensors used are temperature, humidity and CO₂ sensors, with the thermal energy meter being only optional.

Table 10 Main sensors required to control and monitor the considered MVHR system

Characteristic	Sensor	Number of sensors
IEQ	Indoor temperature sensor (thermostat)	At least one per dwelling; optional one per zone
	Indoor humidity sensor	At least one per dwelling; optional one per zone
	CO ₂ sensor	At least one per dwelling; optional one per zone
	VOCs sensor	Optional
System operation and energy flows	Temperature sensors	The ambient, supplied, extracted and exhausted air temperatures (the four temperatures of the HX)
	Mass flow rate sensors	Optional air mass flow rate delivered by the MVHR
	Thermal energy meter	Optional
	Electric energy meter	At least one electric energy meter to monitor the MVHR el. Consumption.

2.3.4. Connection to the District Heating Network

Table 11 presents the main sensors to be considered to control and monitor the energy flows in the case featuring a DHNC.

Table 11 Main sensors required to control and monitor the considered DHNC system

Characteristic	Sensor	Number of sensors
IEQ	Indoor temperature sensor (thermostat)	At least one per dwelling; optional one per zone
	Indoor humidity sensor	At least one per dwelling, optional one per zone (optional if the system does not deliver SC)
	CO ₂ sensor	At least one per dwelling (optional if the system does not control CO ₂)
	VOCs sensor	Optional

System operation and energy flows	Temperature sensors	At least supply and return water temperature from/to the DHN HXs primary and secondary side, temperature in the DHW tanks, Ambient air temperature, water temperature supplied to the SH system
	Mass flow rate sensors	Mass flow rate in the three main system branches: DHN HXs primary side, DHW and SH parts.
	Thermal energy meter	At least one thermal energy meter to monitor the thermal energy flow entering and exiting the DHN HXs and delivered to the single dwellings.
	Electric energy meter	At least one electric energy meter to monitor the electricity consumption of other auxiliary elements (e.g., circulating pumps). Moreover, if a PV + battery system is considered, the PV production, energy to/from the battery and energy to/from the grid are also parameters that should be available for both monitoring and controlling the overall system.

2.4. Smart Readiness Indicator assessment

The Smart Readiness Indicator (SRI) is assessed for the developed active system solutions in the related Historic Buildings following method B. This method is preferred over method A (a simplified method) as the Historic Buildings are considered not standard residential buildings and are often characterised by peculiarities (e.g., limitations in terms of thermal control solutions that can be installed due to the presence of spaces under heritage protection) that a simplified SRI assessment would not consider.

Moreover, to simplify the SRI assessment procedure for Historic Buildings, some of the nine technical domains used to assess this indicator are not considered. More specifically, the domains not accounted for in the assessment are Lighting, Dynamic Building Envelope and Electric Vehicle (EV) Charging. These technical domains are not present in the considered active system solutions within the considered buildings.

This “simplified” assessment, considering a limited number of technical domains, allows for ensuring that the SRI is calculated according to the current detailed method (method B), with results for different buildings and systems that are comparable. On the other hand, the focus on only a few technical domains, avoiding assessing others that are considered less or not relevant in the Historic Buildings and systems accounted for, allows for a faster assessment.

The section 3.4 reports the results in terms of SRI index and the related class for the different active system solutions considered in this document.

As the assessment following method B includes a huge number of inputs resulting in the end in one overall number (the SRI index), it is considered useful to provide two scenarios (called Level 1 and Level 2) representing the SRI that can be achieved with a sort of more standard solution, using, in general, components already available on the market, and a second one, characterised

by smarter components and/or features (e.g., components allowing for demand response management and, overall, grid interactions) that starts to be available on the market (and therefore constitute potentially a solution) but cannot be considered standard as of today.

3. Results and Discussion

This section reports the results of the dynamic simulations performed with the active system solutions in the considered buildings and the SRI assessment for the same solutions.

First, the section 3.1 reports the thermal demand for the different building services (SH, SC, DHW) in the different buildings and considering current and future climates.

Then, in the section 3.2 the analysis focuses on the active system solutions performance. The results will be analysed first in selected (exemplary) weeks considered representative of the active systems' operation in the winter and, where interesting, the summer season. This assessment at a weekly time horizon allows us to note dynamic behaviours visible only at a short time scale, such as the trends in thermal energy delivered and consumed and the evolution of indoor building temperature.

Subsequently, an analysis at a yearly time horizon is reported, focusing first on specific features of the considered system (e.g., the reduction in the SH distribution thermal losses thanks to the adopted climatic curve in the case of the system featuring the connection to a local DHN) and then presenting an overall system performance assessment based mainly on the indicators reported in the Table 12.

The indicators used are, in general, taken from Task 1.6 and reported in D1.6 [11], with minor additions in the case of specific needs for a specific system (e.g., the assessment of WLHP system performance through the system COP).

The section 3.3 verified whether the active system solutions sized for the current climate are able to ensure the desired indoor temperature, also accounting for the future climatic scenario. This analysis is reported for the AWHP in the Spanish building typology n.1 as this is the most critical case.

Finally, section 3.4 reports the SRI for the different active system solutions considered.

Overall, the analysis presented can be considered as a standard and suggested procedure to assess the performance of the active system solutions presented and to have an overall picture of how the systems work.

Table 12 Performance Indicators used to assess active system solutions' performance (extracted from D1.6)

Assessment category	Name	Description	Unit
Energy performance	Non-renewable primary energy demand	Amount of non-renewable primary energy needed to meet the energy demand associated with a typical use of the building, which	kWh/(m ² ·y)

		includes energy used for SH, SC, ventilation and DHW	
	Energy consumption	Energy consumed for SH, SC, ventilation and DHW	kWh/(m ² ·y)
	Self-sufficiency	Share of energy demand met by on-site production	%
	Self-consumption	Share of total energy produced on-site used by the building itself	%
Life cycle assessment (LCA)	Operational GHG emissions	Greenhouse gas emissions associated with the energy consumption of the technical building systems during the use and operation of the building	tCO _{2,eq} /y
Technical compatibility	Smart Readiness Indicator (SRI)	The building's capacity to interact with its occupants and energy systems efficiently	% - SRI class

3.1. Analysis of the buildings' thermal energy demand

This section presents an assessment of the thermal needs of the buildings considered, along with their annual values. The annual values are reported in Table 13.

As can be seen in this table, the Spanish building typology n. 1 is the only one characterised by SH, SC and DHW thermal demand, with SC being the highest yearly building's thermal demand. The simulation performed with the future climatic conditions indicates the highest variations in terms of building demand, in comparison to the current climatic scenario, among all the considered buildings. More specifically, the SH demand is reduced to around 1/3 of the current one, while the SC thermal demand almost doubled. However, it must be noted that these results represent the thermal energy demand over the entire year. As demonstrated in the section 3.3, the AWP system, sized based on the current climatic conditions, will be able to ensure the desired indoor temperature level also in the future climate scenario.

The Polish building typology n.1 is characterised by SH and DHW thermal demand, with SH being the main building's thermal need. In comparison to the current climatic conditions, the future ones indicate a reduction in the SH demand in the range of 25 %. The value of DHW demand, in terms of kWh/m²/y, is notably lower in comparison to the Spanish building typology n.1 as, in the Polish case, only some parts of the building are considered residential and characterised by a DHW consumption.

The Swedish building typology n.1 shows similar variations in the SH demand passing from the current to the future climatic scenario in comparison to the Polish building typology n.1 (-28 %). However, it is interesting to note the lower SH demand in terms of kWh/(m²·y) in comparison to the Polish case. These lower values are obtained, although the climatic conditions in Sweden are colder in the heating season, thanks to the more performant thermal envelope considered in the

Swedish building typology n. 1. No DHW demand is considered in the Swedish building typology n.1 as this building (office building) is not characterised by a specific DHW demand.

Finally, the Scottish building typology n.1 shows a reduction, in terms of SH thermal demand, passing from the current to the future climatic scenario, lower in comparison to the previous cases and in the range of 15 %. Although the Scottish building typology n.1 is a residential building, no specific assessment has been done in terms of DHW demand, as this demand is covered by systems that are outside the scope of the project for this specific demo case. In the case the DHW demand needs to be evaluated, a value in the range of 20 kWh/m²/y is expected, aligned with the typical DHW thermal demand in residential buildings.

Table 13 Thermal demands for SH, SC and DHW of the different building typologies considered in the current (black) and future (red) climatic scenario

Building considered	SH	SC	DHW
	[MWh/y] ([kWh/(m ² ·y)])	[MWh/y] ([kWh/(m ² ·y)])	[MWh/y] ([kWh/(m ² ·y)])
Spanish building typology n. 1	2.858 (15.08) 0.844 (4.45)	4.817 (25.95) 8.906 (47.00)	3.321 (17.53)
Polish building typology n. 1	57.592 (164.57) 42.713 (122.05)	-	2.419 (6.91)
Swedish building typology n. 1	130.937 (68.6) 94.250 (49.4)	-	-
Scottish building typology n. 1	35.914 (96.54) 30.325 (81.52)	-	-

3.2. Analysis of the system operation and consumption

3.2.1. Heat pump system

In the following, the simulation results are analysed, focusing first on specific weeks considered representative of system operation during the winter and summer periods. This detailed analysis allows us to identify and highlight specific system behaviour. Section 3.2.1.3, instead, presents a series of analyses at a yearly time horizon.

3.2.1.1. Exemplary winter week (1-7 Jan)

This section assesses a series of system performance and behaviour over the period 1-7 Jan. This week is considered representative of the typical winter operative conditions.

3.2.1.1.1. Thermal load delivered to the users and from the AWP

In the considered exemplary winter week, the hourly thermal energy delivered for SH to the three dwellings considered is shown in Figure 16. As can be noted in this figure, the SH thermal energy

delivered presents a peak around 07:00 for all dwellings. This is due to the considered indoor temperature set point (taken from the Spanish standard) that, at 07:00, considers a change from 17 to 20 °C as reported in Table 2. After the peak period, a reduced thermal energy is sufficient to maintain the set point temperature (20 °C) until 23:00, when the indoor temperature set point is decreased to 17 °C. This reduced set point temperature results in the switching OFF of the SH system (periods with SH thermal energy equal to 0 in Figure 16).

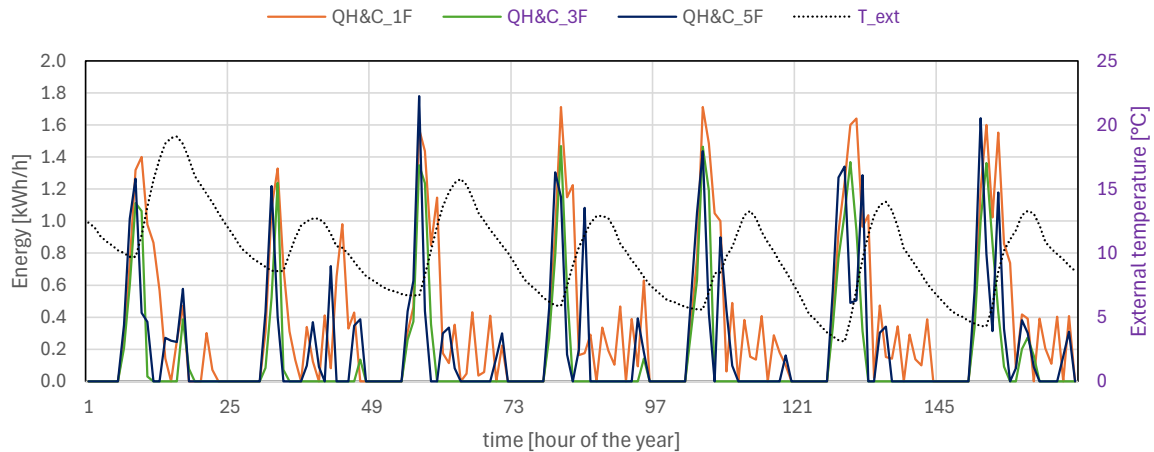


Figure 16 Thermal energy delivered to the users for SH in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Exemplary winter week (1-7 Jan)

Regarding the AWHP operation, Figure 17 shows the thermal energy delivered by the machine in SH and DHW mode. As can be noted in the figure, the SH operation is strictly related to the SH demand of the dwellings visible in Figure 16. Moreover, the AWHP works to charge the DHW tanks, with this operation occurring especially in the morning (06:00-09:00). This is because the DHW tanks considered have a limited volume (120 l) and therefore, in correspondence with the peak DHW users' demand (occurring generally between 06:00 and 09:00), they are often completely discharged and need to be charged by the AWHP system.

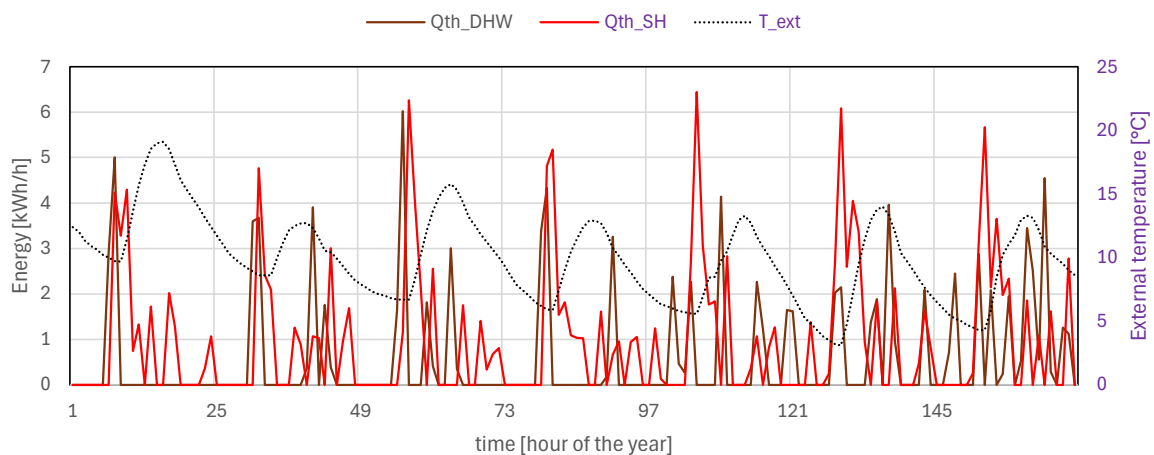


Figure 17 Thermal energy delivered by the AWHP for SH (red) and DHW (brown). Right y-axis: ambient air temperature (dotted black). Exemplary winter week (1-7 Jan)

3.2.1.1.2. Electric consumption and PV + battery system contribution

Figure 18 shows the AWHP electric consumption in SH and DHW mode in the considered exemplary winter week. In the figure, it is possible to see the peaks in SH operation in the early morning due to the increase in the indoor temperature set point as reported above. Moreover, the DHW tanks' charging, although characterised also by a peak in the period 06:00-09:00, presents also similar peaks during the rest of the day. These last peaks are more random in time start due to the variability in the DHW users' demand.

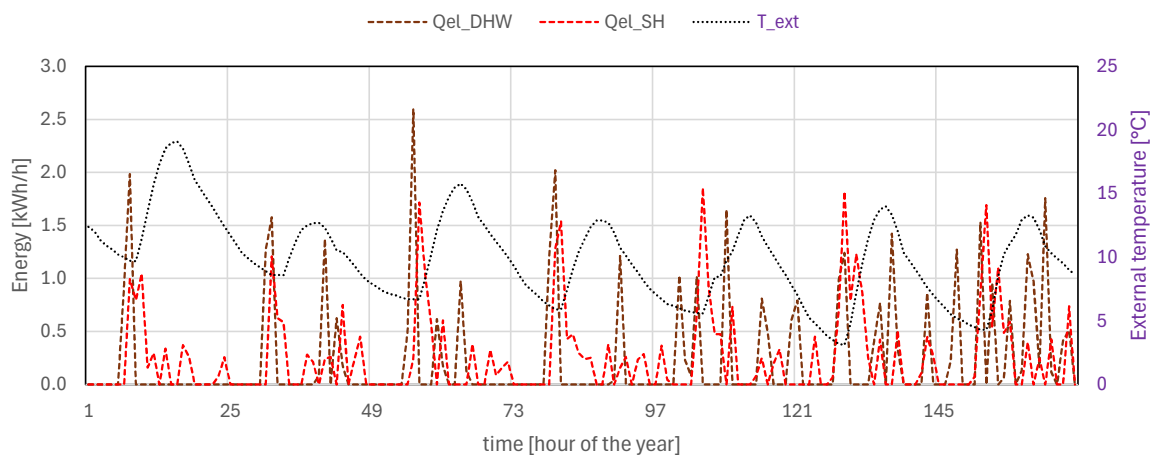


Figure 18 AWHP electric consumption for SH (red) and DHW (brown). Right y-axis: ambient air temperature (dotted black). Exemplary winter week (1-7 Jan)

The HVAC system's electric consumption, which in this case is mainly represented by the AWHP electric consumption and, secondly, by the electric consumption of the circulation pumps, is covered firstly using the PV + battery system and, in case this is not sufficient, the remaining load is covered using electricity from the grid.

Figure 19 reports the electric energy flows, highlighting the contribution to covering the electric load given by the PV, the battery and the grid. Moreover, the eventual PV excess production (PV dumped power) and the battery State of Charge (SoC) are also shown.

As visible in the figure, the electric consumption peak in the early morning is in the range of 3-4 kW, while for the rest of the day, the peaks are limited and up to around 2 kW. Although the PV production is limited, both for the small PV installed power considered (2 kWp) and for the limited solar resource availability in the considered week (1-7 Jan), the PV production is higher than the HVAC system consumption for some hours on almost all days of the considered exemplary winter week, with the surplus that is stored in the battery and used later in the evening. In the considered winter week, electricity from the grid is generally used to cover the morning electric consumption peaks. The figure also shows the battery SoC to highlight the periods when the battery is charged (generally around noon) and discharged (often in the evening). Although the battery SoC is always in the range 0-1, the right y-axis in the figure is set to improve the overall readability of the figure.

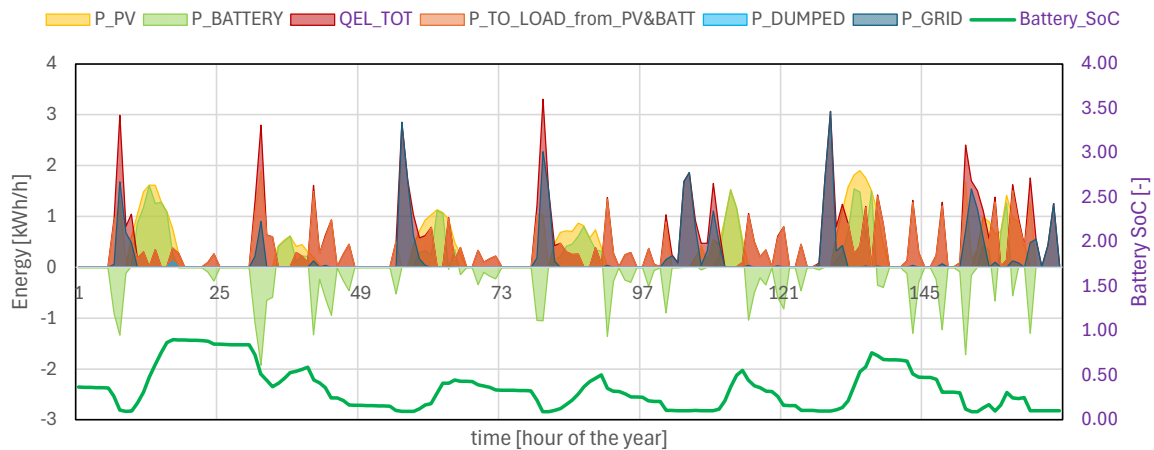


Figure 19 Electrical energy flows: PV production (yellow), power to/from battery (green), total electric consumption (red), electric consumption covered by PV and battery (orange), dumped power (light blue), power from grid (blue). Right y-axis: battery SoC (green line). Exemplary winter week (1-7 Jan)

3.2.1.1.3. System COP evaluated on hourly basis over the different days

Figure 20 put together the thermal and electrical energy assessments reported in the previous sections 3.2.1.1.1 and 3.2.1.1.2 showing, for each day of the considered winter week, the thermal energy delivered for SH (red bar) and DHW (dark red bar) to the users, the HVAC system electric consumption (orange bar), and the system COP (purple circles). In this regard, the system COP is calculated by dividing the total thermal energy delivered to the users (for SH, DHW, SC) by the total HVAC system electric consumption.

As can be noted in the figure, the system COP is in the range 2-3, with higher values in correspondence with days characterised by higher AHP source (ambient air) temperature. Moreover, the system COP is also lower in those days with higher DHW users' demand, as this implies longer operation for the AHP in conditions with a high set point temperature at the condenser side (in the range of 55 °C) to charge the DHW tanks.

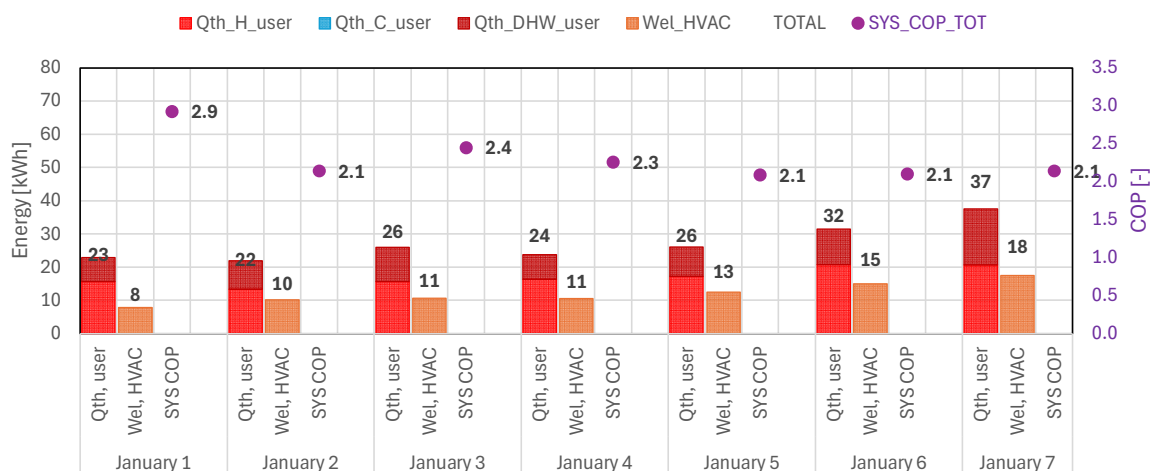


Figure 20 Thermal energy delivered to the users for SH (red bars) and DHW (dark red bars), HVAC system electric consumption (orange bars). Right y-axis: system COP (purple circles). Exemplary winter week (1-7 Jan)

3.2.1.1.4. Indoor temperature

This section aims to verify that the SH thermal energy delivered to the dwellings in the considered winter week is sufficient to ensure the desired indoor temperature set point.

As visible in Figure 21, in the considered winter week, the decrease in temperature during the night is generally limited to 1-1.5 °C. This is partly due to the already improved thermal envelope performance in terms of U-value in comparison to the baseline case due to the planned insulation intervention, and partly due to the mild temperatures in the considered winter week. In any case, it has been checked that, over the entire heating season, the minimum temperature reached by the apartments is in the range 17.5-18.0 °C.

The considered AWHP system also ensures that the indoor temperature is increased in the early morning, in correspondence with the indoor set point temperature increment, in an acceptable short time (max. a few hours). Moreover, it must be noted that eventual delays and slow indoor temperature increments can be due to the control logic considered, which prioritises DHW tanks' charging over SH/SC operation.

Finally, on the first day of the considered winter week, it is possible to observe an increment of the indoor temperatures in the early afternoon. This increment is due to the increment of the indoor temperature set point, as in this period, there is PV production excess that cannot be stored in the battery, as this is already fully charged (see Figure 19). The increment of the set point in these conditions allows for limiting the PV dumped power, using the building as thermal storage and reducing its heating demand in later periods in which PV is less or not available.

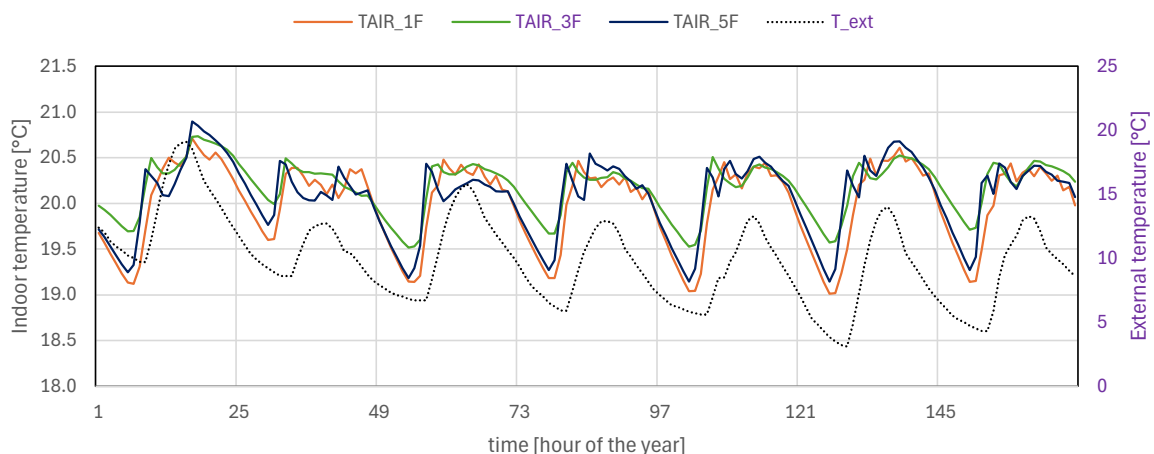


Figure 21 Indoor air temperature in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Exemplary winter week (1-7 Jan)

3.2.1.2. Exemplary summer week (1-7 Jul)

Similar to what is reported in section 3.2.1.1, this section analyses system performance and behaviour over the period 1-7 Jul, which is considered representative of typical system operating conditions in the summer period.

3.2.1.2.1. Thermal load delivered to the users and from the AWHP

Figure 22 shows the SC thermal energy delivered to the three dwellings in the considered exemplary summer week. This week, the ambient temperature varies generally between 20 and 35 °C and the cooling demand is concentrated in the period 15:00-23:00, the one characterised by the minimum indoor air temperature set point (see Table 2). The peaks and valleys trend characteristic of all dwellings is due to two reasons. The first is the priority given to the DHW tanks' charging. In this period, although an SC request from the dwellings' thermostats is detected, this is covered solely using the cooling thermal energy available in the buffer tank. As soon as the temperature in the buffer tank increases, the temperature of the water supplied to the fan coils also increases, consequently resulting in lower cooling thermal energy delivered by these units. This transitory operation ends as soon as the AWHP complete the DHW tank(s)' charging and can be switched to cooling mode to properly re-establish the buffer tank set point temperature. The second is the use of a temperature set point with hysteresis dead bands to control the indoor temperature that leads, especially in cooling mode, where a climatic control is not used, to ON/OFF operation of the fan coils. As shown in Figure 27, the SC system tends to maintain the dwellings in the range 24.5-25.0 °C.

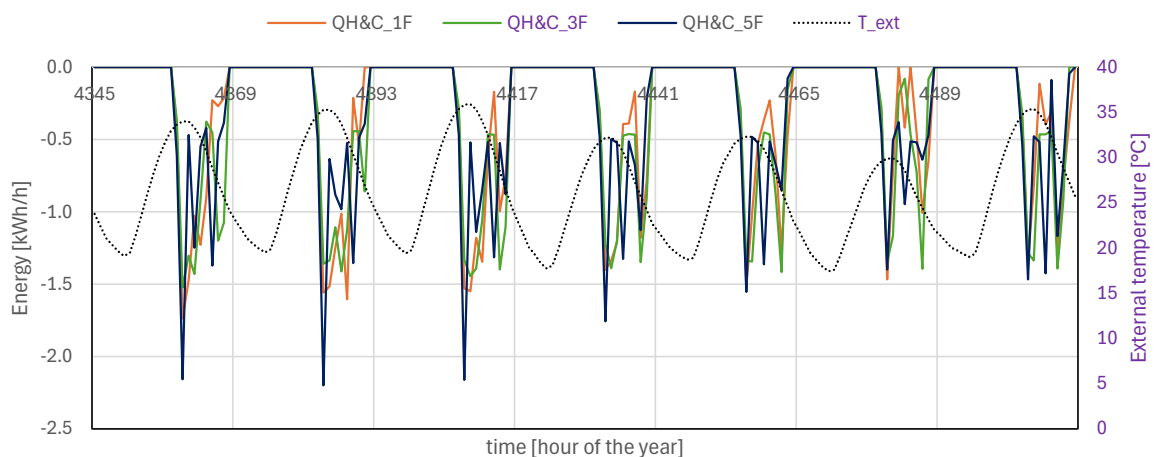


Figure 22 Thermal energy delivered to the users for SC in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Exemplary summer week (1-7 Jul)

Figure 23 shows instead the thermal energy delivered by the AWHP for SC and DHW tanks' charging. As visible in this figure, in the considered summer week, SC thermal demand is the dominant one with the peaks in the period 15:00-23:00 for the reasons described above.

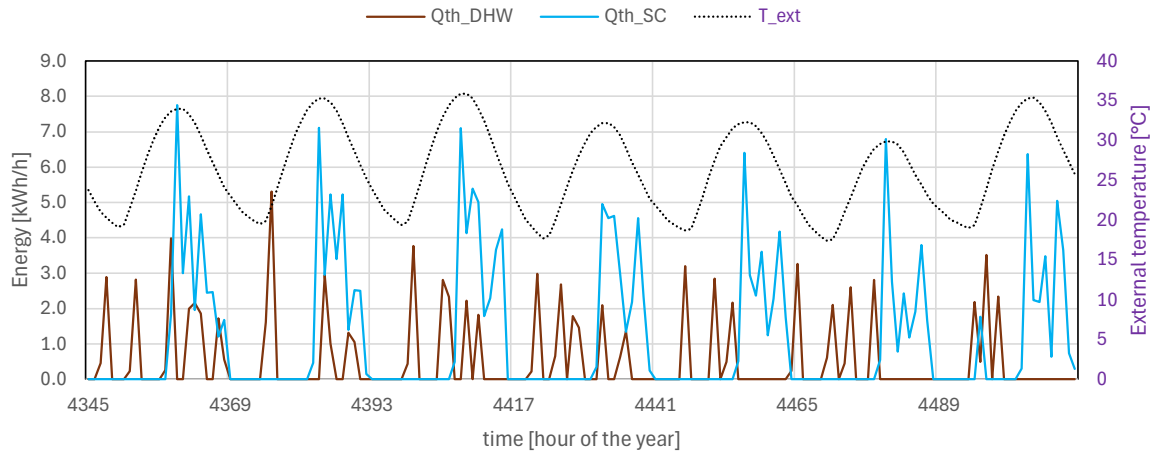


Figure 23 Thermal energy delivered by the AWP for SC (blue) and DHW (brown). Right y-axis: ambient air temperature (dotted black). Exemplary summer week (1-7 Jul)

3.2.1.2.2. Electric consumption and PV + battery system contribution

Regarding the electric consumption, Figure 24 reports the AWP electric consumption in DHW and SC mode. As visible in the figure, the main peaks are due to AWP SC operation and occur at around 15:00 when the indoor temperature set point is decreased to 25 °C, activating the system operation in SC mode.

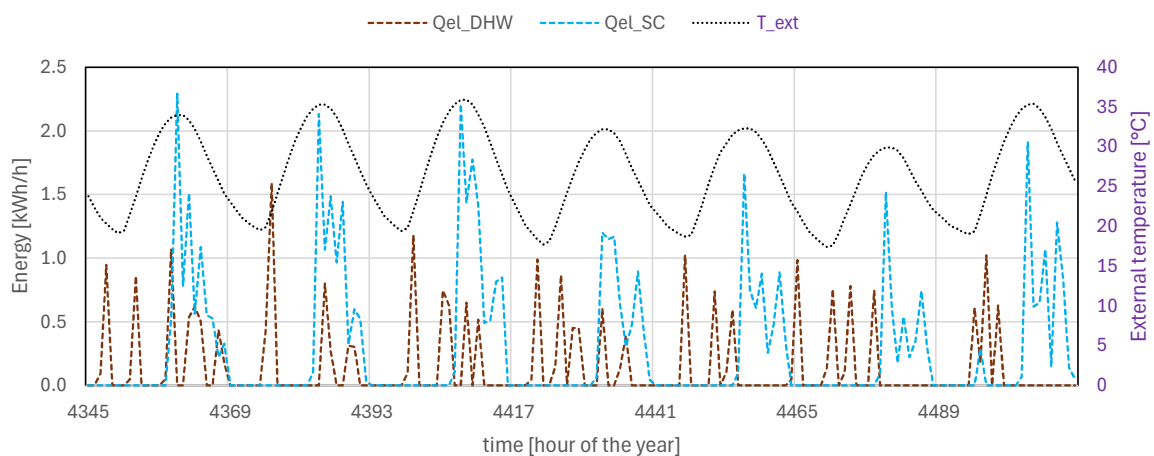


Figure 24 AWP electric consumption for SC (blue) and DHW (brown). Right y-axis: ambient air temperature (dotted black). Exemplary summer week (1-7 Jul)

Lastly, Figure 25 shows the electrical energy flows in the considered exemplary summer week. In this period, the PV and battery are often able to cover the majority of the HVAC system's electric consumption, with the grid contribution limited and concentrated especially around 15:00 when there is the peak consumption due to SC. In these conditions, it could happen that the considered inverter, sized based on the PV system power, is not able to cover the HVAC system power consumption entirely, therefore requiring a small contribution from the electric grid.

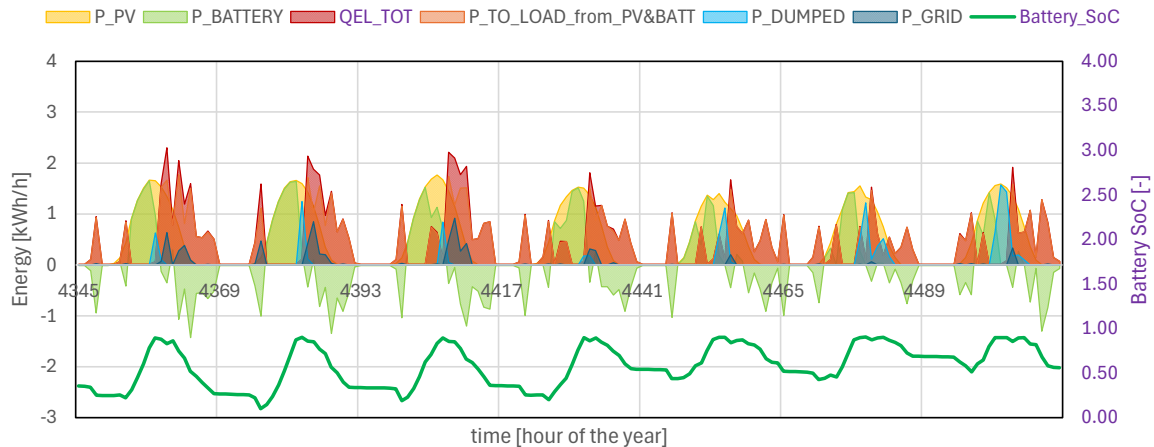


Figure 25 Electrical energy flows: PV production (yellow), power to/from battery (green), total electric consumption (red), electric consumption covered by PV and battery (orange), dumped power (light blue), power from grid (blue). Right y-axis: battery SoC (green line). Exemplary summer week (1-7 Jul)

3.2.1.2.3. System COP evaluated on an hourly basis over the different days

Similar to Figure 20, Figure 26 puts together thermal energy delivered to the users for DHW and SC, the related HVAC system electric consumption and the consequent system COP.

The performance in terms of daily system COP in the considered summer exemplary week is in the range 2.5-3, values similar to those obtained in the exemplary winter week, although the system works in different operative conditions and partly different operational modes. The system COP is relatively low because the SC demand peaks often occur in the hottest hours of the day (see Figure 23), when the AWHP COP in cooling mode (AWHP Energy Efficiency Ratio, EER) is low, as the ambient air (which is used as a thermal sink to reject the heat extracted from the indoor ambient) temperature is particularly high.

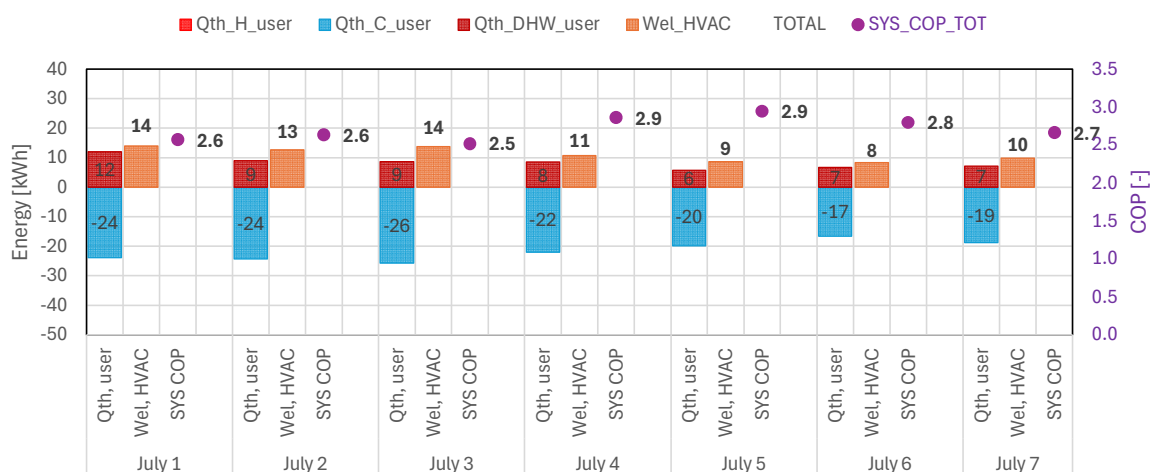


Figure 26 Thermal energy delivered to the users for SC (blue bars) and DHW (dark red bars), HVAC system electric consumption (orange bars). Right y-axis: system COP (purple circles). Exemplary summer week (1-7 Jul)

3.2.1.2.4. Indoor temperature

Figure 27 reports the indoor temperature trends for the three dwellings. As visible in the figure, the considered AHP system is able to ensure the reaching of the desired temperature set point in a short time in the considered exemplary summer week.

It has also been verified that the system can almost always ensure the reaching of the desired indoor temperature set point, even on the hottest days of the year, characterised in the used climatic file, by ambient air temperature up to around 42 °C.

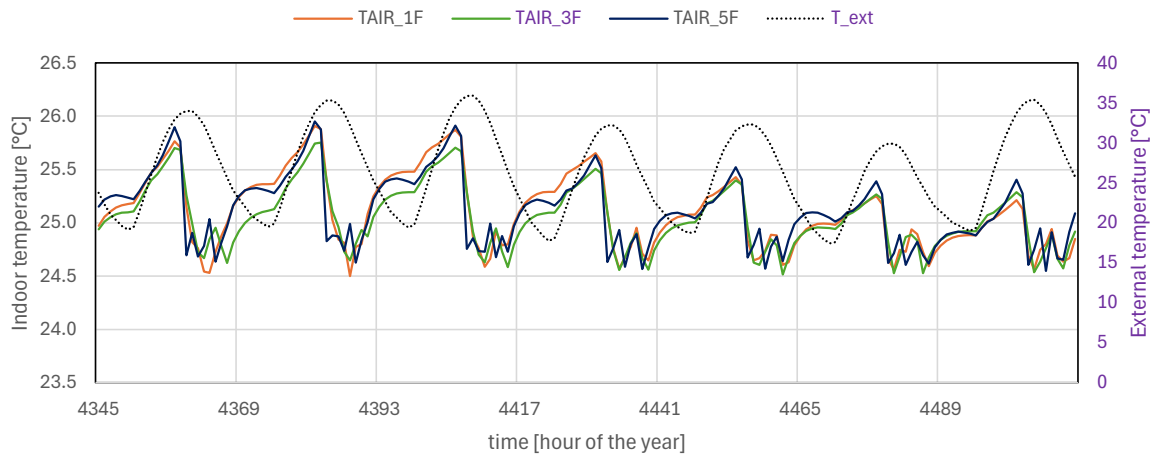


Figure 27 Indoor air temperature in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Exemplary summer week (1-7 Jul)

3.2.1.3. Yearly assessment

This section reports the assessment at the yearly level of the system performance with, in some cases, also monthly assessments (e.g., for a better understanding of the PV and battery contribution to cover the electric consumption through self-consumption and self-sufficiency).

3.2.1.3.1. PV and battery system self-consumption and self-sufficiency

Self-consumption (the electric consumption considered which is covered by PV and battery divided by the total PV production) and self-sufficiency (the electric consumption considered which is covered by PV and battery divided by the total electric consumption considered) are calculated not only at yearly time horizon but also at the monthly one to better analyse how, along the year, PV and battery contribute to the covering of the HVAC system electric consumption.

As visible in Figure 28, self-consumption is maximised in winter and summer months. This is because these months are characterised by high HVAC system consumption to cover the SH and SC thermal loads and, therefore, the limited PV production (limited mainly by the reduced size of the PV system, equal to 2 kWp) is mainly consumed within the building. Moreover, the presence of a relatively large battery (9 kWh) in comparison to the considered PV nominal power allows for storing a good portion of the PV surplus for later usage within the building. On the contrary, self-

consumption is low in mid-season months, when the building is characterised by a limited SH or SC demand. In this condition, an important fraction (at least 40 % in April, May and October) of the PV production is sent to the grid.

The self-sufficiency trend over the months is instead almost the opposite in comparison to the self-consumption one, with the highest values in the mid-season months and the lowest in the winter period. Being self-sufficiency an indication of how much the electric consumption is covered by electricity locally produced (and eventually temporarily stored), the low values in the winter period are the result of the limited PV production due to the limited solar availability, and the high consumption needed to cover the SH thermal demand. In the mid-season months, the limited electric consumption (due to the absence of both SH and SC demand) can be covered almost entirely by the PV and battery system. In summer, the increased AHP system consumption to cover the SC thermal needs of the building and the maximum solar availability result in monthly self-sufficiency values that are between those of the winter period and those of the mid-season period.

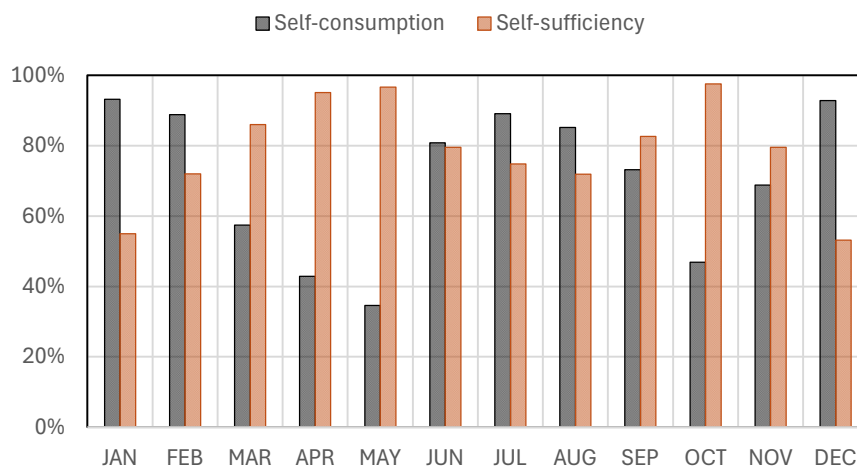


Figure 28 Monthly self-consumption (dark grey) and self-sufficiency (orange) values

Moreover, Figure 29 analyses in more detail which part of the self-sufficiency is due to the instantaneous consumption of the PV production and to energy temporarily stored in the battery.

As visible in the figure, for the coldest winter months (Dec, Jan), the PV production that is consumed within the building comes half from the battery, while the other half is instantaneously produced and self-consumed. This indicates that, although there is limited solar availability in the coldest months, in the considered case, there are periods during the day in which there is PV surplus, and this can be stored in the battery.

For the rest of the year, instead, the main contribution to self-sufficiency is given by the battery, indicating that there is a certain temporal mismatch between the electric consumption and the PV production, and the presence of the battery is particularly beneficial in increasing the self-sufficiency. However, it must be noted that the particularly large capacity of the considered battery in relation to the considered PV system power and the considered indoor air set point

temperature (with notable variations along the day) are both factors that push towards a higher importance of the battery in the considered system.

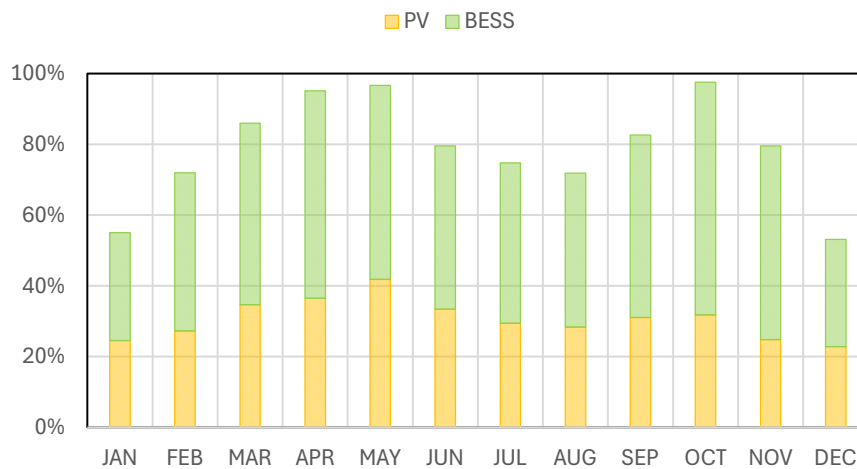


Figure 29 Monthly self-sufficiency associated with PV production instantaneously self-consumed (PV contribution, yellow), and PV production temporarily stored in the battery and later used (BESS contribution, green)

3.2.1.3.2. Overall yearly assessment

The Table 14 reports a series of Performance Indicators (PIs) used to assess system performance in different scenarios. In terms of the building's thermal envelope, the wall construction (and therefore the U-values) considered are those of the Spanish building typology n.1 after an ideal renovation that includes insulating a series of opaque elements and improving the thermal performance of the windows.

In terms of the active system solution, the reference point (base scenario with only passive renovation in the table) accounts for electric radiators to cover the SH thermal demand, electric boilers for the DHW production, and air/air HPs (split units) for covering the SC demand. The efficiency of both electric radiators and electric boilers for DHW production is assumed, for the sake of simplicity, equal to 1. On the contrary, the same efficiency of the AWHP system in SC mode is used for the split units. Although this is also a simplification, it is considered acceptable for the scope of this comparison.

As shown in the table, the use of an AWHP system covering all the building thermal needs results in a reduction from 8.492 MWh/y to 3.571 MWh/y of the electricity consumed to deliver the same thermal energy for SH, DHW and SC. Moreover, if a PV and battery system is also considered, the final energy electric consumption is equal to 3.584 MWh/y (value not visible in the table), with only a minor fraction (0.932 MWh/y) taken from the grid, and the rest (74 %) coming from the PV or from the battery.

In terms of non-renewable primary energy consumption, the Base scenario with the AWHP system allows for more than halving the value obtained for the base scenario with electric radiators and electric boilers (7.168 MWh/y vs. 17.043 MWh/y), while the reduction is of around

89 % in the case in which the AWHP system is coupled with the PV and battery system (1.861 MWh/y).

The same reduction in percentage terms is also obtained for the GHG emission that passes from 1.8 tCO₂,eq/y in the base scenario with electric radiators and electric boilers to 0.6 tCO₂,eq/y in the case with only the AWHP system and to 0.2 tCO₂,eq/y in the case with also the PV and battery system.

Table 14 Overall yearly assessment for the AWHP system in the Spanish building typology n.1. Primary energy consumption and GHG emissions are calculated based on the factors reported in the section 6.4 for Spain

Variable	Unit	Base scenario (only passive renovation)	Base scenario with AWHP	Base scenario with AWHP, PV and battery
Ef, el. SH	MWh/y (kWh/(m ² ·y))	2.360 (12.46)	0.649 (3.43)	0.651 (3.44)
Ef, el. SC	MWh/y (kWh/(m ² ·y))	1.136 (6.00)	1.136 (6.00)	1.147 (6.05)
Ef, el. DHW	MWh/y (kWh/(m ² ·y))	4.995 (26.36)	1.693 (8.94)	1.692 (8.93)
Ef, el. From the grid	MWh/y (kWh/(m ² ·y))	8.492 (44.82)	3.571 (18.85)	0.932 (4.92)
Ep,ren	MWh/y (kWh/(m ² ·y))	3.363 (17.75)	1.414 (7.46)	3.024 (15.96)
Ep,nren	MWh/y (kWh/(m ² ·y))	17.043 (89.95)	7.168 (37.83)	1.861 (9.82)
Ep,tot	MWh/y (kWh/(m ² ·y))	20.406 (107.70)	8.582 (45.29)	4.885 (25.78)
Self- sufficiency	%	-	-	74
Self- consumption	%	-	-	70
GHG	tCO ₂ ,eq/y	1.5	0.6	0.2

Table 15 reports the AWHP COP, calculated by dividing the thermal energy delivered by the AWHP in the considered mode (SH, SC, DHW) by the electric consumption of the AWHP in that operational mode.

On the contrary, the system COP is calculated by dividing the thermal energy delivered to the users in the considered mode by the total HVAC system electric consumption in that operational mode. Therefore, the system COP is always lower as, on one side, it accounts for all the thermal losses between the AWHP and the users that decrease the thermal energy delivered and, on the other, it accounts for a higher electric consumption, including not only the AWHP electric consumption but also the one of the auxiliary elements (e.g., circulating pumps).

As visible in the table, the AWHP COP is in the range of 3.6-3.7 for SH and SC operation, while it is around 3.0 in DHW mode. The lower value in DHW mode is due to the temperature level

requested at the condenser side of the AWHP, which is always higher than 50 °C to ensure the DHW tanks are charged in a short time.

Table 15 AWHP and system COP in the different operational modes (SH, SC, DHW)

Variable	Unit	SH	DHW	SC
AWHP COP	-	3.7	3.0	3.6
SYS COP	-	2.7	2.0	2.7

Regarding the IEQ, Figure 30 shows the number of hours per year in which the indoor air temperature is in the defined temperature ranges.

In the building model, two thermal zones are used to model each dwelling, with the thermal zone “A” representing the living zone facing south and the thermal zone “B” representing the night zone and the bathroom facing north. The three dwellings, located on the ground, mid and top floors, are indicated in the figure as 1F, 3F and 5F, respectively. The six columns on the left of the figure analyse the indoor temperature in the six thermal zones of the three dwellings considered, while the three columns on the right are calculated as the weighted average of zones A and B of each apartment, weighting their contribution based on the respective net floor area.

As shown in the figure, there are basically no underheating problems for the considered building, with the thermal zone of the ground floor facing north characterised by the minimum temperatures, but never below 18 °C. On the contrary, overheating appears in all thermal zones of the building, with indoor air temperature exceeding 28 °C in all thermal zones for more than 200 h/y. However, on closer analysis, it emerged that the overheating problem is not due to an undersized AWHP system that cannot meet the SC demand across the different zones, but, instead, to the limited period in which the AWHP system can work in SC mode. In fact, according to Spanish regulation, the system can work in SC mode from June 1st to September 30th. This schedule has been used in the performed simulations, although it has been verified that the SC demand is also present in May and October. During these months, the SC demand is not covered by the system, and this results in the overheating problem visible in Figure 30. To demonstrate the previous statements, Figure 31 shows, for the entire year, the indoor air temperature in the three dwellings considered and the ambient air temperature, highlighting the high indoor air temperatures reached in months like May and October.

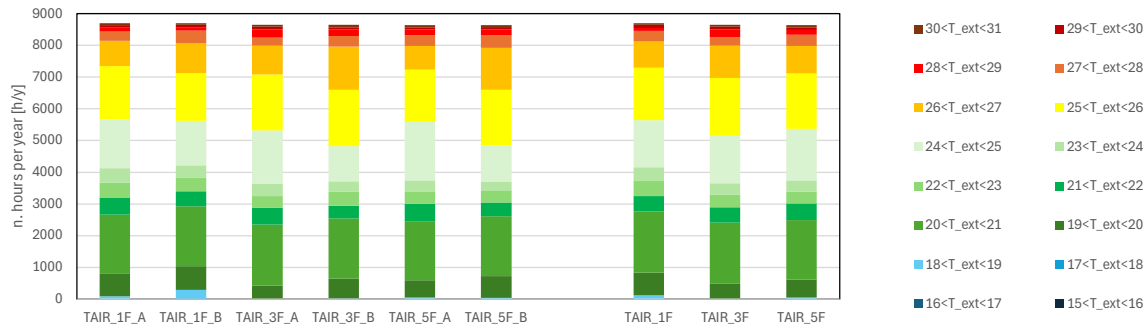


Figure 30 Number of hours throughout the year with building indoor air temperature in defined ranges. The left columns represent the situation for all six thermal zones, while the right columns represent the situation at the dwelling level. The dwellings on the ground, mid and top floors are indicated in the figure with the notation 1F, 3F and 5F, respectively

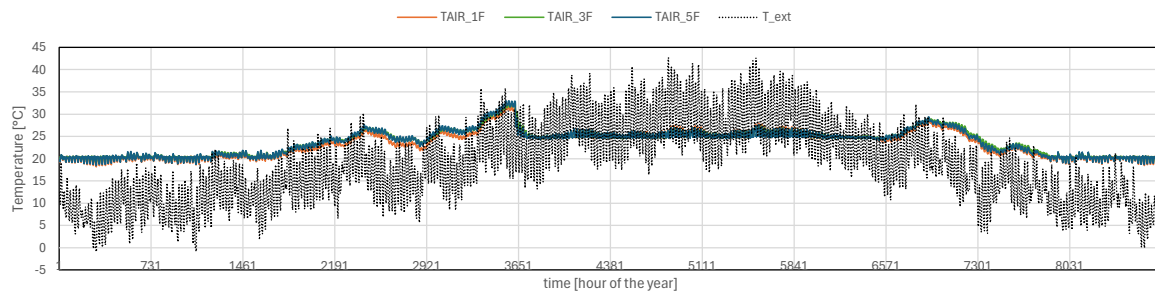


Figure 31 Indoor air temperature in the different dwellings (1F, ground floor: orange; 3F, mid floor: green; 5F, top floor: blue) and ambient air temperature (black dotted line). The vertical grid of the figure divides the year into 12 parts with the same duration and can be considered representative of the different months for this analysis

3.2.1.4. Main outcomes for the considered systems

Overall, the AWHP system presented and considered for the Spanish building typology n.1 ensures the covering of all building's thermal needs (SH, SC, DHW). This is done with a reduction in the final energy consumption of around 55-60 % in comparison to the reference system accounted for (electric radiators for SH, electric boiler for DHW, split units for SC), with this reduction being higher if a PV and battery system is installed.

3.2.2. Water loop heat pump system

The WLHP system performance is analysed in this section, focusing, as already done for the AWHP system, first on a series of analyses at the weekly level and then presenting analyses at the yearly level. However, as the WLHP system considered in this work covers only SH thermal demand, the weekly analysis is reported only in one winter week.

3.2.2.1. Exemplary winter week (1-7 Feb)

This section reports a series of analyses focusing on one week (1-7 Feb), which is considered representative of the winter period.

3.2.2.1.1. Thermal energy delivered to the users

In the considered exemplary winter week, the SH thermal energy demand of the building is in the range 10-33 kW as shown in Figure 32 (black line). This SH thermal demand is obtained from a simulation performed in IDA ICE, while the WLHP system is modelled in TRNSYS and is controlled to cover this SH thermal demand. As visible in the same figure, the red line shows the SH thermal energy delivered by the WAHPs (also called micro-HPs, or mHPs) and is well aligned to the SH thermal demand. This indicates that the WAHPs' control ensures that the WAHPs deliver almost exactly the thermal energy required to maintain the desired indoor temperature in the building. As shown in the figure, there is a time shift between the two curves (red and black). This shift can be up to 2 hours and is related to differences in how the integration is made by the different simulation software.

Moreover, the figure also shows the hourly AWHPs (red triangles) and WAHPs COPs (green squares). As reported in the section 2.2.2.5, the used control logic in winter aims to have similar COPs for all the machines working in cascade to maximise the system COP according to the formula reported in the section 2.2.2.5. As visible in the figure, the applied control logic leads to COPs similar for the two types of machines.

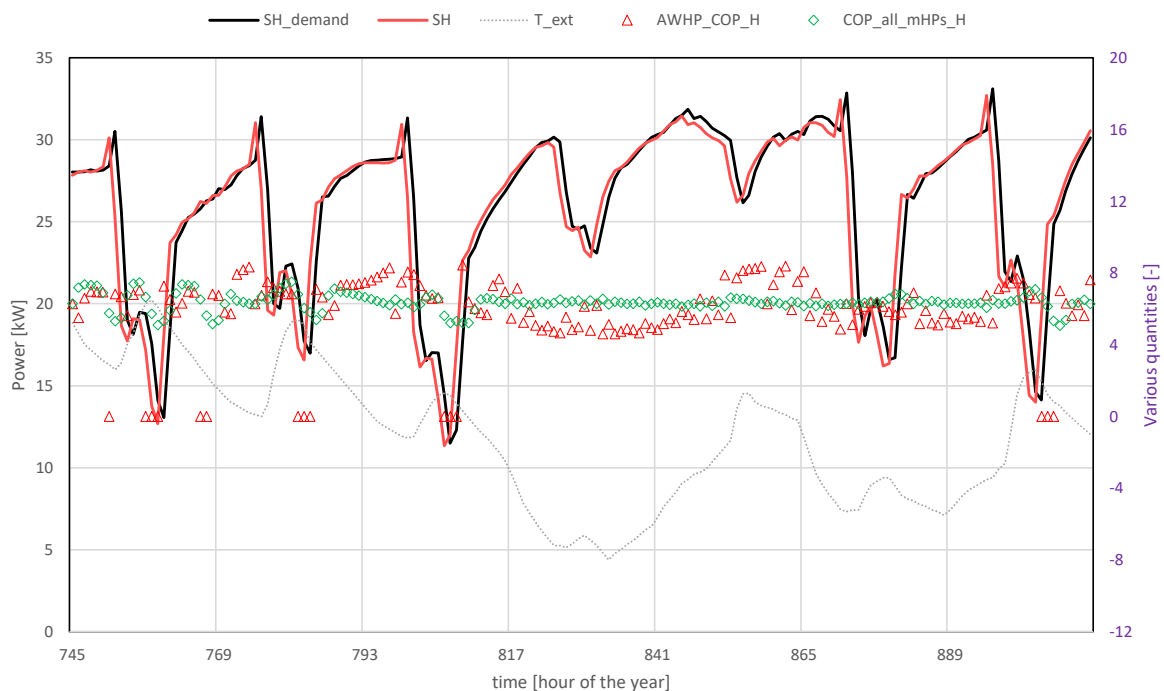


Figure 32 Building's SH thermal energy demand calculated in IDA ICE (black line) and SH thermal energy delivered to the building by the mHPs (red line). Right y-axis: ambient air temperature (dotted grey), AWHPs COP (red triangles) and mHPs COP (green squares). Exemplary winter week (1-7 Feb)

3.2.2.1.2. Electric consumption and PV + battery system contribution

Being the Swedish building typology n. 1 a non-residential building, it is considered possible to cover, with the PV and battery system, not only the electric consumption associated with the WLHP system but also the one due to the use of electrical appliances and lights. Figure 33 shows

the electric consumption of the HVAC system and the one due to electrical appliances and lights, with the HVAC system representing the major fraction of the total building's electric consumption.

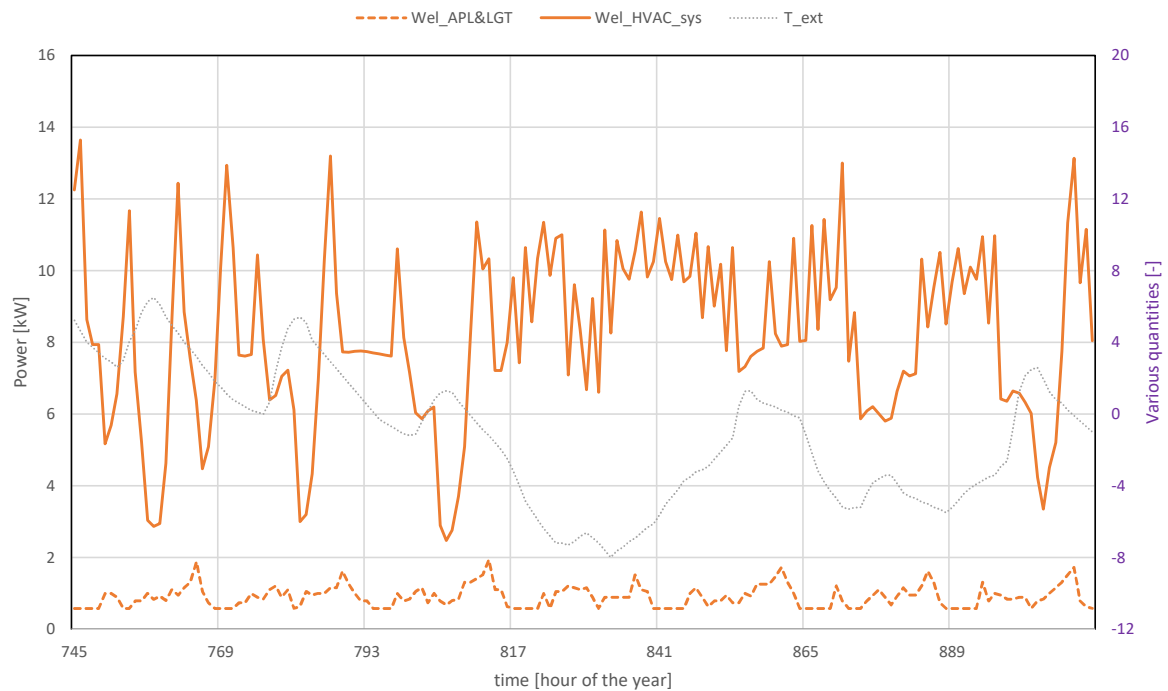


Figure 33 HVAC system electric consumption (orange continuous line) and electric consumption due to electric appliances and lights (orange dashed line). Right y-axis: ambient air temperature (dotted grey). Exemplary winter week (1-7 Feb)

Figure 34 reports the electrical energy flows in the considered exemplary winter week. As visible in the figure, the building's electric consumption is in the range 4-15 kW, with the PV production exceeding 5 kW only in some hours of the 1st day of the considered winter week. The combination of limited solar availability and the high building's electric consumption results in the instantaneous consumption of the PV production, with the battery that is almost unused in this period and most of the electric load covered using electricity from the grid.

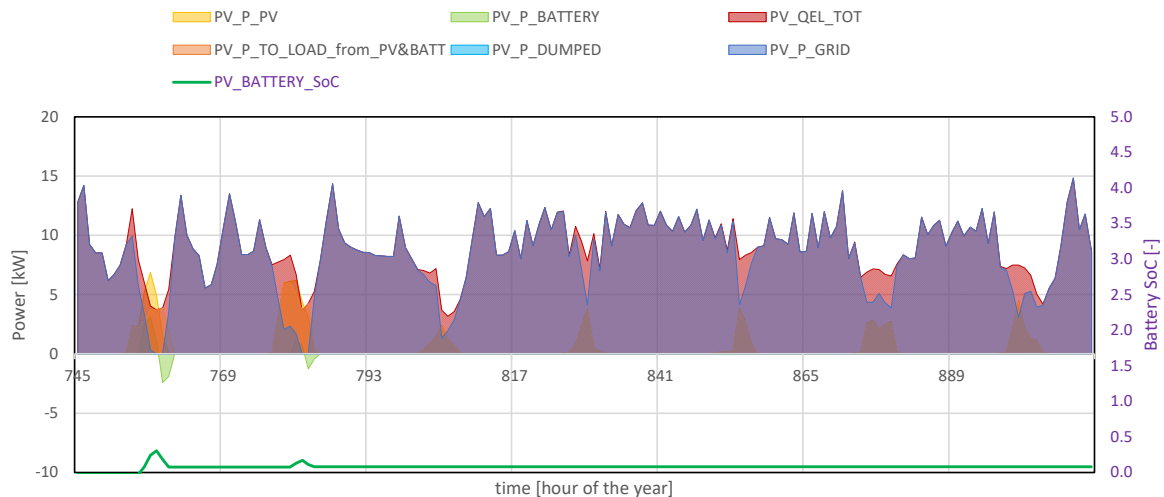


Figure 34 Electrical energy flows: PV production (yellow), power to/from battery (green), total electric consumption (red), electric consumption covered by PV and battery (orange), dumped power (light blue), power from grid (blue). Right y-axis: battery SoC (green line). Exemplary winter week (1-7 Feb)

3.2.2.1.3. System COP evaluated on an hourly basis over the different days

The SH thermal energy delivered to the building and the associated HVAC system electric consumption are put together in Figure 35. The figure also shows the AWHPs and WAHPs COPs calculated on an hourly basis for the different days. As visible in the figure, the COPs of the two types of machines are similar, with the day showing the highest difference being February 4th. On this day, the ambient air temperature is particularly low, as shown in Figure 32, and in these conditions, the AWHPs have a COP slightly lower in comparison to the WAHPs, although the set point temperature at the condenser side is minimised according to the control logic used, already described in the section 2.2.2.5.

In terms of system COP, calculated as the thermal energy delivered to the users divided by the HVAC system's electric consumption, this is around 3, with slightly higher values on milder days and lower on the coldest ones. However, it is interesting to note that, also on February 4th, a day characterised by ambient temperature ranging from -3 °C to -8 °C, the system COP remained in the range of 3 (2.9). This is possible thanks to the WLHP system configuration, having multiple HPs working in cascade, and also to the specific control logic adopted. Moreover, the obtained system COP is always close to the maximum theoretical limit calculated based on the formula reported in the section 2.2.2.5. This emphasises the importance of the system control for this kind of system. The minor difference between the theoretical and the real system COP is due to imperfect control and to the minor, but non-zero, thermal losses of the buffer tank and of the water loop.

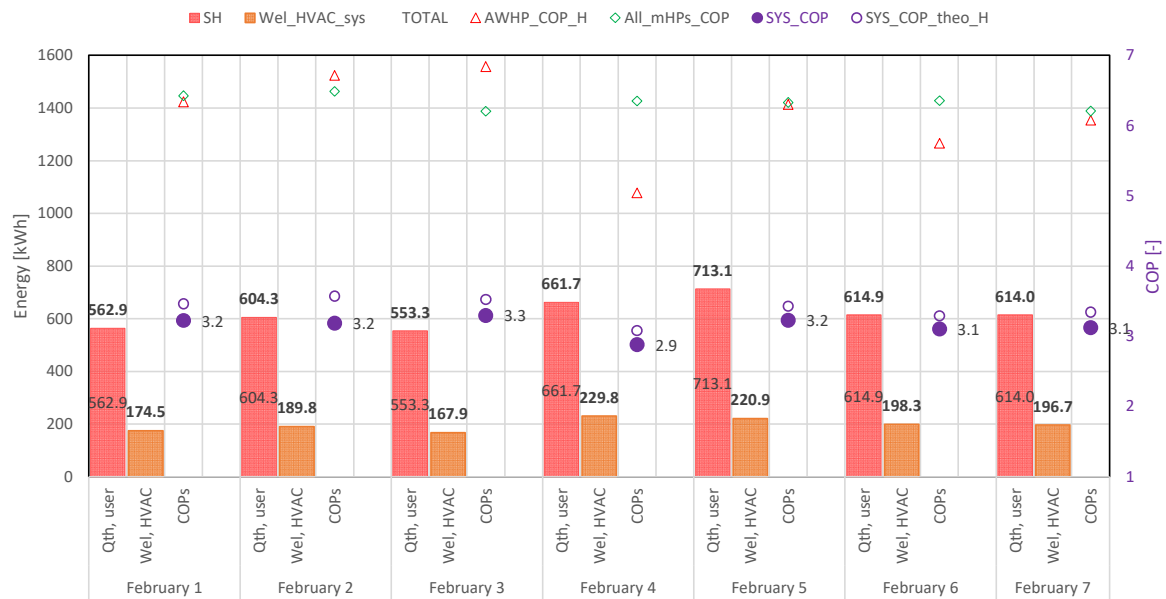


Figure 35 Thermal energy delivered to the users for SH (red bars) and HVAC system electric consumption (orange bars). Right y-axis: AWHPs COP (red triangles), mHPs COP (green squares), system COP (purple filled circles) and theoretical system COP (purple empty circles). Exemplary winter week (1-7 Feb)

3.2.2.1.4. Indoor temperature analysis

No specific indoor temperature analysis is reported here as the simulation performed in TRNSYS uses as input the thermal demand profile obtained from IDA ICE simulations and, therefore, the building is accounted for as a static hourly demand. However, the WLHP system is able to follow the SH thermal demand, as shown in Figure 32, which is the amount of thermal energy needed to ensure the set point temperature (equal to 21 °C in the case considered). On this basis, it can be considered that the desired indoor air temperature is maintained throughout the entire winter season.

3.2.2.2. Yearly assessment

This section aims to assess the WLHP system performance at a yearly time horizon. In addition to the analysis of the PV and battery contribution over the various months and those in terms of final and primary energy consumption and GHG emission over the entire year, it also presents a verification of the specific thermal power ensured by the WAHPs in comparison to the SH thermal needs of the most critical thermal zones. Moreover, an assessment of the advantage, in terms of reduced distribution system thermal losses, of this system, using a water loop at almost neutral temperature (20-35 °C), is reported.

3.2.2.2.1. Verification of the terminal units' size in relation to the SH thermal demand in the coldest building's thermal zones

Although in the previous sections the building is considered as a unique thermal zone, it has also been verified that there are, on the market, terminal units with a thermal power in nominal conditions able to cover the thermal demand of the most critical building's thermal zones. In this

context, the three most critical thermal zones are identified as those characterised by the highest specific (W/m^2) SH thermal demand among all building's thermal zones.

The Table 16 shows, for these three thermal zones (two offices and one small meeting room, generally located in the building's corners and therefore having a higher surface exposed to the external ambient), the net floor area and the peak SH thermal demand. Moreover, the table reports the thermal power delivered in nominal conditions⁵ by one (in the case of the Office 23, two) WAHP available on the market, just to give an idea of the thermal power that can be delivered by this machine. As visible in the table, there are examples of machines available on the market able to cover the thermal demand of the most critical zones.

Table 16 Net floor area and peak SH thermal demand (in [W] and [W/m^2]) for the three thermal zones characterised by the highest specific SH thermal demand and thermal power in nominal conditions of a WAHP used as an example

Thermal zone	Net floor area	Peak SH demand	Peak SH demand specific	Thermal power of a WAHP used as an example in nominal conditions ^{5,6}
	[m^2]	[W]	[W/m^2]	[W]
214 Office	10.2	949	93	1270 ⁶
420 Small meeting room	11.5	734	64	1270 ⁶
Office 23	18.0	1337	74	1270 or 2140 ⁶

3.2.2.2.2. Assessment of distribution system thermal losses

As already written in the section 2.2.2, one of the advantages of the WLHP system in comparison to a typical system using radiators as emission units is the possibility to reduce the temperature of the water in the distribution circuit to around 20-35 °C and, consequently, reduce the distribution system thermal losses.

As reported in Table 17, over the heating season, the distribution system thermal losses in the case of the WLHP system are reduced to almost 0 (0.7 % of the SH thermal energy delivered by the AWHPs and the buffer tank). This value is compared to a reference system, which, in this case, is represented by a system using radiators as heat emission units. In the reference system, the water supply temperature to the radiators is regulated using a climatic curve defined to ensure the SH thermal demand covering with the minimum supply water temperature level (60 °C at ambient temperature equal to -15 °C and 30 °C at ambient temperature equal to 20 °C) and, with this control, around 3.9 MWh/y (equivalent to around 3 % of the thermal energy entering the distribution circuit) is lost. However, it must be noted that this value is obtained considering a

⁶ Thermal power in nominal conditions for an exemplary WAHP. More than one WAHP can be installed in the same room or, alternatively, WAHPs with different capacity are available. Source: <https://www.innova.it/prodotti/terminali-in-pompa-di-calore-wlhp/wlhp/wlhp/>

distribution system with insulated pipes (insulation thickness equal to 1 cm and thermal conductivity of the insulation material equal to 0.04 W/(m·K)). The situation used as a reference is already a sort of optimised situation because the use of such a low supply water temperature is not frequent in Historic Buildings equipped with radiators. However, it is used to highlight the improvements, in terms of reduction of distribution system thermal losses, against a system, using radiators, that is already optimised in terms of control. The situation would be worse in terms of distribution circuit thermal losses, and, therefore, the improvements considered in the case of the WLHP system would be higher, if the distribution system is not insulated and a climatic curve with higher temperatures is used.

Table 17 SH thermal energy delivered by the AWHPs and the buffer tank to the distribution circuit (SH including thermal losses), SH thermal energy delivered to the emission units (radiators in the reference system, WAHPs in the WLHP system) and related thermal losses in absolute and percentage values. The percentage is calculated considering as base the SH including thermal losses

Thermal zone	SH including thermal losses	SH excluding thermal losses	SH thermal losses	SH thermal losses %
	[MWh/y]	[MWh/y]	[MWh/y]	[%]
Reference system	134.856	130.937	3.919	3.0
WLHP system	131.880	130.937	0.943	0.7

3.2.2.2.3. PV and battery system self-consumption and self-sufficiency

The self-consumption and self-sufficiency indicators are also evaluated at monthly level to analyse in more detail the interactions between the PV + battery system and the building's electric consumption.

On this basis, Figure 36 shows the self-consumption and self-sufficiency for the different months. As visible in the figure, the self-consumption is close to 100 % in the coldest winter months, while it shows the minimum values in summer. This behaviour is due to the opposite trends of PV production and the building's electric consumption over the year. In fact, in winter, the building presents its highest electric consumption, due to the electric consumption of the WLHP system used to cover the building's thermal demand, in winter. During the same period, the low solar availability results in limited PV production, which is almost entirely consumed within the building. On the contrary, the fact that an SC system is not needed/considered in the summer months in the target building implies that, in this period, the building's electric consumption is reduced. In the same period, the PV production is at its maximum due to the high solar availability. These two aspects result in a limited self-consumption in the summer months and in the export of almost half of the PV production to the grid in the period May-September.

Regarding self-sufficiency, instead, the trend is opposite to the self-consumption one. In fact, in the winter months, self-sufficiency presents the minimum values as the building's electric consumption is covered only for a small fraction by the PV production, while the majority of the building's electric consumption is covered using electricity coming from the grid. The monthly self-sufficiency values increase in the mid-season months as a result of the reduced building's

electric consumption due to the milder ambient conditions and the increased solar availability, and reach their peaks in the summer months, when the building's electric consumption is at its minimum and the PV production is at its maximum.

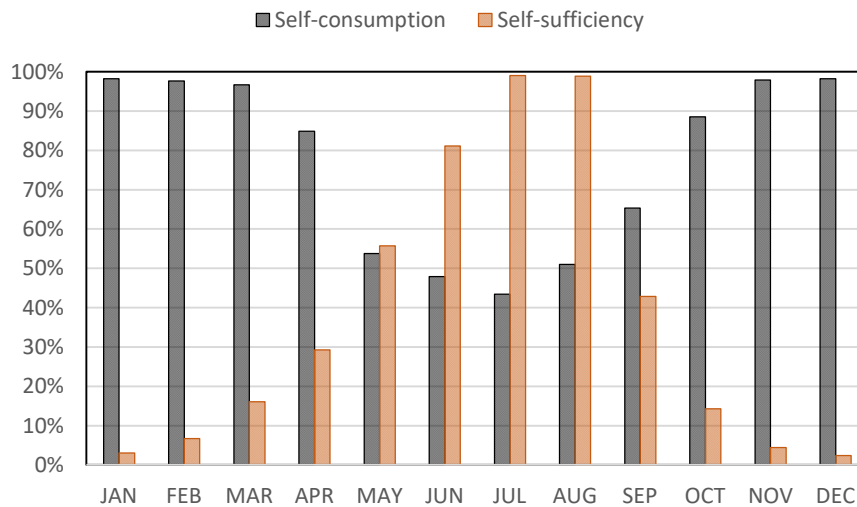


Figure 36 Monthly self-consumption (dark grey) and self-sufficiency (orange) values

To analyse in more detail the contribution to self-sufficiency given by the PV and battery, the Figure 37 is presented. As visible in this figure, the contribution given by the battery is limited or almost null in the period October-March. In this period, the limited PV production is almost completely instantaneously consumed in the building. The battery contribution increases in the mid-season months, indicating that there are periods in these months with PV surplus that can be stored in the battery. In the summer months, the battery and PV contribute almost the same percentage (around 50 %) to the self-sufficiency.

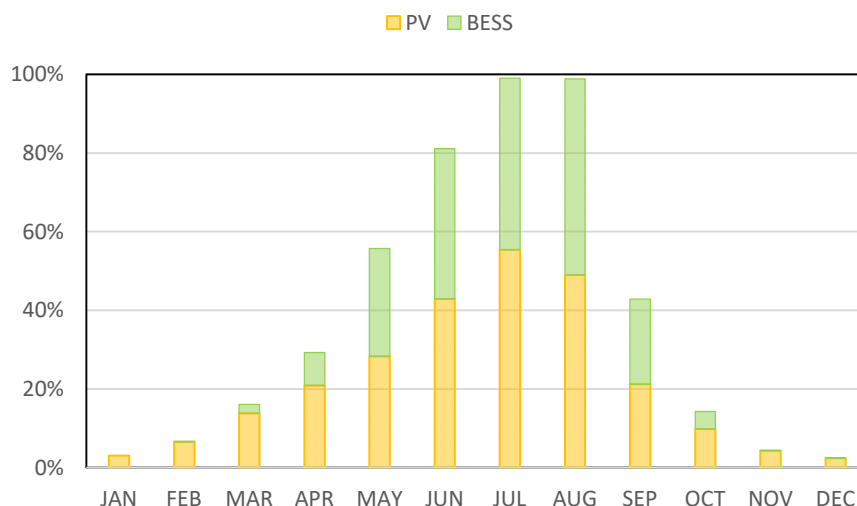


Figure 37 Monthly self-sufficiency associated with PV production instantaneously self-consumed (PV contribution, yellow), and PV production temporarily stored in the battery and later used (BESS contribution, green)

3.2.2.2.4. Overall yearly assessment

The Table 18 summarised a series of PIs for the Swedish building typology n.1 considering an Ideal scenario with DHNC, one with a WLHP system and one with the WLHP system, PV and battery. All scenarios are called “Ideal” as, in comparison to the typical building’s current status, some insulation interventions to improve thermal envelope performance are considered.

In terms of SH thermal energy demand, this is in the range of 130 MWh/y, a value that remains almost the same (except for small variations) for all three system cases considered. However, this SH thermal demand is covered in different ways, resulting in a thermal final energy consumption of 146.892 MWh/y from the DHN, or in an electric final energy consumption of 49.512 MWh/y in the case of a WLHP system is used to cover the SH thermal load. If PV and battery are also considered, the electric final energy consumption from the grid is reduced to 41.862 MWh/y. It is interesting to highlight that, also in the case featuring the DHNC, an electric final energy consumption, due to the presence of electrical appliances and lights, is considered.

The interpretation of the results in terms of non-renewable primary energy consumption and GHG emissions is not straightforward in this case. In fact, in terms of non-renewable primary energy consumption, the solution featuring the DHNC appears to be the best. However, analysing the GHG emissions, those associated with this system are notably higher in comparison to those obtained considering the WLHP system. The reason that explains this behaviour lies in the used non-renewable primary energy and GHG emissions factors. In fact, the factors considered for the DHN are those specific to the Linköping DHN, which result in particularly low non-renewable primary energy factor (0.07) and relatively high (0.108 tCO_{2,eq}/MWh) GHG emission factor. The main reason explaining the particularly low non-renewable primary energy factor is that the considered DHN is mainly based on an existing incinerator plant. On the other hand, the electricity coming from the grid is characterised by a notably higher non-renewable primary energy factor (1.8) and a notably lower GHG emissions factor (0.015 tCO_{2,eq}/MWh).

The combination of these factors explains the advantage in terms of non-renewable primary energy consumption of the DHNC and in terms of GHG emissions of the WLHP system.

Table 18 Overall yearly assessment for the WLHP system in the Swedish building typology n.1. Primary energy consumption and GHG emissions are calculated based on the factors reported in the section 6.4 for Sweden

Variable	Unit	Ideal scenario with DHNC	Ideal scenario with WLHP system	Ideal scenario with WLHP system, PV and battery
Ed, th. SH	MWh/y (kWh/(m ² ·y))	130.937 (68.59)	129.093 (67.62)	129.093 (67.62)
Ef, th. From the DHN	MWh/y (kWh/(m ² ·y))	146.892 (76.95)	-	-
Ef, el. From the grid	MWh/y (kWh/(m ² ·y))	7.910 (4.14)	49.512 (25.94)	41.862 (21.93)
Ep,nren	MWh/y (kWh/(m ² ·y))	24.521 (12.84)	89.122 (46.68)	75.352 (39.47)
Self-sufficiency	%	-	-	15

Self-consumption	%	-	-	67
GHG	tCO ₂ ,eq/y	16.0	0.7	0.6

3.2.2.3. Main outcomes for the considered system

Based on the results described above, the WLHP can be considered a feasible solution for buildings such as the Swedish typology n.1. The main advantages of this system are the possibility to cover SH demand also in contexts with cold climatic conditions, maintaining good performance in terms of system COP and with almost null distribution system thermal losses. Moreover, the same terminal emission system can deliver both SH and SC with limited interventions and visual impact related to the replacement of the existing radiators with WAHPs. The limited visual impact and required interventions are parameters that are essential in the context of Historic Buildings.

3.2.3. Mechanical ventilation with heat recovery system

The MVHR system performance is analysed in this section. The analysis is performed focusing on single thermal zones as well as the entire building level. As this system aims to ensure an adequate IEQ, a focus on the CO₂ level inside the considered zones is also reported.

3.2.3.1. Exemplary winter week (1-7 Jan)

This section reports a series of analyses in terms of SH thermal energy demand, indoor air temperature trend and CO₂ level for the three dwellings located at the ground, mid and top floor of the considered building for the week 1-7 Jan, which is considered representative of the winter period.

3.2.3.1.1. SH thermal energy demand

Although as written in the section 2.2.3, the MVHR considered is not responsible for covering the SH thermal demand, the SH thermal needs of three thermal zones considered representative of the building (the kitchen, the living room and the master bedroom), for the three dwellings, are reported in the Figure 38.

As visible in the figure, the SH demand is discontinuous due to the used schedule for the SH system that, according to the SAP 10.2 regulation [12], considers SH operation only in limited periods (in the period 07:00-09:00 and from 16:00 to 23:00 on weekdays and from 07:00 to 23:00 on weekend days). In these periods, the considered SH system is able to ensure the indoor air temperature set point (equal to 21 °C), while for the rest of the time, the indoor air temperature evolves without a temperature set point or a reduced temperature set point.

The SH thermal demand profile presents, for all cases, a peak when the system is switched ON, as, at that moment, the indoor air temperature is generally quite low and always lower than the desired temperature set point. In these conditions, the SH system works at full power to reach the desired set point temperature in the shortest time possible. After this peak, the SH demand is reduced as less power is needed to maintain the set point temperature (21 °C).

Among the three dwellings simulated, the ones at the ground and top floors show the highest SH thermal demands due to the higher thermal envelope surface exposed to external conditions through the roof (top floor) and the ground (ground floor).

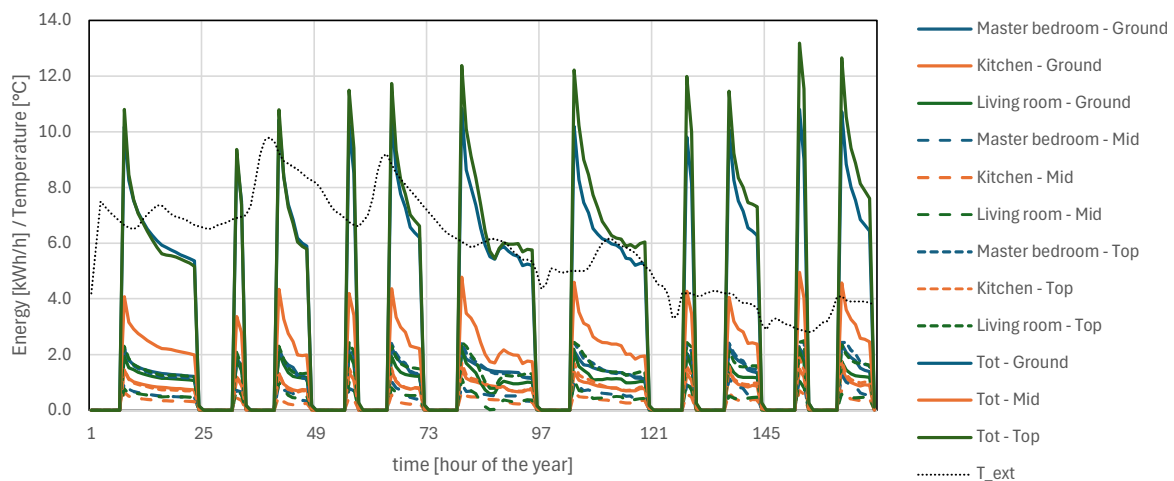


Figure 38 SH thermal energy demand for three thermal zones (master bedroom: blue; kitchen: orange; living room: dark green) for the three dwellings located on different floors (ground: continuous line; mid: long-dashed line; top: dashed line). Moreover, the ambient air temperature is also shown (black dotted line). Exemplary winter week (1-7 Jan)

3.2.3.1.2. Indoor temperature analysis

Figure 39 shows the indoor temperature trend for the exemplary winter week considered for the same three thermal zones considered above (kitchen, living room, master bedroom) in all three dwellings. As can be seen in the figure, the indoor temperature decreases to values often in the range 12-15 °C, with minimum values for the thermal zones of the dwelling on the top floor. This, however, is due to the considered schedule for the SH system, as already described above. The only dwelling in which night indoor temperature reduction is limited is the middle one, due to the presence of heated spaces above and below it, reducing the thermal losses through these zones.

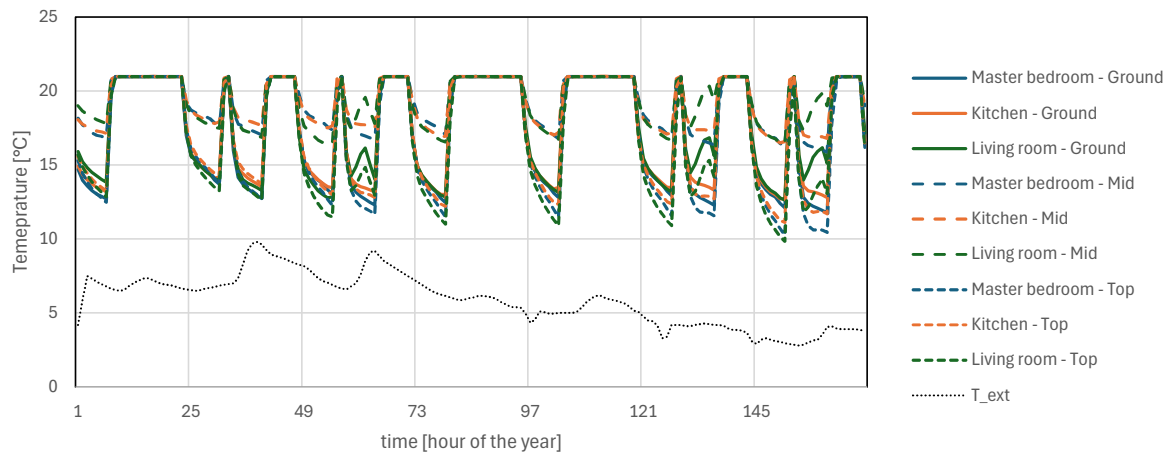


Figure 39 Indoor air temperature for three thermal zones (master bedroom: blue; kitchen: orange; living room: dark green) for the three dwellings located on different floors (ground: continuous line; mid: long-dashed line; top: dashed line). Moreover, the ambient air temperature is also shown (black dotted line). Exemplary winter week (1-7 Jan)

3.2.3.1.3. Indoor CO₂ levels

Regarding the IEQ in terms of CO₂ levels, Figure 40 presents the CO₂ level trends for the considered exemplary winter week and for the same thermal zones used in the previous sections. From the figure, it is possible to understand that the ventilation air change supplied by the MVHR is adequate to ensure the indoor comfort of the users. In fact, for most of the time, the CO₂ levels are in all the zones considered in the range 400-800 ppmv. Only in a few hours during the night, the CO₂ levels exceed 1000 ppmv in the bedrooms; however, they never reach the threshold of 1200, which is considered the threshold above which the air quality is considered low (CAT IV from EN-ISO 16798-1).

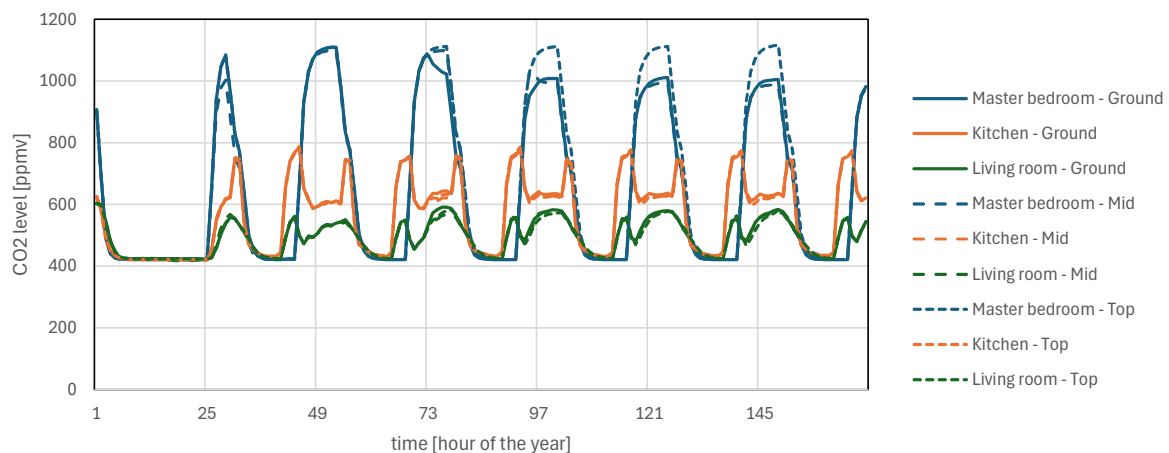


Figure 40 CO₂ levels for three thermal zones (master bedroom: blue; kitchen: orange; living room: dark green) for the three dwellings located on different floors (ground: continuous line; mid: long-dashed line; top: dashed line). Moreover, the ambient air temperature is also shown (black dotted line). Exemplary winter week (1-7 Jan)

3.2.3.2. Yearly assessment

This section analyses a series of indicators/quantities at a yearly time horizon. More specifically, it reports the number of hours in which indoor temperature and CO₂ concentration are within specific ranges. Moreover, the section is concluded with a series of indicators reporting SH thermal energy demand, final and primary energy consumption, as well as GHG emissions.

3.2.3.2.1. Indoor temperature levels

Figure 41 shows the number of hours in the year with indoor temperature in specific ranges. This analysis is reported in the figure for the same zones considered in the assessment over the winter exemplary week. As shown in the figure, all the zones on the ground and top floors show low indoor air temperatures, with minimum values reaching 10 °C in the master bedroom. On the contrary, all analysed zones on the mid floor show higher values, never lower than 16 °C, due to the presence of heated zones above and below this floor. However, it is important to underline also here that the low indoor temperature levels seen in the figure are mainly due to the considered schedule for SH.

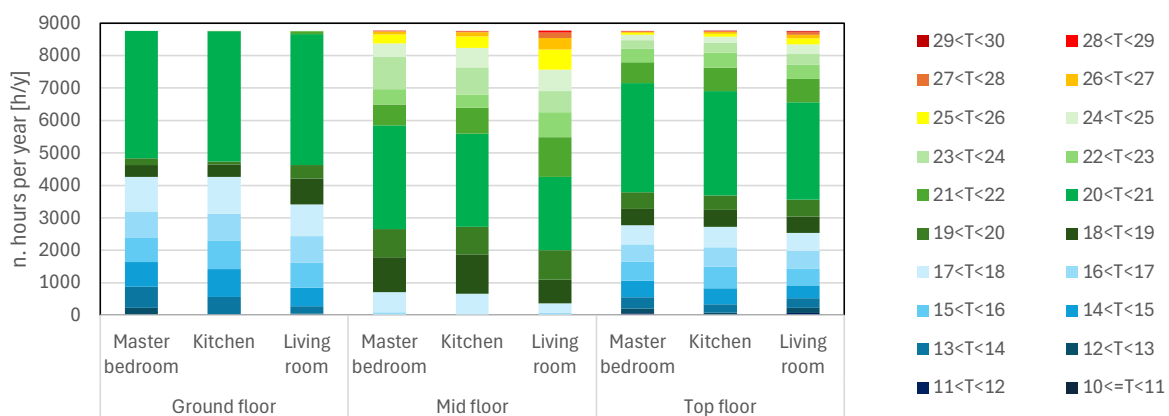


Figure 41 Number of hours with indoor temperature in specific ranges for three thermal zones (master bedroom, kitchen, living room) for the three dwellings located on different floors (ground, mid, top)

3.2.3.2.2. Indoor CO₂ levels

In terms of indoor CO₂ levels yearly assessment, Figure 42 reports the number of hours in the year with CO₂ levels in different ranges. This quantity is reported for the three zones considered (master bedroom, kitchen and living room) for the three simulated dwellings on the ground, mid and top floors. As visible in the figure, the kitchen and the living room of all dwellings show CO₂ levels lower than 800 ppmv, values indicative of a good air quality in terms of CO₂ concentration. The master bedrooms of all dwellings show instead higher values that occur during the night, as shown in Figure 40. However, also at the yearly time horizon, these values never reach the limit of 1200 ppmv.

To highlight the effect of the MVHR system in terms of CO₂ level, Figure 43 shows the same quantities already presented in Figure 42, but considering a case without an MVHR system. As visible in the Figure 43, without the MVHR system, the CO₂ level is above 1200 ppmv for more than

2000 h/y in the master bedrooms, resulting in uncomfortable conditions for the users. Similarly, also in the kitchen on all floors, values higher than 1200 ppmv are observed for more than 1000 h/y.

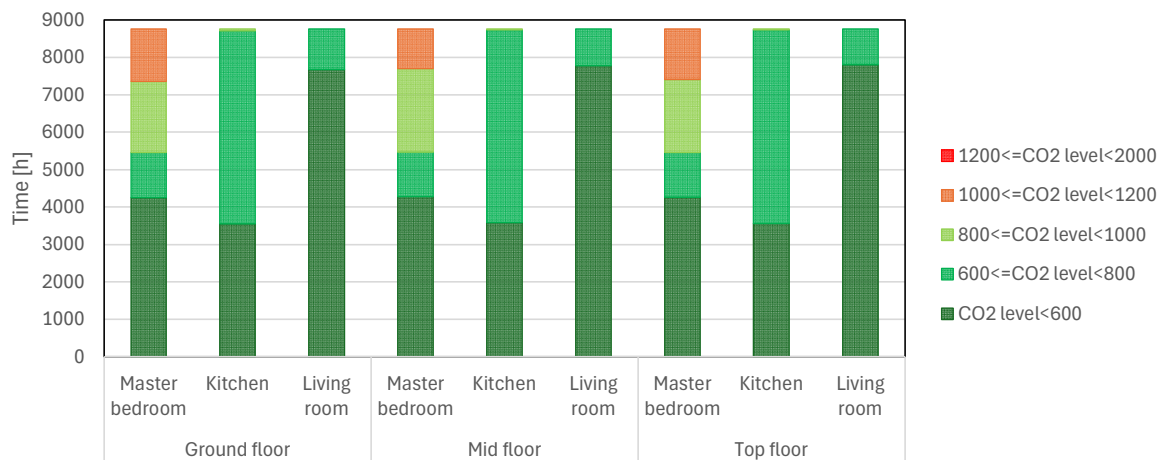


Figure 42 Number of hours with CO₂ levels in specific ranges for three thermal zones (master bedroom, kitchen, living room) for the three dwellings located at different floors (ground, mid, top). Case with the MVHR system

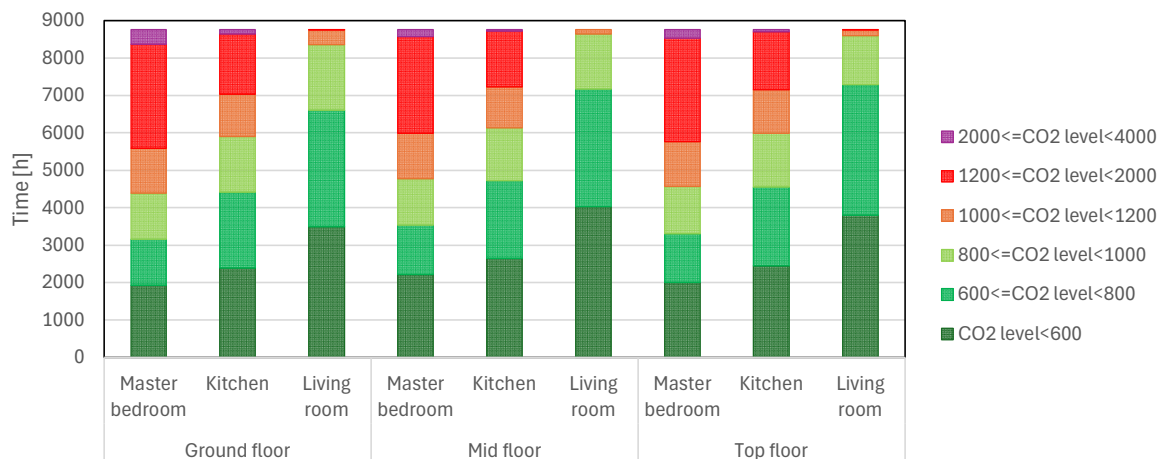


Figure 43 Number of hours with CO₂ levels in specific ranges for three thermal zones (master bedroom, kitchen, living room) for the three dwellings located at different floors (ground, mid, top). Case without the MVHR system

3.2.3.2.3. Overall yearly assessment

The Table 19 summarises the SH thermal demand, final and primary non-renewable energy consumption and the GHG emission for the MVHR system in the Scottish typology n.1.

As visible in the table, the presence of the MVHR, thanks to the HR efficiency (90 %), allows for reducing the building's ventilation thermal losses, and, consequently, the building's SH thermal demand, which passes from 41.480 to 35.914 MWh/y. This reduction is obtained with an additional electric consumption of 0.631 MWh/y associated with the MVHR system. In terms of non-renewable primary energy consumption and GHG emissions, the presence of the MVHR leads to a reduction in the range of 12 % of both quantities.

Table 19 Overall yearly assessment for the MVHR active system solution in the Scottish building typology n.1. Primary energy consumption and GHG emissions are calculated based on the factors reported in the section 6.4 for Scotland

Variable	Unit	Base scenario	Base scenario with MVHR
Ed, th, for SH	MWh/y (kWh/(m ² ·y))	41.480 (111.51)	35.914 (96.54)
Ef, el. From the grid	MWh/y (kWh/(m ² ·y))	41.480 (111.51)	36.545 (98.24)
Ep,nren	MWh/y (kWh/(m ² ·y))	62.220 (167.26)	54.817 (147.36)
GHG	tCO ₂ ,eq/y	5.6	5.0

3.2.3.3. Main outcomes for the considered system

Based on the results above, two main advantages are associated with the use of the MVHR. First, the system improves the IEQ in terms of both indoor air temperature and CO₂ levels. In particular, with the MVHR, the CO₂ levels in all analysed building zones are always lower than 1200 ppmv, indicating a good air quality. Second, the electric consumption associated with the MVHR system is more than offset by the reduction in the building's SH thermal demand, resulting, overall, in reduced final and non-renewable primary energy consumption and GHG emissions.

3.2.4. Connection to the District Heating Network

3.2.4.1. Exemplary winter week (1-7 Jan)

This section aims to analyse the system behaviour, focusing on a winter week (1-7 Jan) selected as representative of the system operation for the winter period. The scope of the analysis reported in this section is to identify the effect of the MVHR on the SH thermal demand and to assess whether the used radiators and climatic curves are adequate to cover the building's SH thermal demand. Moreover, as the Polish demo building (representative of the building considered in this section, the Polish building typology n. 1) will also have a PV and battery system, a detailed analysis of the electrical energy used to cover the electric load of the HVAC system (including the electric consumption of the circulating pumps and the MVHR system) is reported.

3.2.4.1.1. Influence of the presence of a MVHR on the climatic curve used

The presence of the MVHR system reduces the building's SH demand, as part of the heat in the exhaust air is used to pre-heat the air entering the building. The effect on the reduction of the SH thermal energy demand and, consequently, on the thermal energy that the radiators should supply to the different thermal zones, is visible when comparing Figure 44 and Figure 45. The figures show the SH demand (continuous lines) of the three building zones considered (green, orange and red lines) and their sum (dark red line) in the case in which any MVHR is considered (Figure 44) and in the one featuring an MVHR system (Figure 45). As visible in the first figure, all thermal zones present an SH demand profile (continuous line) with some steps. These steps are

due to the schedule used for the MVHR, which is considered active with a higher mass flow rate only in some hours of the day (10:00 – 22:00), while, for the rest of the time, it works with a reduced mass flow rate. In the periods with a higher ventilation mass flow rate, the higher ventilation air exchange leads to an increase in the thermal losses and, consequently, in the SH thermal demand. The high HR efficiency considered (equal to 90%) basically cancels the steps visible in the first figure, with the variation of the ventilation air mass flow rate that has a reduced effect on the ventilation thermal losses.

Moreover, from the same two figures, it is possible to note that the SH thermal energy delivered by the radiators using the climatic curves reported in Table 6 is aligned with the SH thermal demand. This check can be done by comparing the continuous and dotted lines showing the SH thermal demand calculated in DesignBuilder (continuous lines) and the thermal energy delivered by the radiators calculated in TRNSYS (dotted lines). Therefore, it can be concluded that the used climatic curves allow for minimising the supply water temperature at the radiators, maintaining the indoor comfort conditions in terms of indoor temperature.

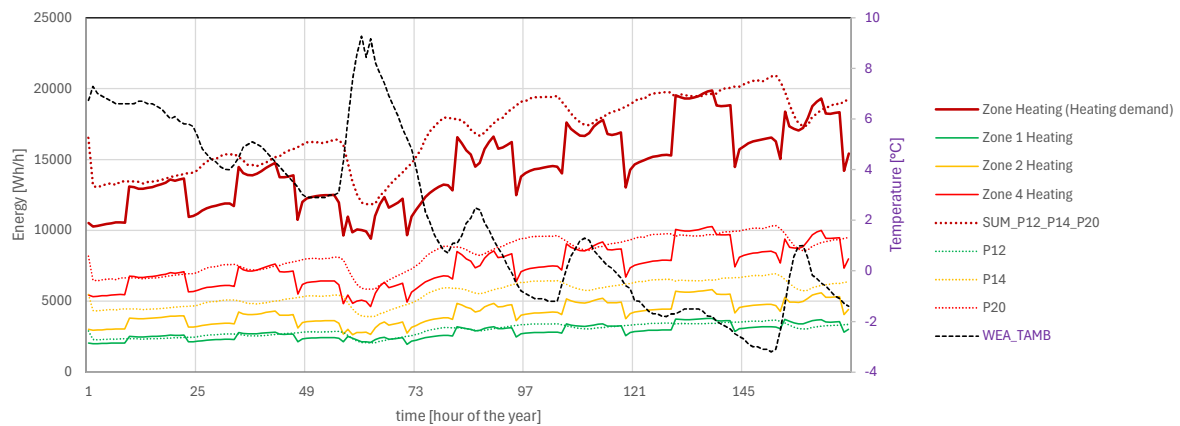


Figure 44 SH thermal demand (continuous lines) and SH thermal energy delivered by the radiators (dotted line) for the different thermal zones (green, orange, red) and their sum (dark red). Case without MVHR. Right y-axis: ambient air temperature (black dashed line). Exemplary winter week (1-7 Jan)

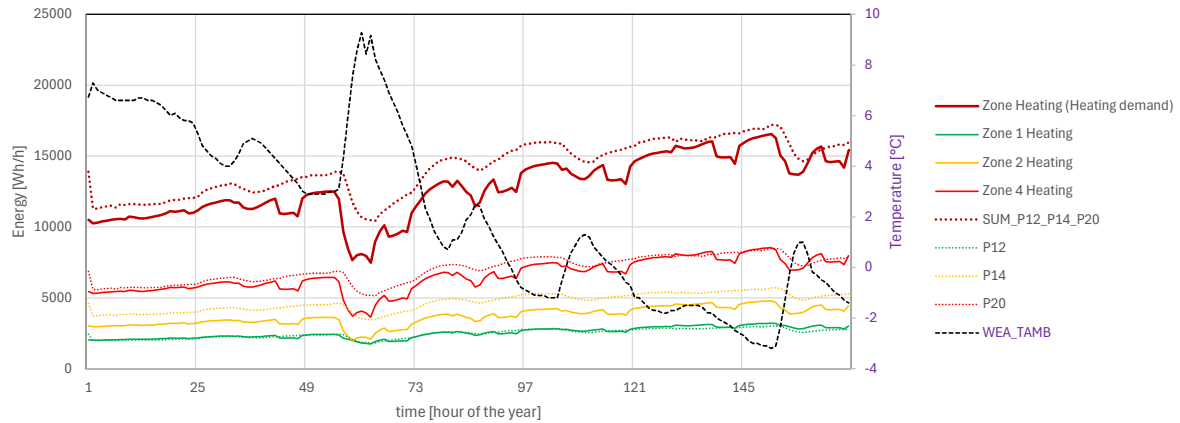


Figure 45 SH thermal demand (continuous lines) and SH thermal energy delivered by the radiators (dotted line) for the different thermal zones (green, orange, red) and their sum (dark red). Case with MVHR. Right y-axis: ambient air temperature (black dashed line). Exemplary winter week (1-7 Jan)

3.2.4.1.2. Electric consumption and PV + battery system contribution

The Figure 46 presents how the electric consumption is covered by the PV system, the battery and the electric grid in the considered exemplary winter week. As can be noted in the figure, the electric load presents limited variations along the day, while the PV production is generally limited due to the low solar availability in this period. On this basis, most of the electric load is covered by electricity coming from the grid in the considered week.

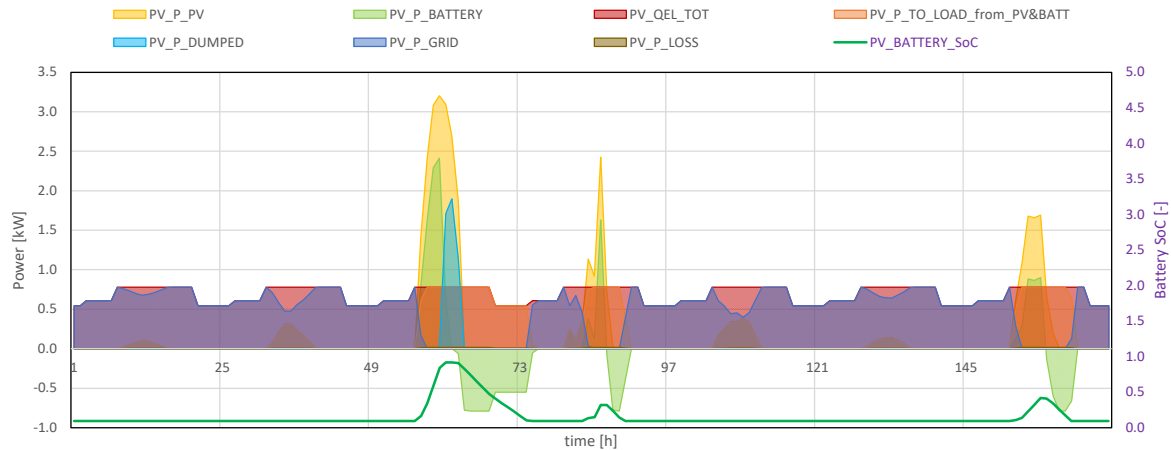


Figure 46 Electrical energy flows: PV production (yellow), power to/from battery (green), total electric consumption (red), electric consumption covered by PV and battery (orange), dumped power (light blue), power from grid (blue). Right y-axis: battery SoC (green line). Exemplary winter week (1-7 Jan)

3.2.4.2. Exemplary summer week (1-7 Jul)

Although the focus of the analysis presented in this section is to assess the behaviour of the HVAC system in winter, as the overall system also considers the presence of PV and battery, this section aims to analyse, in one representative summer week (1-7 Jul), the electrical energy flows.

3.2.4.2.1. Electric consumption and PV + battery system contribution

In the summer week used as reference, the PV + battery system is able to completely cover the building's electric load, as visible in Figure 47. In this period, the electric load is reduced in comparison to the winter season as the SH circulation pumps are not operating. On the other hand, in this period, the PV production is at its maximum due to the high solar availability. The considered battery is generally completely charged in a few hours in the morning, and during the night is only partially discharged (the battery's SoC never falls below 40 %, see the green line in the figure). As a result, the main fraction of the PV production in the considered week is dumped into the grid (light blue area in the figure).

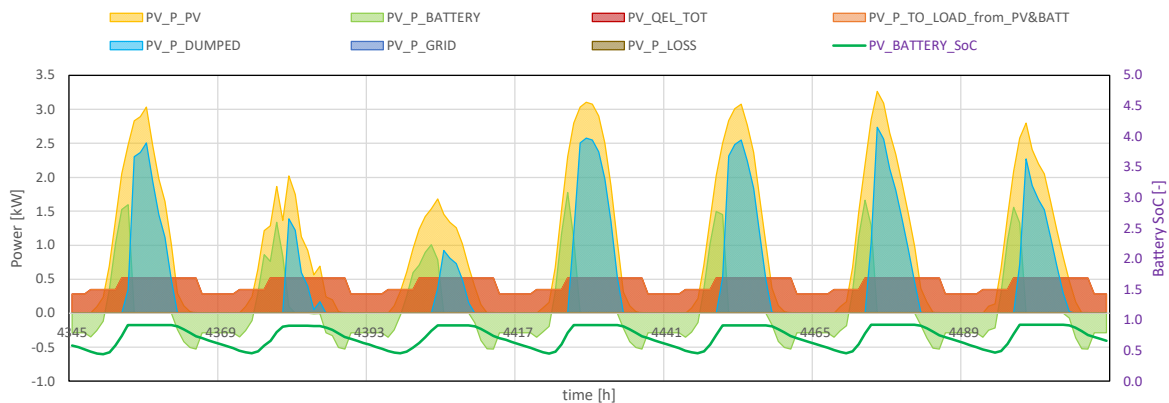


Figure 47 Electrical energy flows: PV production (yellow), power to/from battery (green), total electric consumption (red), electric consumption covered by PV and battery (orange), dumped power (light blue), power from grid (blue). Right y-axis: battery SoC (green line). Exemplary summer week (1-7 Jul)

3.2.4.3. Yearly assessment

This section reports a series of analyses at a yearly time horizon in terms of reduction of the distribution system thermal losses due to the considered climatic curve, PV and battery system self-consumption and self-sufficiency and a table summarising the most important indicators.

3.2.4.3.1. Reduction of the distribution system thermal losses

As written in the section 2.2.4.5, the considered climatic curve allows for reducing the SH distribution system thermal losses. On this basis, this section aims to quantify the SH distribution system thermal losses reduction using, as a reference scenario, the same system working with a climatic curve with extreme points being 70 °C at an ambient temperature equal to -13 °C and 50 °C at an ambient temperature equal to 20 °C. This reference climatic curve represents a common choice for the SH supply water temperature control, as reported in the section 2.2.4.

As visible in Figure 48, assuming equal to 100 % the SH thermal energy delivered from the radiators to the building, the considered climatic control allows for reducing the distribution system thermal losses from 9 % to 6 %. These percentages are calculated by dividing the distribution system thermal losses by the thermal energy delivered by the radiators.

It must be noted that these results are obtained considering, in the simulations, a distribution system characterised by thermally insulated pipes, with an insulation thickness of 1 cm and an insulation material characterised by a thermal conductivity (λ) of 0.04 W/(m·K). The advantage, in terms of reduced distribution system thermal losses, would be higher if the distribution system is not thermally insulated, a case which can be common in Historic Buildings.

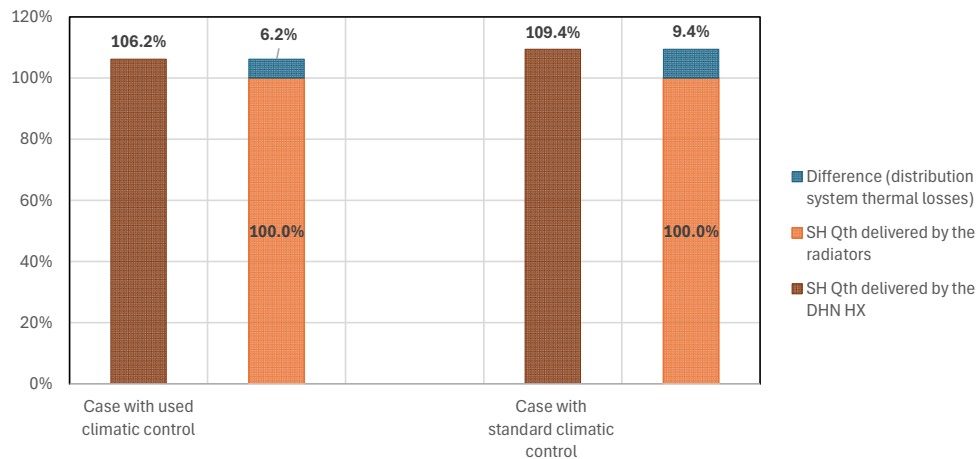


Figure 48 SH thermal energy delivered by the DHN HX (brown bars), delivered by the radiators (orange bars) and distribution system thermal losses (blue bars) obtained with the used climatic control (left) and with the reference (standard) control (right)

3.2.4.3.2. PV and battery system self-consumption and self-sufficiency

Figure 49 presents the monthly self-consumption and self-sufficiency values, highlighting their two opposite trends.

In terms of self-consumption, as for the other active system solutions considered, it reaches its maximum values in the winter months, where the electric consumption is high (see section 3.2.4.1.2) and the PV production is limited. On the contrary, during summer, the reduced electric consumption and the concurrent peak in PV production result in around 40-50 % of the PV production that is not used onsite and is dumped into the grid.

In terms of self-sufficiency, instead, the winter months show the minimum values as the limited PV production, together with the battery, can cover 25-50 % of the consumption. During summer, instead, the PV and battery system can almost completely cover the electric load (self-sufficiency values close to 100 %).

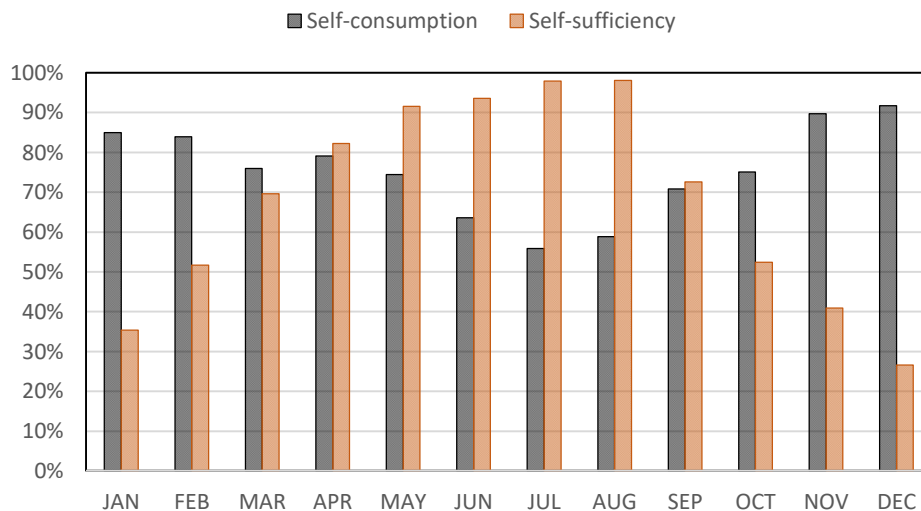


Figure 49 Monthly self-consumption (dark grey) and self-sufficiency (orange) values

Figure 50 shows instead the part of the energy that is produced by the PV system and self-consumed instantaneously (yellow bars) and the part that is stored in the battery and used at a later moment (green). As shown in the figure, in the winter months, the battery contribution is limited. However, due to the limited but almost constant electric consumption of the considered systems, there are moments with PV surplus also in the winter months that allow for the battery to be charged. On the other hand, the almost constant consumption also in the summer months implies that the battery contributes to almost half of the self-sufficiency, covering the electric load in the period between the evening and the morning of the following day, before the PV start to produce again.

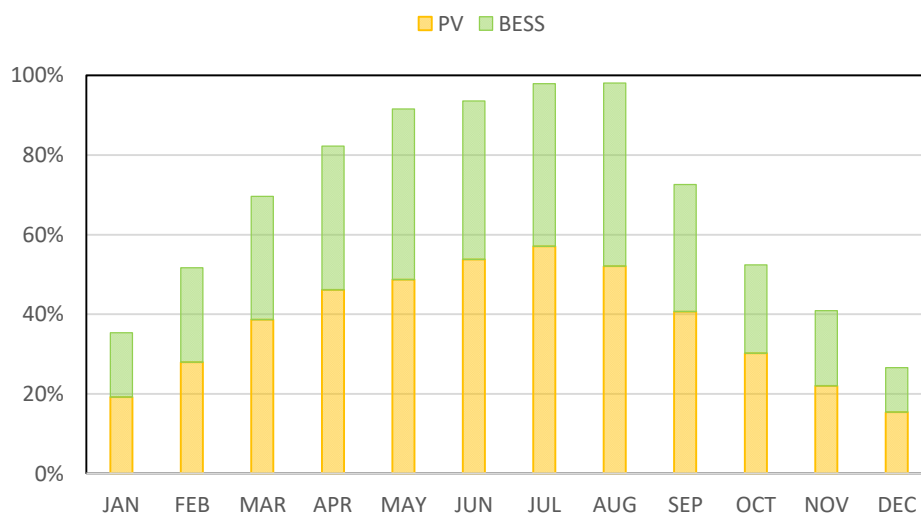


Figure 50 Monthly self-sufficiency associated with PV production instantaneously self-consumed (PV contribution, yellow), and PV production temporarily stored in the battery and later used (BESS contribution, green)

3.2.4.3.3. Overall yearly assessment

In this section,

Table 20 summarises a series of indicators at the yearly level, ranging from the assessment of the thermal energy demand for the different building thermal needs covered by the considered system solution (SH and DHW) to the final thermal and electrical energy consumed. Moreover, non-renewable primary energy consumption is calculated using the available non-renewable primary energy factors for the DHN, the electricity from the grid and the one from PV and battery and the same is done for the calculation of the GHG emissions using the related factors. All the primary energy and GHG emission factors used are reported in the section 6.4. Finally, the table reports, for the case featuring a PV and battery system, the self-consumption and self-sufficiency indicators.

As visible in the table, passing from the baseline scenario to the ideal one (therefore improving the thermal envelope performances) almost halves the SH thermal demand (119.528 MWh/y vs. 65.059 MWh/y). Moreover, if the MVHR system is considered, this further reduces the SH thermal demand by 7.467 MWh/y, reaching 57.592 MWh/y. The DHW thermal demand is instead independent of variations in the thermal envelope or of the system considered.

The total thermal final energy consumption passes from 142.579 MWh/y to 82.678 MWh/y in the case where only interventions on the thermal envelope are considered and to 73.609 MWh/y in the case in which the MVHR is also considered.

The presence of the MVHR is beneficial in terms of SH thermal demand reduction (7.467 MWh/y), however, as can be noted in the table below, it is characterised by an electric consumption that is in the range of 3 MWh/y.

In terms of yearly self-consumption and self-sufficiency, these values are equal to 72 % and 65 %, respectively, indicating that 65 % of the building's electric consumption is covered using renewable electricity locally produced and that 72 % of the PV production is used on site.

Regarding the non-renewable primary energy consumption, it is interesting to note that the solution with only the MVHR presents a higher non-renewable primary energy consumption in comparison to the same case without the MVHR system. This is because the primary energy factor used for the thermal energy coming from the DHN (0.722) is notably lower than the one considered for the electricity coming from the grid (2.3). Similarly, the low emission factor of the DHN (0.433 tCO_{2,eq}/MWh) and the higher one considered for the electricity coming from the grid (0.779 tCO_{2,eq}/MWh) explain the limited reduction in GHG emission in the case a MVHR system is added to the Ideal scenario.

Table 20 Overall yearly assessment for the DHN connection active system solution in the Polish building typology n.1. Primary energy consumption and GHG emissions are calculated based on the factors reported in the section 6.4 for Poland

Variable	Unit	Baseline scenario	Ideal scenario without MVHR	Ideal scenario with MVHR	Ideal scenario with MVHR, PV and battery
Ed, th, for SH	MWh/y (kWh/(m ² ·y))	119.528 (341.55)	65.059 (185.90)	57.592 (164.57)	57.592 (164.57)
Ed, th, for DHW	MWh/y (kWh/(m ² ·y))	2.420 (6.92)	2.420 (6.92)	2.420 (6.92)	2.420 (6.92)
Ef, th. From the DHN	MWh/y (kWh/(m ² ·y))	140.890 (402.59)	77.961 (222.77)	69.334 (198.12)	69.334 (198.12)
Ef, el. From the grid	MWh/y (kWh/(m ² ·y))	2.277 (6.51)	2.277 (6.51)	5.341 (15.26)	1.889 (5.40)
Ep,nren	MWh/y (kWh/(m ² ·y))	113.233 (323.56)	64.996 (185.72)	65.430 (186.96)	57.491 (164.28)
Self-sufficiency	%	-	-	-	65
Self-consumption	%	-	-	-	72
GHG	tCO ₂ ,eq/y	66.6	37.6	36.1	33.4

Regarding the IEQ, Figure 51 shows the number of hours along the year with the indoor air temperature being in different ranges. In this case, the building temperature shown is the average indoor building temperature, calculated as the weighted average of the temperatures of the three thermal zones simulated, weighted based on the net floor area of each thermal zone. As visible in the figure, the system considered (and the related climatic control) ensures the desired set point temperature (equal to 21 °C) for most of the time throughout the year. In any case, both air and operative temperatures are never lower than 20 °C. Regarding overheating conditions, instead, indoor air temperature is, for a few (less than 10 hours in the year), higher than 28 °C. However, SC is not considered in this case, as this active system solution cannot deliver SC.

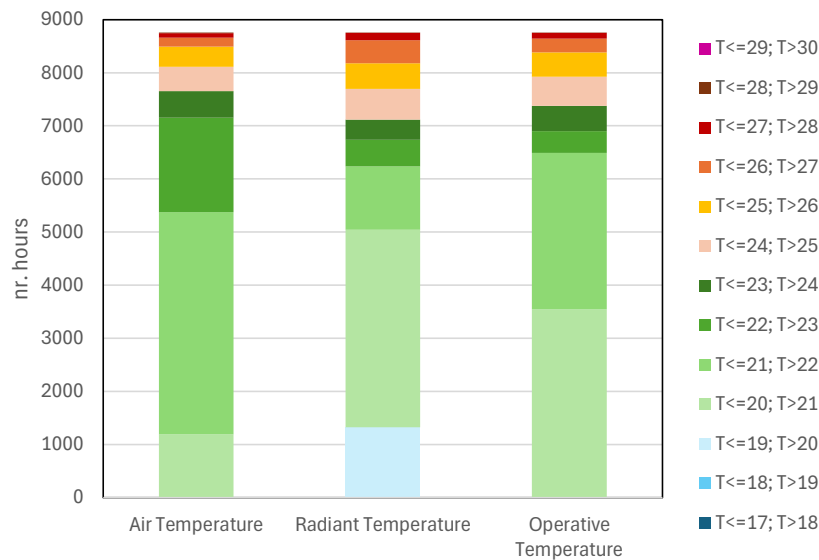


Figure 51 Number of hours throughout the year with building indoor air, radiant, and operative temperature in defined ranges

3.2.4.4. Main outcomes for the considered system

Based on the above results, it can be concluded that, also in the case of a building connected (or that will be connected) to the DHN, there are a series of interventions, in this case limited to the system control, that allows to improve the system performance. More specifically, the use of a properly set climatic curve allows for covering the building's SH thermal demand with reduced thermal losses in the distribution circuit.

3.3. Active system solutions in the future climate

One of the objectives of this work is to assess whether the considered active system solutions are able to ensure indoor comfort conditions also in a future climatic scenario affected by climate change.

Dynamic simulations were performed to assess, for all four Historic Building typologies considered in this work, how the yearly SH and SC change as a result of the changed climate in the same location (see section 3.1).

However, the focus of this section is to assess whether the AWHP system considered in the Spain building typology n.1, without changing its size (mainly in terms of thermal power in nominal conditions), is able to cover the SC demand obtained with the future climatic scenario. This building and the related AWHP system represent the most challenging scenario in terms of different SH/SC thermal demand to be covered in a future climatic scenario.

Figure 52 shows the SC thermal energy delivered to the different dwellings of the Spain building typology n.1 in one of the hottest summer weeks in the future climatic scenario, characterised by temperatures up to 47 °C. Figure 53 shows the indoor air temperature profile in the same week.

As visible from the second figure, the system is able to maintain the desired indoor air temperature set point (25 °C). However, it must be noted that, in this simulation, no schedule has been considered for the SC system operation as, due to the particularly high ambient air temperature, it is assumed that in these conditions the system can run 24/7.

It is interesting to note that there is a period of some hours on the 2nd day of the considered hot summer week in which the AWHP system is switched OFF. This can be noted by observing the delivered SC thermal energy, which results equal to 0 in the first figure, or the indoor air temperature increase in the second figure. This behaviour is because the AWHP considered in the simulations has some limitations in terms of operative conditions. More specifically, the AWHP is blocked if at the condenser inlet it receives air with a temperature higher than 45 °C in SC mode. As similar limitations are valid for all the machines available on the market, it is important to verify, in the case of AWHP system installation in particularly hot climates, the operational limits of the units to be installed.

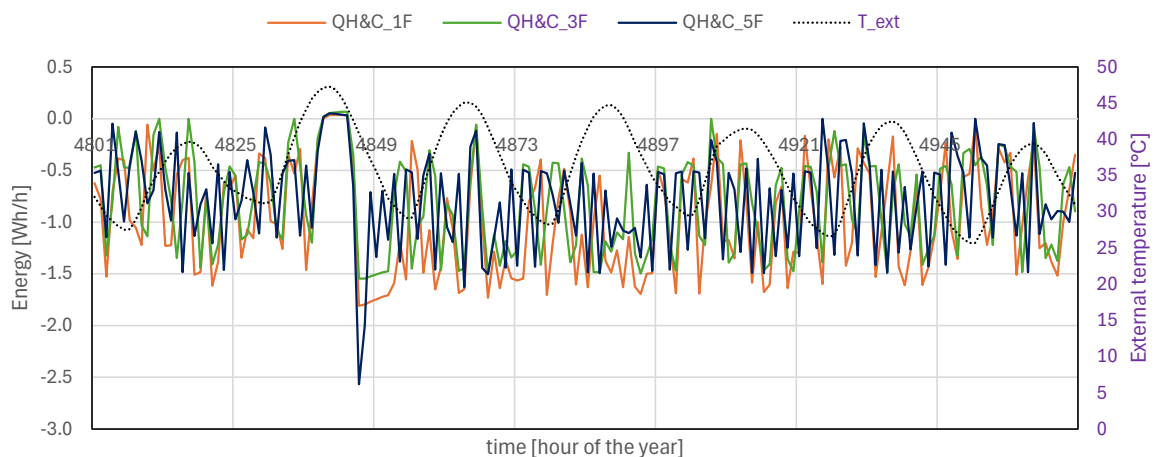


Figure 52 Thermal energy delivered to the users for SC in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Considered hot summer week in the future climate scenario (20-27 Jul)

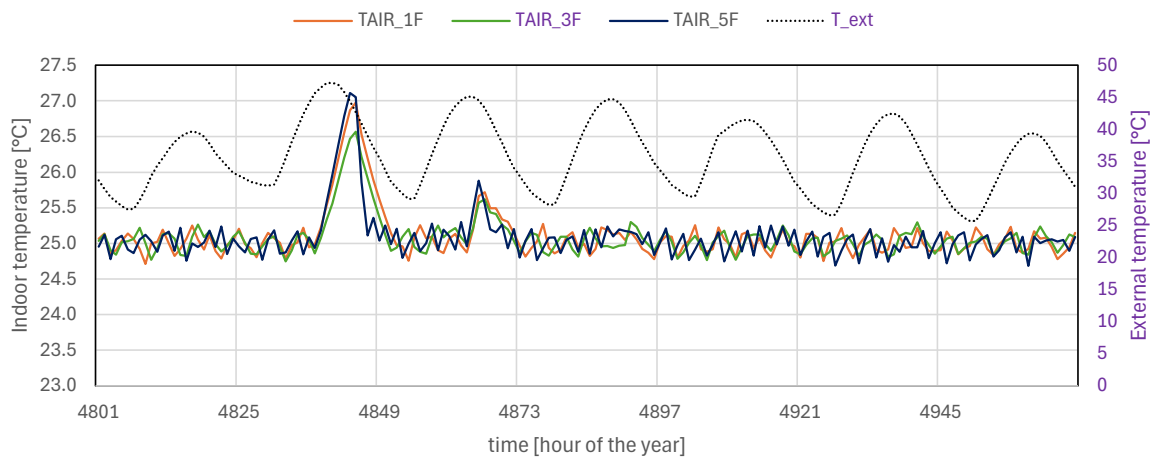


Figure 53 Indoor air temperature in the three dwellings (orange, green, dark blue). Right y-axis: ambient air temperature (dotted black). Considered hot summer week in the future climate scenario (20-27 Jul)

3.4. Smart Readiness Indicator of the developed active system solutions

This section reports the SRI index and the related class for the different active system solutions considered.

As visible in Table 21, the solutions with an HP system (AWHP and WLHP systems) are characterised by SRIs that are similar and relatively high, already at the level 1 case. In level 2, the index is further increased as more possibilities for interactions with the electrical grid are assumed. More specifically, it is assumed that the control can potentially receive signals from the electric grid operator (Distributor System Operator, DSO) and is also able to react to the sent signal.

The solution that considers the connection to the DHN is characterised by slightly lower levels of SRI as, in general, the possible interactions with the electrical grid are limited.

Finally, the MVHR system presents values drastically lower in comparison to the other active system solutions considered. This is because the MVHR is considered alone in the SRI assessment (i.e. without considering also a SH and DHW system). Moreover, in general, the possibilities of control for the MVHR are more limited in comparison to a system delivering SH and DHW, and this is also valid for the possible interactions with the electric grid.

Section 6.3 reports, for all solutions, the values used as input for the assessment of the SRI index.

Table 21 SRI index and class for the active system solutions considered

Active system solution	SRI index Level 1	SRI class Level 1	SRI index Level 2	SRI class Level 2
	[%]	[-]	[%]	[-]
AWHP system (Spanish building typology n.1)	58	Class D (50-65)	75	Class C (65-80)
WLHP system (Swedish building typology n.1)	57	Class D (50-65)	78	Class C (65-80)
MVHR system (Scottish building typology n.1)	28	Class F (20-35)	36	Class E (35-50)
DHNC system (Polish building typology n.1)	53	Class D (50-65)	65	Class C (65-80)

4. Conclusions and outlooks

This deliverable describes four active system solutions that can be considered suitable for Historic Buildings' application.

The building typologies to which the different project demonstrator buildings belong are identified and their thermal needs, in terms of space heating and cooling, are obtained from dynamic simulations using both current and future climatic scenarios.

The four active system solutions have been identified for the considered building typologies. These are comparable with those that are going to be installed in the five project's demonstrator buildings (with some modifications needed for specific adaptation to the demonstrator buildings). More specifically, two heat pump solutions (one more standard air/water heat pump system and one more advanced water-loop heat pump system) are presented, together with a solution considering the connection to a local district heating network and one featuring a mechanical ventilation with heat recovery system.

The solutions are described both in terms of main system components and system control, with specific sections reporting the simplified technical drawings and the main characteristics of the control system.

The active system solutions are then simulated using dynamic simulation software, and the related results are presented and discussed. These results focus on both short time horizons, to focus on the details of the systems' operation in representative weeks, and longer ones (system performance over the various months and at the yearly level).

Regarding the air/water heat pump system considered in the Spanish building typology n.1, it has been verified that the system solution drastically reduces the primary energy consumption (- 58 %) in comparison to the base scenario featuring electric radiators and electric boilers for covering space heating and domestic hot water thermal needs and split units for covering the space cooling demand. Moreover, it has been verified that the air/water heat pump system, sized based on the current climatic conditions, will be able to ensure the desired indoor temperature level also in a future climatic scenario.

For what concern the water loop heat pump system, although this system will not be installed in any demonstrator building, it has been verified that it can cover the space heating thermal demand of the Swedish building typology n.1 with performance, in terms of system COP, in the range of 3; a value that is difficult to reach with a standard air/water heat pump system in the cold winter days in the considered climate. Moreover, the use of a water loop at almost neutral temperature (20-35 °C) reduces to almost zero the distribution system thermal losses.

In the case of the district heating network connection, the focus was on optimising the system control, reducing the supply water temperature to the radiators to minimise the distribution system thermal losses. In this context, it has been proven that the reduced supply temperature to the radiators considered is sufficient to cover the space heating thermal demand of the Polish building typology n.1.

Regarding the mechanical ventilation with a heat recovery system, the performed simulations focused on assessing that the indoor comfort, in terms of CO₂ level in the building, is ensured. In this context, the simulations proved that the use of this system is able to maintain the CO₂ level always below 1200 ppmv in the Scottish building typology n.1, resulting for most of the time in values lower than 800 ppmv, representative of good air quality in terms of CO₂ concentration. At the same time, the building's space heating thermal demand is reduced thanks to the use of a mechanical ventilation system with heat recovery.

Lastly, the Smart Readiness Indicator of the four active system solutions developed is calculated. To give a more complete analysis, two assessments are reported for each active system solution, one considering devices generally available on the market, and one considering more advanced components, in general, allowing for more interactions with the electric grid.

Overall, all four active system solutions developed present advantages in comparison to those typically installed in the considered buildings, mainly in terms of energy efficiency and, where considered, in terms of indoor environmental quality. Moreover, their future installation in the project demo sites confirms that they constitute a potential choice also in Historic Buildings, where there could be limitations in the proposed interventions.

This document will serve as a base for the future detailed definition of the active system solutions to be installed at the demonstrator buildings and, in general, in buildings belonging to the considered building typologies, and to give a first assessment of the system performance achievable in these cases.

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6. Annexes

6.1. Annex 1. Detailed analysis of the climatic files used

This section reports an analysis of the climatic conditions of the four considered locations for both the “Contemporary” and the future (IPCC RCP8.5, year 2070 scenario) climatic conditions. The analysis is reported, for each demo location, in terms of hourly ambient temperature, relative humidity and solar irradiation on a horizontal surface over the entire year. In addition, for each variable, a duration curve is also shown.

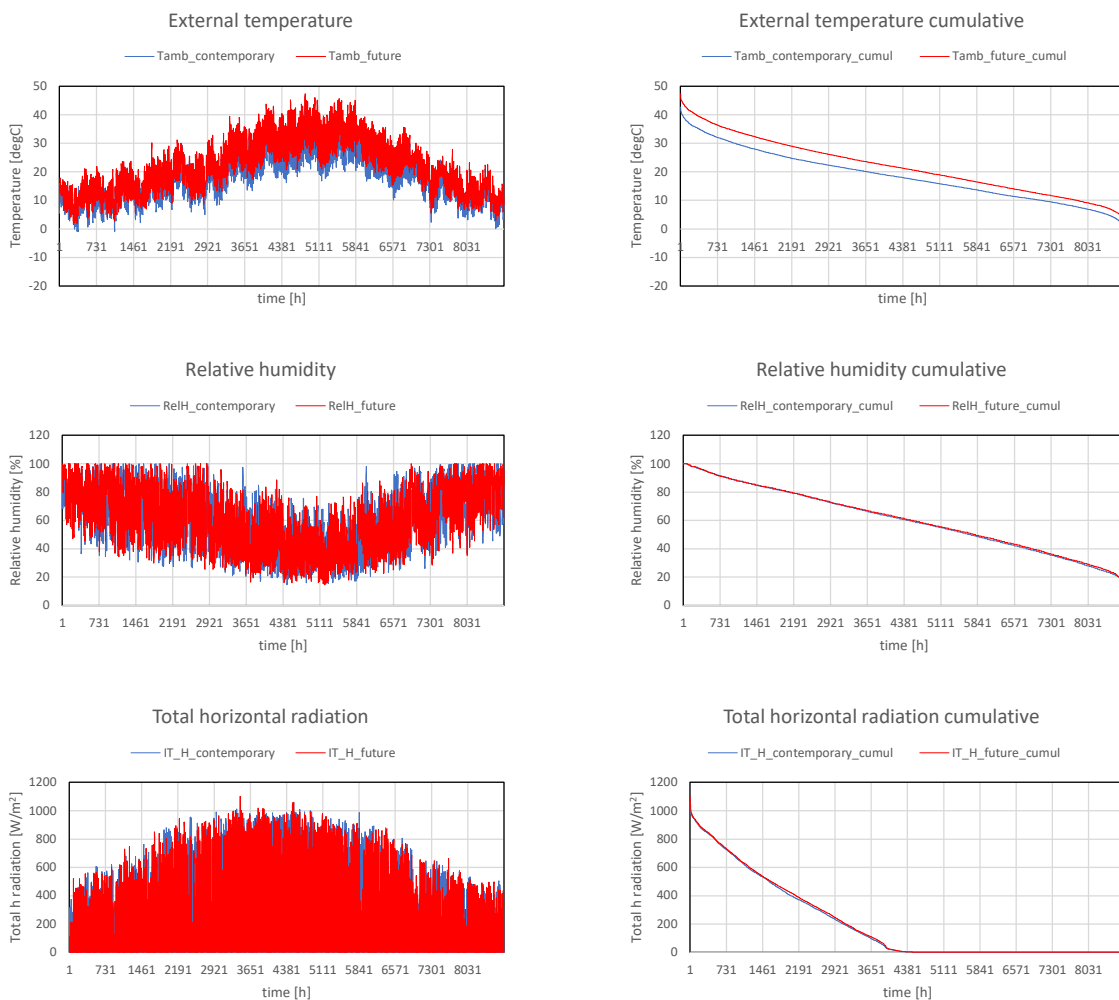


Figure 54 Cordoba “Contemporary” (blue) and future (IPCC RCP8.5, year 2070, red) climatic conditions in terms of ambient temperature (top row figures), relative humidity (middle row figure) and solar irradiation on a horizontal surface (bottom figure)

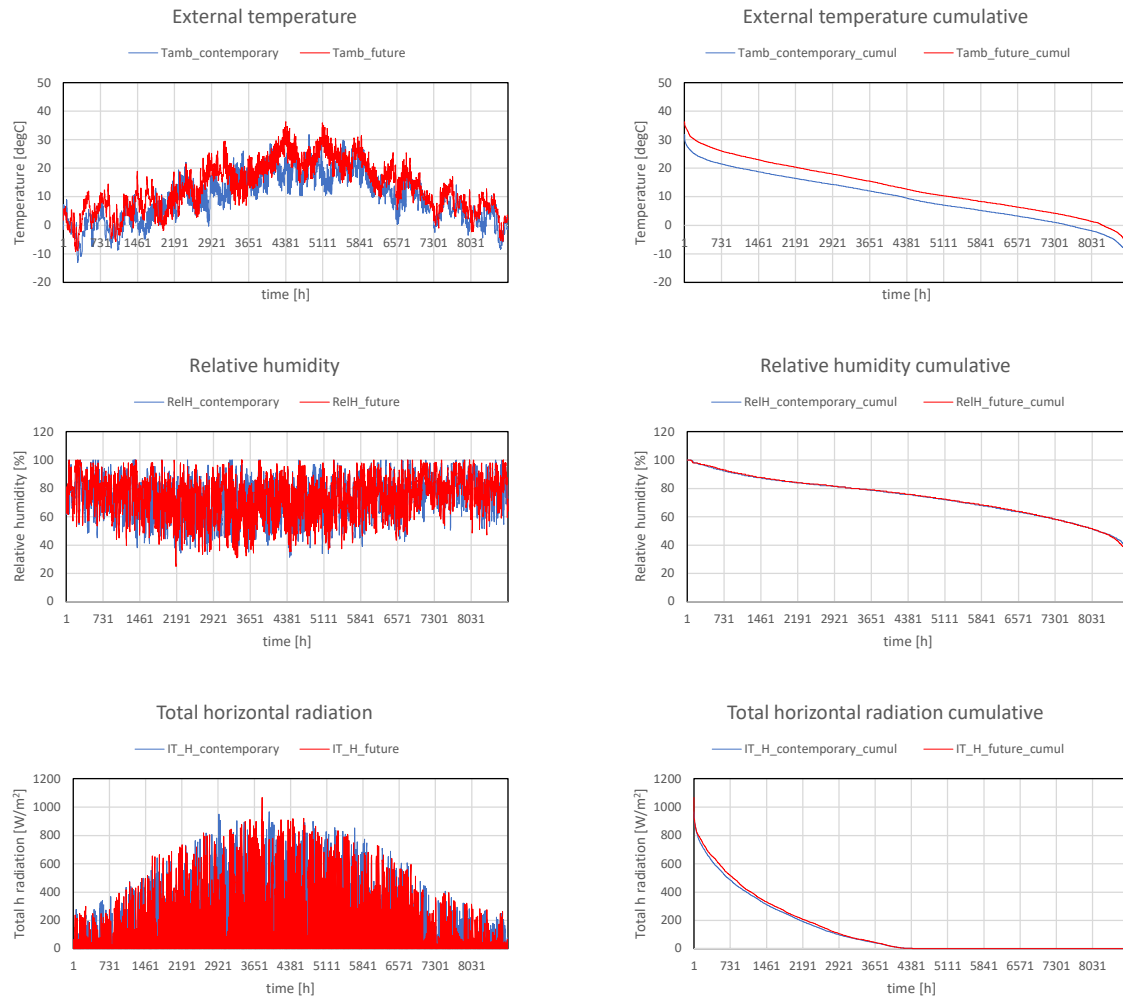


Figure 55 Krakow “Contemporary” (blue) and future (IPCC RCP8.5, year 2070, red) climatic conditions in terms of ambient temperature (top row figures), relative humidity (middle row figure) and solar irradiation on a horizontal surface (bottom figure)

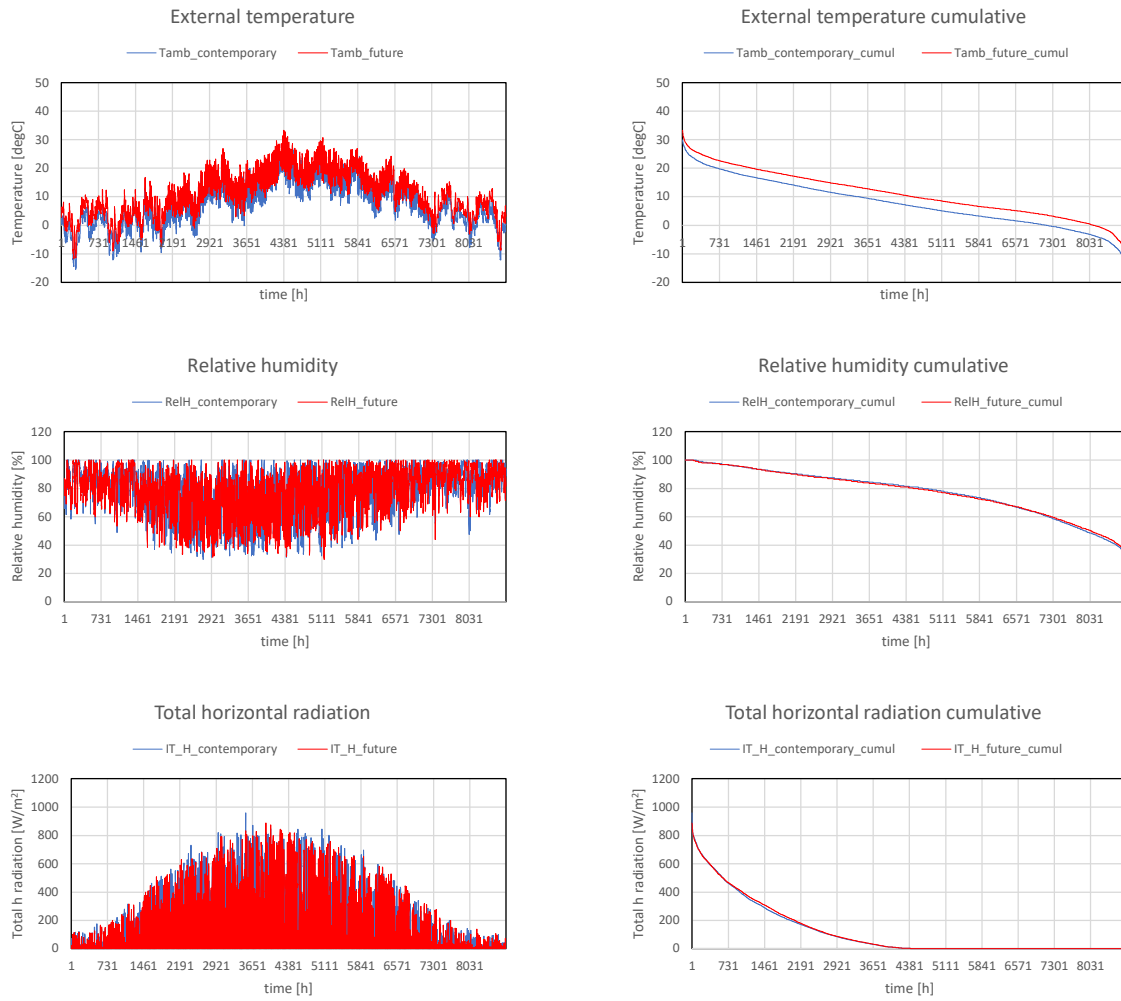


Figure 56 Linköping “Contemporary” (blue) and future (IPCC RCP8.5, year 2070, red) climatic conditions in terms of ambient temperature (top row figures), relative humidity (middle row figure) and solar irradiation on a horizontal surface (bottom figure)

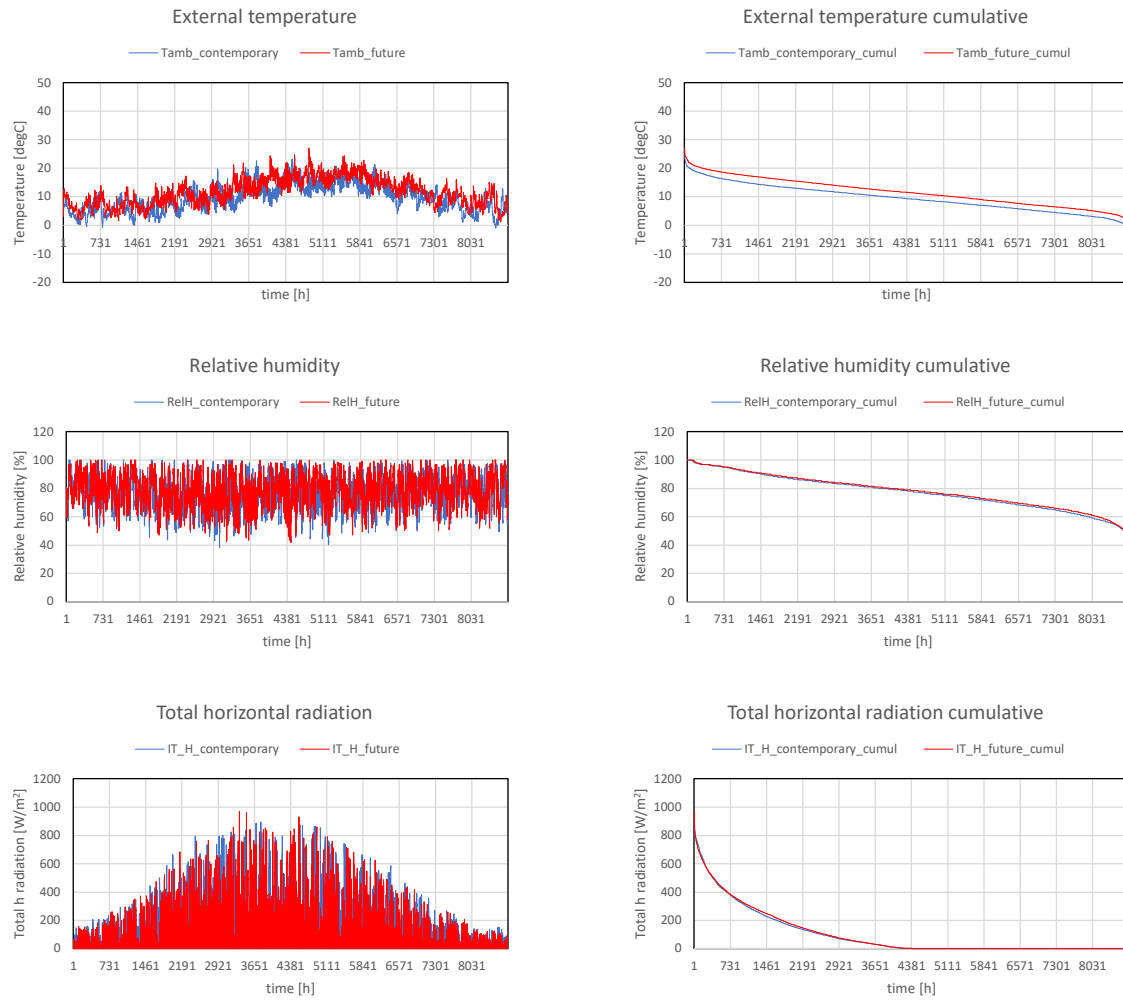


Figure 57 Edinburgh “Contemporary” (blue) and future (IPCC RCP8.5, year 2070, red) climatic conditions in terms of ambient temperature (top row figures), relative humidity (middle row figure) and solar irradiation on a horizontal surface (bottom row figure)

6.2. Annex 2. Detailed P&ID of the developed active system solutions

This Annex includes a more complete version of the P&IDs of the AWHP, WLHP, MVHR and DHNC systems. These P&IDs also feature safety valves, expansion vessels, and, in general, all the main components typically present in the active system solutions. Moreover, the main monitoring and control devices are also provided in separate drawings, in some cases, to improve clarity.

6.2.1. Heat Pump system

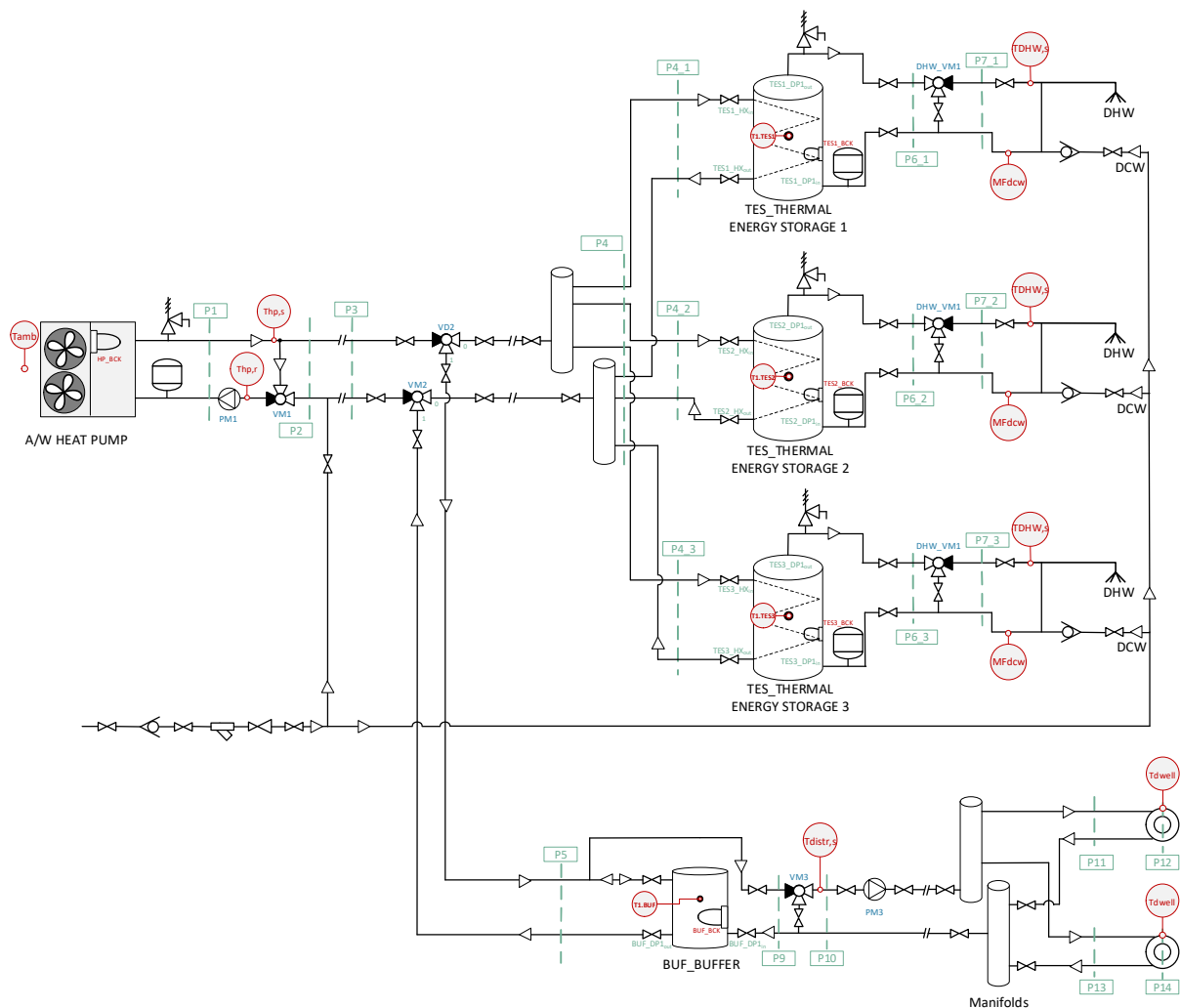


Figure 58 A/W HP system P&ID with main hydraulic components

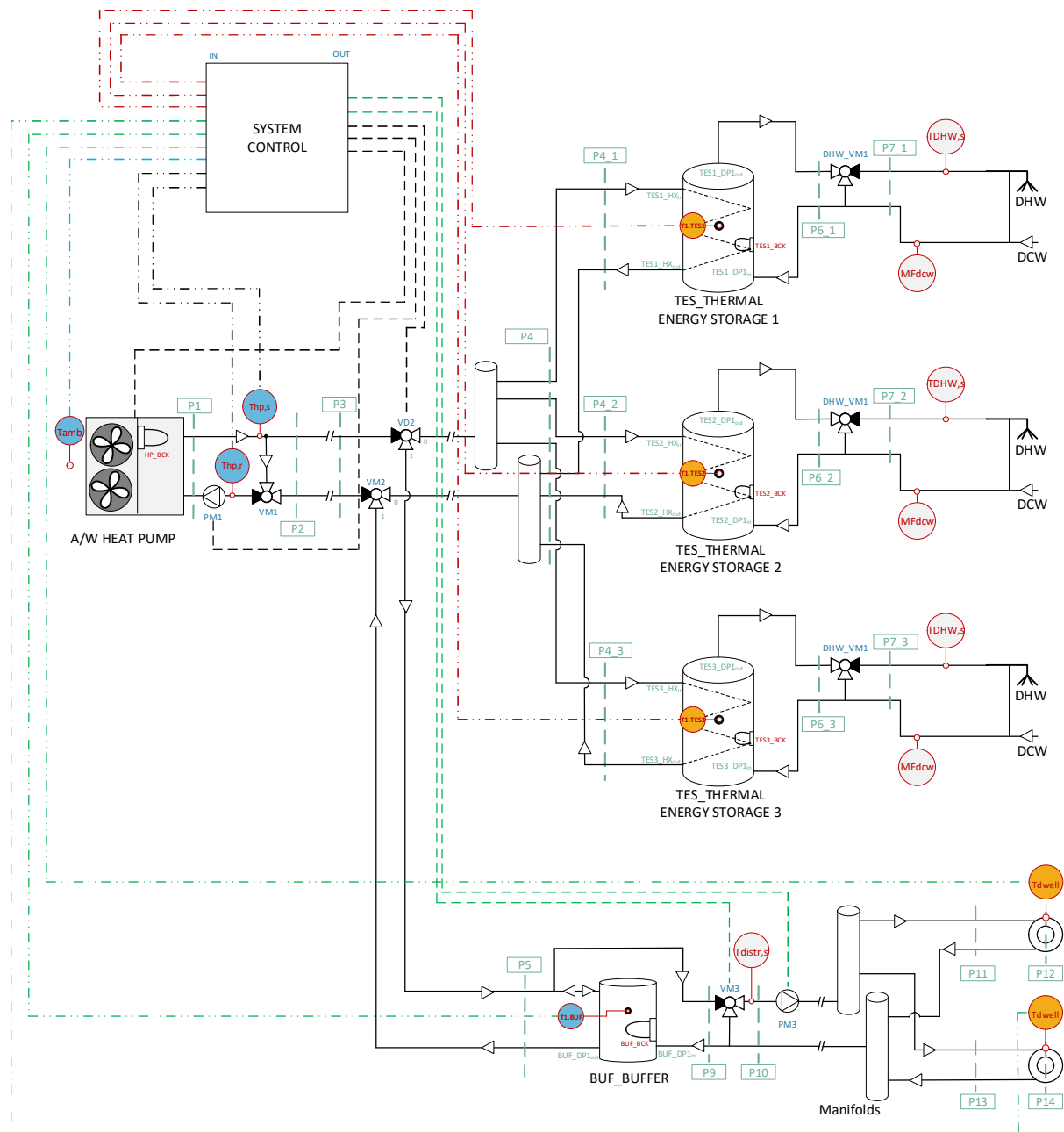


Figure 59 AWP system P&ID highlighting the control sensors' connection to the central controller

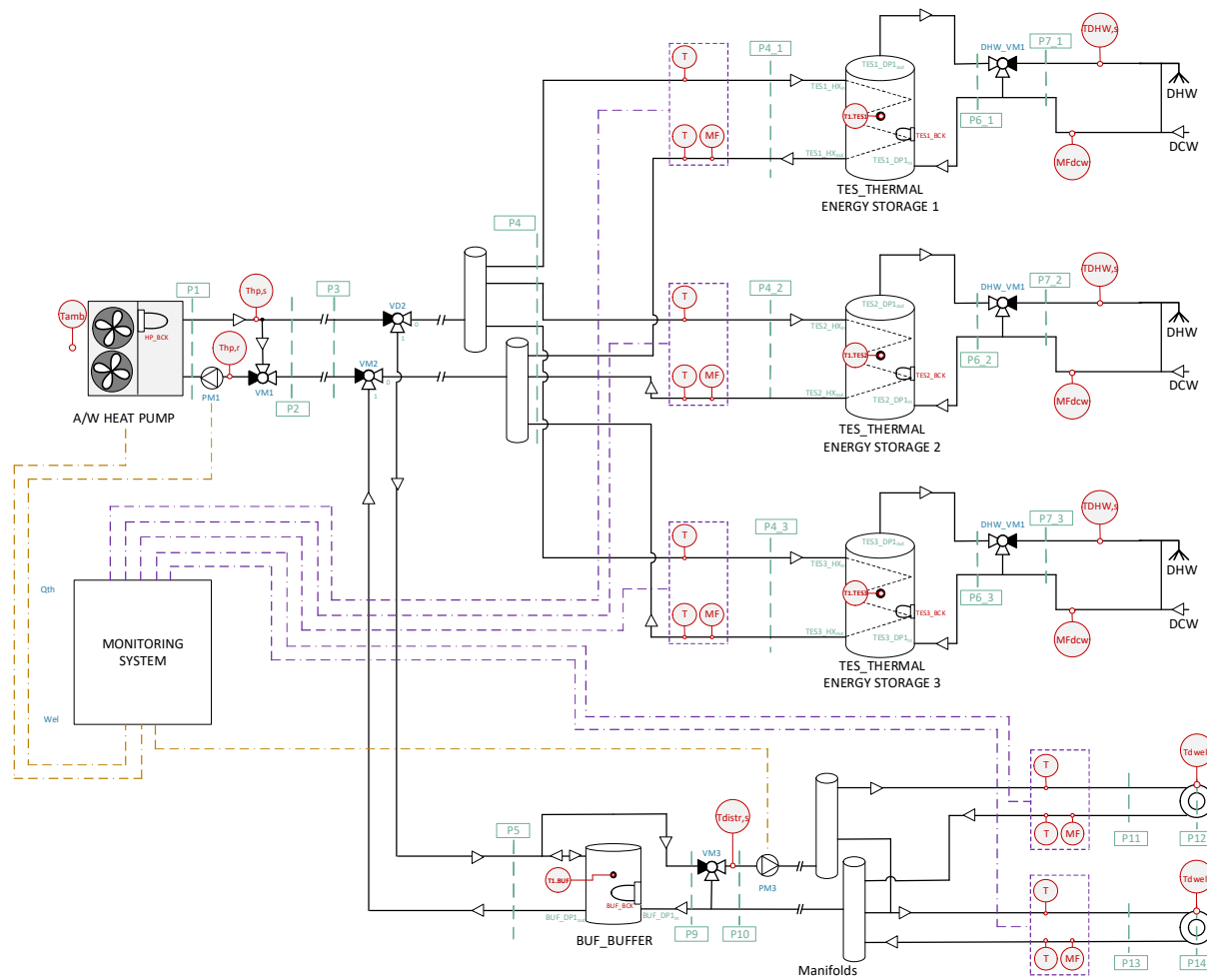


Figure 60 A/WHP system P&ID highlighting the connection of the thermal energy meters to the monitoring system

6.2.2. Water Loop Heat Pump system

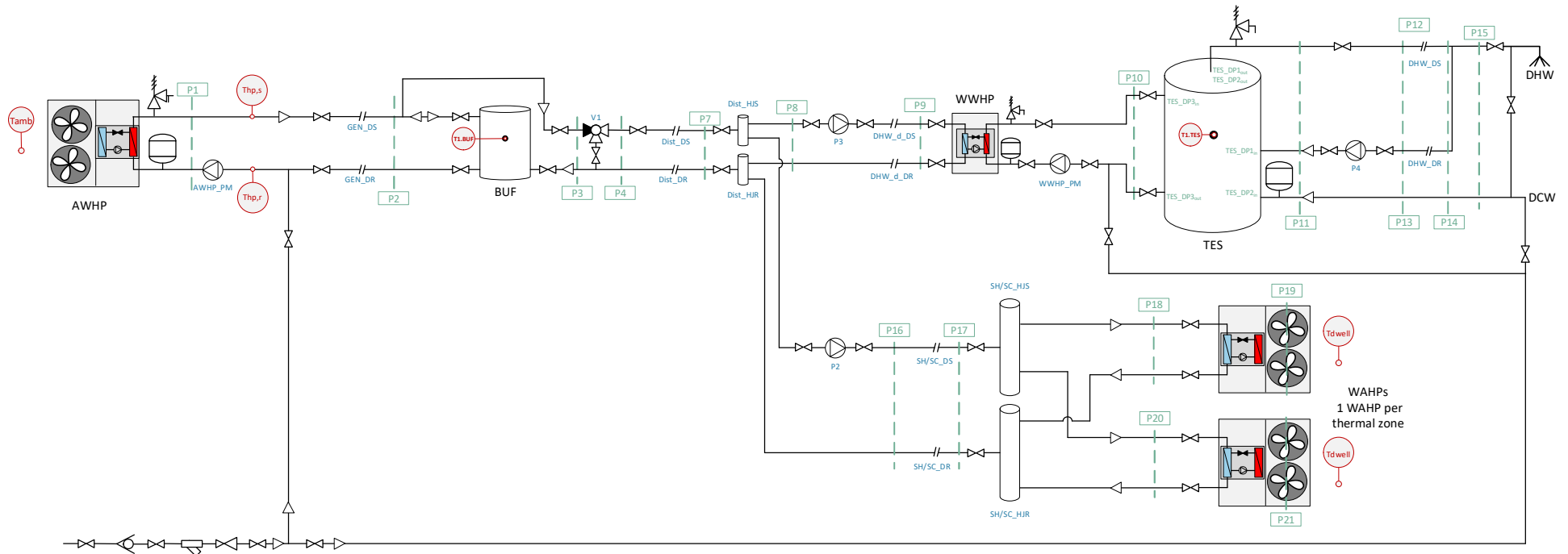


Figure 61 WLHP system P&ID with main hydraulic components

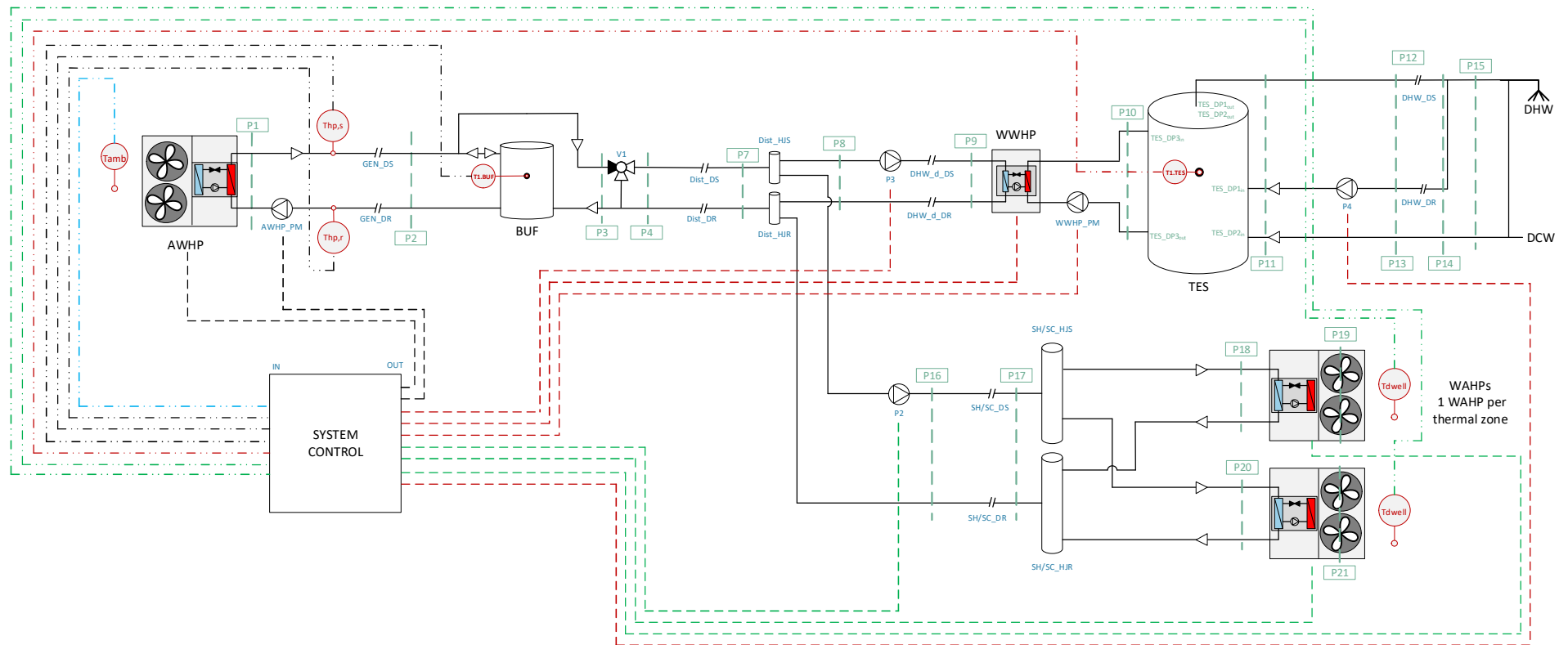


Figure 62 WLHP system P&ID highlighting the control sensors' connection to the central controller.

6.2.3. Mechanical ventilation with heat recovery system

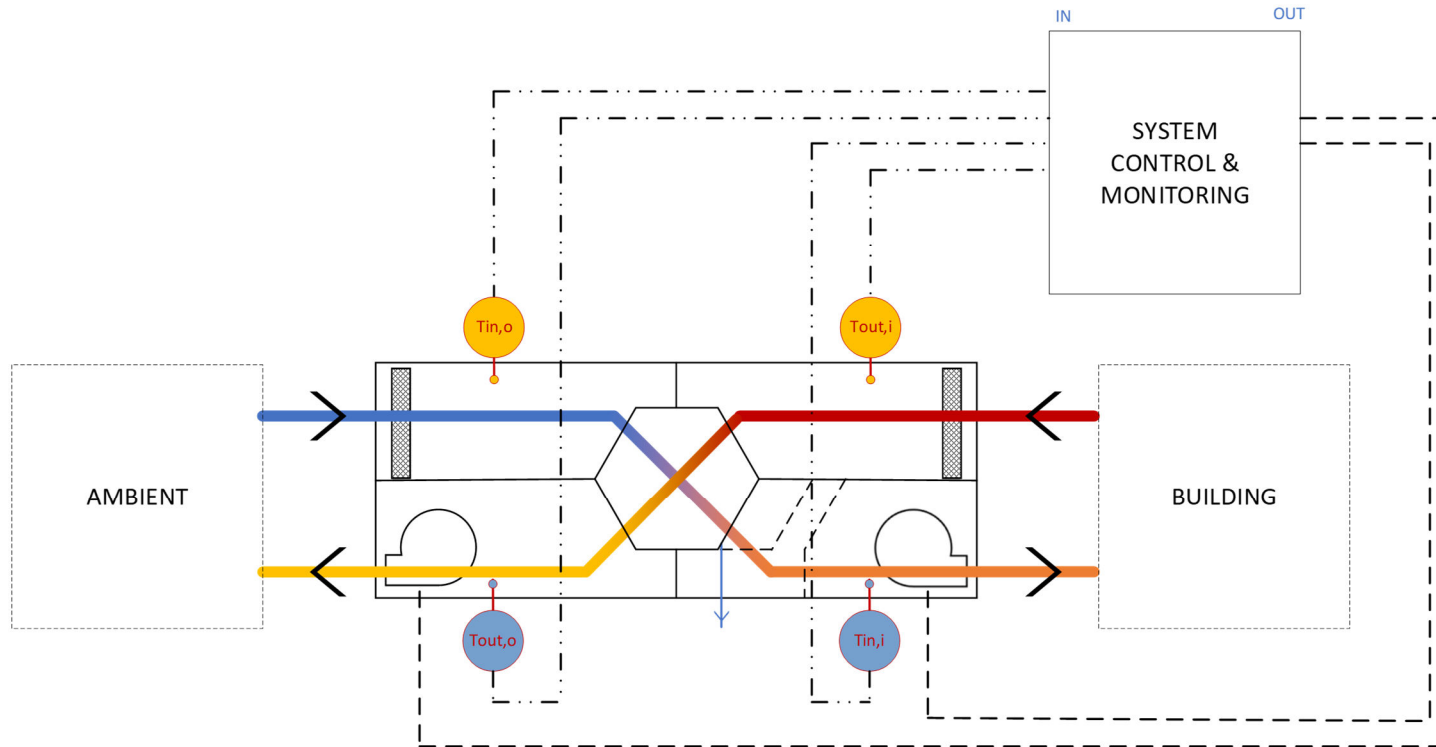


Figure 63 MVHR system P&ID highlighting the control sensors' connection to the central controller

6.2.4. Connection to the District Heating Network

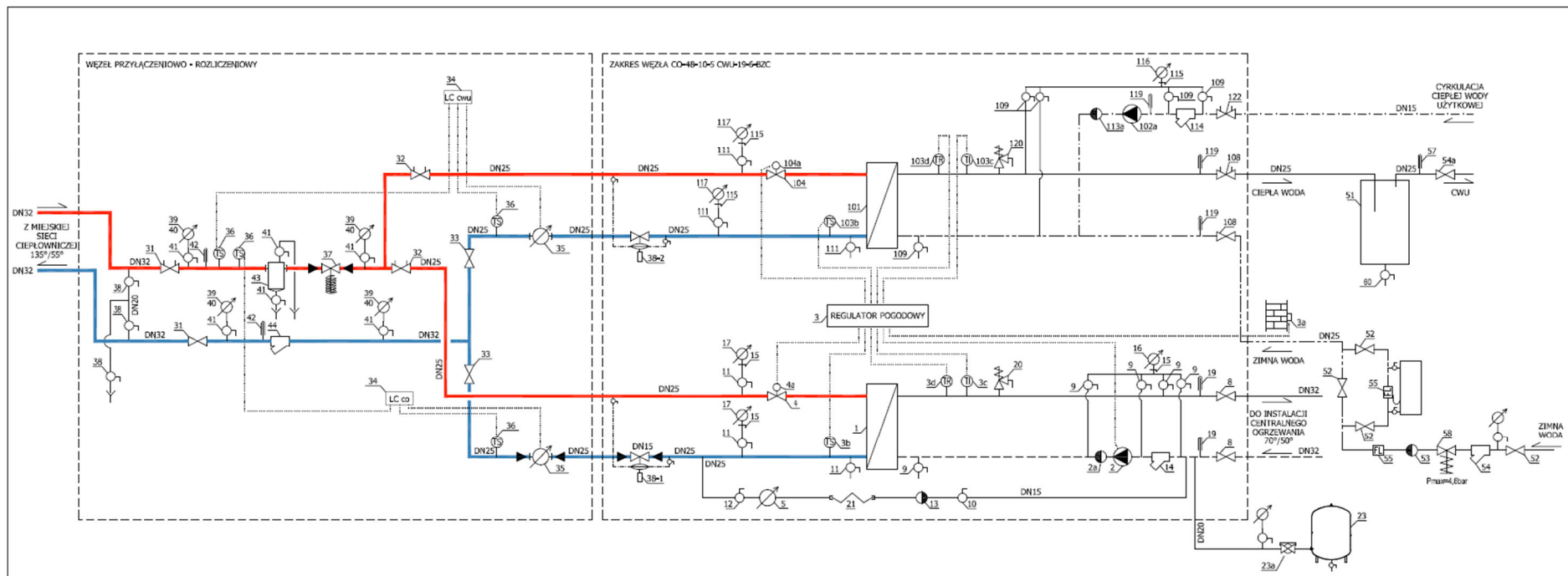


Figure 64 DHNC system P&ID highlighting all the hydraulic devices and sensors used to control the system

6.3. Annex 3. Details about the SRI calculation

This Annex reports the inputs used for the SRI calculation for all active system solutions and the two levels considered.

Table 22 SRI inputs used for the calculation of the SRI in levels 1 and 2 of the active system solutions considered

Code	Main functionality level							
	AWHP system		WLHP system		MVHR system		DHNC system	
	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
H-1a	3	4	3	4			3	4
H-1b	-	-	-	-			-	-
H-1c	2	2	2	2			2	2
H-1d	3	3	3	3			3	3
H-1f	2	3	2	3			2	2
H-2a	-	-	-	-			1	2
H-2b	2	3	2	3			-	-
H-2d	2	2	2	2			-	-
H-3	3	4	3	4			3	4
H-4	2	3	2	3			2	2
DHW-1a	-	-	-	-			-	-
DHW-1b	2	2	2	2			1	2
DHW-1d	1	1	1	1			1	1
DHW-2b	2	2	2	2			-	-
DHW-3	3	4	3	4			3	4
C-1a	3	4	3	4				
C-1b	-	-	-	-				
C-1c	2	2	2	2				
C-1d	3	3	3	3				
C-1f	2	2	2	2				
C-1g	2	3	2	3				
C-2a	2	3	2	3				
C-2b	2	2	2	2				

C-3	3	4	3	4				
C-4	2	3	2	3				
V-1a					1	3	2	3
V-1c					2	3	3	3
V-2c					1	2	1	2
V-2d					2	2	2	2
V-3					1	3	1	3
V-6					2	2	2	2
E-2	2	3	2	3			2	3
E-3	3	3	3	3			1	1
E-4	2	2	2	2			1	1
E-5	-	-	-	-			-	-
E-8	-	-	-	-			-	-
E-11	2	3	2	3			2	3
E-12	1	2	1	2			1	2
MC-3	2	2	2	2	-	-	1	1
MC-4	1	2	1	2	1	1	1	1
MC-9	1	1	1	1	1	1	1	1
MC-13	2	2	2	2	2	2	2	2
MC-25	1	2	1	2	-	-	1	2
MC-28	1	1	1	1	-	-	1	1
MC-29	2	2	2	2	-	-	2	2
MC-30	1	1	1	1	-	-	1	1

6.4. Annex 4. Primary energy and GHG emission factors used in the calculation

This annex summarised the primary energy and GHG emission factors used in the calculation.

Table 23 Primary energy factors and GHG emission factors for the different energy vectors and countries used for the calculation

Country	Energy vector	Variable	Unit	Value	Source
Spain	Electricity	fp,ren	-	0.396	[13]
		fp,nren	-	2.007	[13]
		fp,tot	-	2.403	[13]
		fGHG	tCO ₂ ,eq/MWh	0.175	From Table 2_EU_IPCC_GHG, year 2021 in [14]
Poland	Electricity	fp,nren	-	2.3	ISO 52000-1, table B.16
		fGHG	tCO ₂ ,eq/MWh	0.779	From Table2_EU_IPCC_GHG, year 2021 in [14]
	District Heating Network	fp,nren	-	0.7220	Specific value for the Kraków District Heating Network / MPEC, 2025
		fGHG	tCO ₂ ,eq/MWh	0.43324	Specific value for the Kraków District Heating Network / MPEC, 2025
Scotland	Electricity	fp,nren	-	1.501	[12]
		fGHG	tCO ₂ ,eq/MWh	0.136	[12]
Sweden	Electricity	fp,nren	-	1.8	[15]
		fGHG	tCO ₂ ,eq/MWh	0.015	From Table2_EU_IPCC_GHG, year 2021 in [14]
	District Heating Network	fp,nren	-	0.07	From specific document about Linköping DHN
		fGHG	tCO ₂ ,eq/MWh	0.108	From specific document about Linköping DHN



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