D3.3 Overall Result Analysis

WP3, T3.4

Date of document: 29th October 2024 (2024/10/29)

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HAPPENING – H2020-LC-SC3-EE-2020-1

GRANT AGREEMENT No. 957007

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957007

Technical references

Project Acronym	HAPPENING
Project Title	**H**e**A**t **P**um**P**s in existing multi-family buildings for achieving union's **EN**ergy and envIro**N**mental **G**oals
Project Coordinator	Irantzu Urkola Tecnalia irantzu.urcola@tecnalia.com
Project Duration	1st October 2020 – 30th September 2024 (48 months)

Deliverable number	D3.3 Overall result analysis
Dissemination Level	PU[1]
Work Package	WP3 Monitoring for performance evaluation and smart controls
Task (s)	T 3.4 Cross comparison of main results
Lead beneficiary	FRAUNHOFER
Contributing beneficiary(ies)	TECNALIA, TECNOZENITH, AEE
Due date of deliverable	30th September 2024 (2023/09/30)
Actual submission date	29th October 2024 (2023/10/29)

[1] PU = Public

CO = Confidential

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Tables & Figures

Versions

No.	Name SURNAME	Partner	Contribution	Date
0.1	Mu HUANG	FRAUNHOFER	Creation of the deliverable	2024/03/11
0.2	Sebastian Helmling	FRAUNHOFER	Content to all chapters	2024/09/27
0.3	Mu HUANG	FRAUNHOFER	Content to all chapters	2024/10/18
0.4	Jakob HÜTTER	AEE	REVIEW	2024/10/21
0.5	Mu HUANG	FRAUNHOFER	Final revision in different sections	2024/10/21
0.6	Irantzu URKOLA	TECNALIA	Final quick review for submission	2024/10/29

Abbreviations and acronyms

Acronym	Description
AWHP	Air-to-Water Heat Pump
DHW	Domestic Hot Water
EP	Energy Performance
EPB	Energy Performance of Buildings
ESCO	Energy Service Company
GHG	Greenhouse Gas
HP	Heat Pump
HVAC	Heating, Ventilation and Air Conditioning
KPI	Key Performance Indicator
OT	Operation Temperature
PE	Primary Energy
PEU	Primary Energy Use
PV	Photovoltaic
RER	Renewable Energy Ratio
SC	Space Cooling
SH	Space Heating
SPF	Seasonal Performance Factor
SSR	Self-sufficiency ratio
WAHP	Water-to-Air Heat Pump
WP	Work Package
WWHP	Water-to-Water Heat Pump

Abstract of the HAPPENING project

Currently, **buildings are responsible for 40 % of the energy demand and 36% of the CO_2 emissions in Europe**. Decarbonisation of existing buildings plays a key role in order to reach the overall climate protection targets. However, current renovation rates lie in the order of 1%.

Heat pumps are a key technology in bringing renewable shares into heat supply of buildings; especially their combination with on-site renewable electricity production e.g. by photovoltaic systems, allows to bring high renewable shares. Their current installation in existing multi-family buildings is, however, still marginal.

The proposed technological solution is based on decentralized heat pumps, in such a way that it results an easy-to-install solution for installers, low-intrusive for the occupants and easily adaptable to a large number of different building situations. This is flanked by developing near-zero planning, implementation and operation processes, in order to facilitate the work during the planning phase, to ensure a high-quality installation and effective operation, and to reduce the efforts and costs within the whole retrofitting project. The challenge of cost-competitiveness is addressed by developing new financial and business models. Bringing new players (such as financial experts) and financing models to the renovation market is expected to bring the needed paradigm change and boost investments in the residential retrofitting sector. Dissemination of measured performance and system characteristics from HAPPENING will be one of the key results of the project.

Through **3 demo sites (Spain, Italy and Austria)**, the project will demonstrate a highly versatile, scalable and replicable solution package for buildings energy system retrofitting, allowing 70-75% of renewable energy fraction, 30-50% of PE and GHG savings, reduction of planning time by 50% and installation/operation time by 30% and payback time for ESCOs and investors of less than 8 years, compared to best available solution existing today.

1. Introduction

1.1 Objectives of the Deliverable

The work package 3 (WP3) aims to assess the energy performance and to determine the optimization potential of the HAPPENING system. The main objectives of the WP3 are to carry out the monitoring at three demo sites and to provide validated and reliable measurement data for a comparable evaluation. The WP3 consists of four tasks:

- Task 3.1 Definition of monitoring concept (T3.1)
- Task 3.2 Technical realization of the monitoring (T3.2)
- Task 3.3 Data evaluation and online platform (T3.3)
- Task 3.4 Cross comparison of main results (T3.4)

The deliverable 3.3 (D3.3) is related to the T3.4 and aims at comparing the results obtained at each demo site. The objective of the T3.4 is to evaluate the key performance indicators (KPIs) of the three demo sites with consideration of the individual circumstances (e.g. required temperature levels or building properties, types of emitters and resident behaviour).

1.2 Deliverable Description

The deliverable D3.3 is structured in several chapters explaining the following key aspects related to the cross comparison of the HAPPENING systems at three demo sites:

- In the chapter 2, the description of the Demo Sites is included.
- Then, in chapter 3, the energy performance is assessed.
- Chapter 4 explains the limitations of the Cross Comparison.
- Conclusions of the analysis carried out are detailed in chapter 5.
- To finalize, at the end of the document, an appendix and references are provided.

1.3 Contribution of Partners

Work Package 3 is led by FRAUNHOFER, which conceived the analysis, processed the measured data, performed the calculations, drafted the deliverable D3.3, and designed the figures. The operation of the system, including the measurement technology, is the responsibility of the respective on-site project partner. Furthermore, they contributed to the raw data transfer to the FRAUNHOFER server and maintained the measurement technology. For the Italian demo site, TECHNOZENITH, together with EURAC, managed local tasks; for the Austrian demo site, AEE Intec and GWS assumed responsibility; and for the Spanish demo site, TECNALIA with CARTIF took over local duties.

The results of this deliverable have been discussed among the entire consortium, and this deliverable was finally revied by AEE INTEC.

1.4 Relation with Other Activities in the Project

The deliverable D3.3 is related to the following activities in the project:

- The KPIs for assessing the energy performance of the demo sites in T3.4 was defined in T3.1 (Definition of Monitoring Concept).
- The measurement system for collecting the data used in T3.4 was selected and implemented in T3.2 (Technical Realization of the Monitoring).
- The raw data collected in T3.2 was visualized and evaluated in T3.3 (Data Evaluation and Online Platform). The calculated KPIs in T3.3 served as the basis for the energy performance assessment in T3.4.
- T4.4 (Techno-Economic Assessment) focused on details of each demo site separately, complementing the cross comparison carried out in T3.4.

2. Description of the Demo Sites

This chapter provides an overview of the three demo sites, focusing on building characteristics, technical system design, and the availability of measurement data for assessing the energy performance of buildings (EPB).

2.1 Building Characteristics

The three buildings where the HAPPENING systems have been installed are existing multi-family houses, comprising 10 dwellings at the Italian demo site (*demo_it*), 18 at the Austrian demo site (*demo_at*), and 8 at the Spanish demo site (*demo_es*). The Italian building features a restaurant on the ground floor. However, the technical system and the energy use of the restaurant are not considered in this project.

Before the retrofitting of the HAPPENING systems, space heating (SH) and domestic hot water (DHW) were provided by gas boilers at the Italian and Spanish demo sites. The Austrian demo site previously utilized various decentralized stoves that used different fossil and biogenic energy sources, as detailed in Appendix - Table A1.

The Table 2.1 below presents an overview about the main building characteristics of the three demo sites:

Name	***demo_it***	***demo_at***	***demo_es***
Picture of the building			
Location	Verzuolo (Italy)	Liezen (Austria)	Pasaia (Spain)
Heating degree days	1 718	2 523	958
Year built	16^{th} century	1940 - 1945	2008
Total heated floor area in m^2	400	980	620
Number of dwellings	10	18	8
Heating degree days	1 718	2 523	958
Annual DHW demand in kWh/m^2	19	26	30
Annual SH demand in kWh/m^2	52	52	15
Annual SC demand in kWh/m^2	26	-	-

Table 2.1: Building characteristic of the three demo sites

2.2 System Design

HAPPENING concept in short

The energy supply system demonstrated in the HAPPENING project allows the energy transformation of existing buildings from fossil fuels to green electricity, allowing high quotas of renewable energy. Thus, it presents a suitable solution for the HVAC and DHW systems within building renovation sector.

The HAPPENING system relies on heat pumps (HPs) as main equipment for SH, DHW and SC (if needed), supported by locally generated renewable energy, typically from photovoltaic (PV), and thermal and electrical energy storage as needed.

HAPPENING proposes a cascade HP concept. First, the combination of centralized air-to-water heat pumps (AWHPs) coupled with an intermediate heat storage tank, connected to a low-medium temperature distribution system. Thanks to this cascade configuration of the HPs, the heat distribution within the building is carried out at low-medium temperatures, minimizing thermal losses. Then, at dwelling level, individual decentralized water-to-water heat pumps (WWHPs) covers each specific heat demand connected through a wide range of emitters that can be chosen by the occupants depending on their needs: from the most conventional solutions, such as radiators (implying minimum implementation works but also lower efficiency), to the most innovative, such as water-to-air heat pumps (WAHPs) including cooling services in addition to heating and DHW (very efficient but also more works required).

Schematically, the HAPPENING concept based on cascading HPs is described as follows:

1. **Centralized** AWHP: covering 1st thermal gap (**ΔT_1**) up to 25-30 ºC. Enabling high COP due to low ΔT.
2. **Thermal energy storage:** decoupling generation and consumption which enables optimizing COP by running the centralized HP on most favourable outdoor T conditions or PV production (favouring self-consumption).
3. Locally generated and consumed **renewable energy.**
4. **Smart** management and **control system** for optimization.
5. **Distribution** at low temperature (T ≈ 20 °C) to dwellings leading to minimum distribution heat losses.
6. 2nd thermal gap (**ΔT_2**) up to consumption T covered **individually** by water source HPs:
   - Optimized demand response adjusted per dwelling
   - Different configurations possible for each user

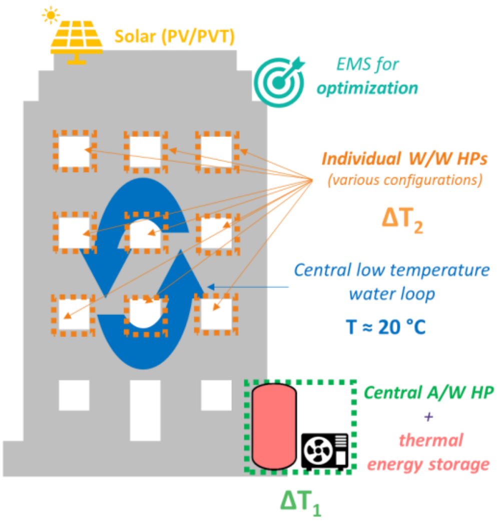

Figure 2.1: HAPPENING concept

HAPPENING systems at the three demo sites

The key specifications of the HAPPENING system implemented in the three demo sites are described in Table 2.2. The HAPPENING systems implemented in all three demo sites are controlled to meet the thermal demands of the inhabitants during the monitoring period, and some strategies for optimizing PV-self-consumption were also implemented.

Name	*demo_it*	*demo_at*	*demo_es*
Total heat capacity (A7W35) of centralized AWHPs in kW	45	124	36
Total volume of centralized heat storage tank in litres	1300	3200	2000
Heat capacity (W10W45) of centralized DHW HP in kW	11	-	-
Volume of centralized DHW storage tank in litres	500	-	-
Total heat capacity (W20A20) of decentralized WAHPs in kW	99	-	-
Total heat capacity (W10W35) of decentralized WWHPs in kW	-	132	48
Total volume of decentralized DHW storage tanks in litres	-	3060	1320
Peak power PV-Panels in kW_p	10	28	15
Capacity of battery storage in kWh	22	-	15

Table 2.2: HAPPENING System key specifications for the three demo sites

PASAIA - Spanish demo site

Figure 2.2 shows a simplified hydraulic schematic of the HAPPENING system implemented at the Spanish demo site, detailing the positions of the thermal energy meters:

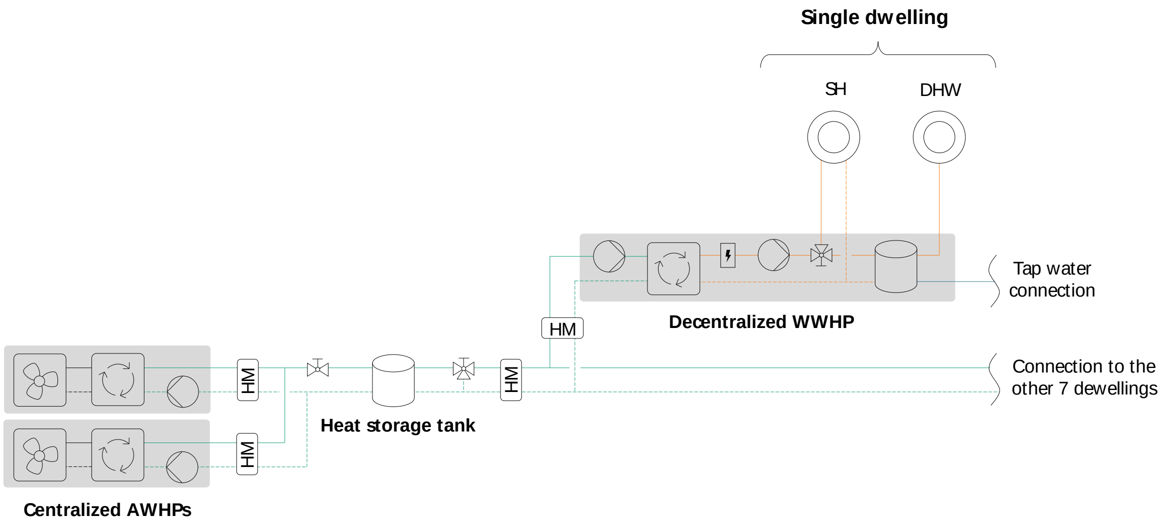

Figure 2.2: Simplified hydraulic schematic for the Spanish demo site, illustrating the position of the thermal energy meters

The system comprises two centralized air-to-water heat pumps (AWHP) each with 18 kW heat capacity, coupled with a 2000-liter heat storage tank. Both the centralized AWHPs and the heat storage tank are in the parking area of the building.

The heat storage tank is connected to the low-temperature distribution loop to preheat the water in that loop, which serves as the heat source for the decentralized water-to-water heat pumps (WWHP) in the dwellings. Each dwelling is equipped with a WWHP with 6 kW heat capacity to provide the required heating supply temperature for SH and DHW. The decentralized HPs contain a heating rod as a backup system, providing 2 kW of heating energy in case of problems with the compression cycle, and an integrated 165-liter DHW storage tank. On the electrical side, PV panels with a peak power output of 15 kW_p have been installed on the roof of the building. The battery modules with a total capacity of 15 kWh, are integrated into the PV system.

VERZUOLO - Italian demo site

Figure 2.3 illustrates a simplified hydraulic schematic of the HAPPENING system installed at the Italian demo site, detailing the positions of the thermal energy meters:

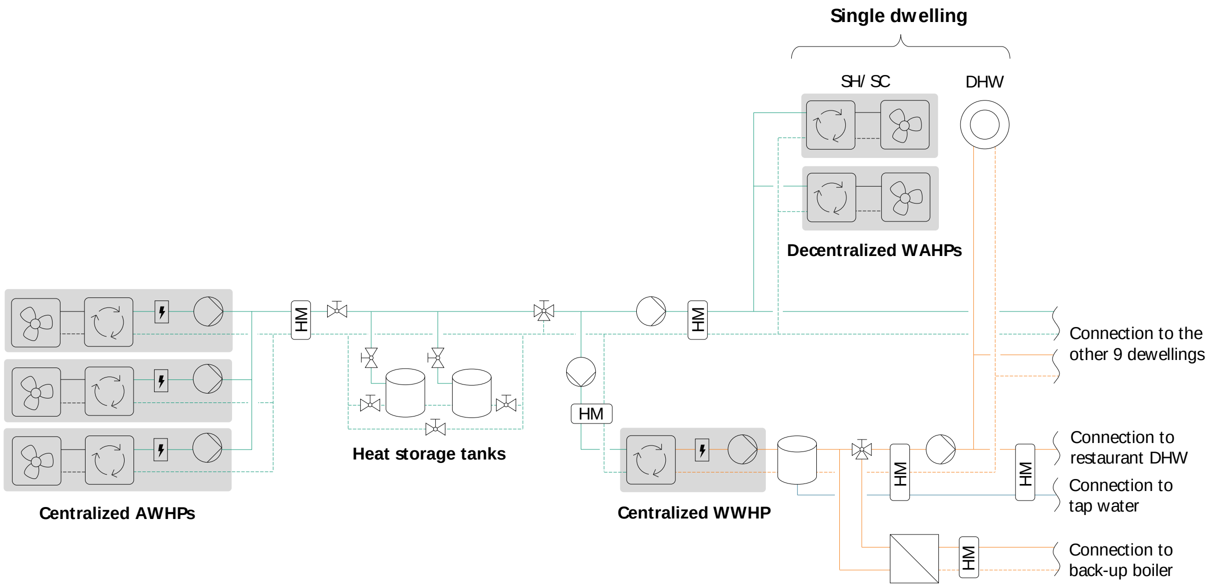

Figure 2.3: Simplified hydraulic schematic for the Italian demo site, illustrating the position of the thermal energy meters

The system comprises three centralized AWHPs with a total heat capacity of 45 kW, coupled with two heat storage tanks (totalling 1300 litres). Both the centralized AWHPs and the centralized heat storage tanks are connected to the low-temperature distribution loop to preheat the water within that loop. The distribution network utilizes the existing hot water distribution pipes. To heat the centralized DHW storage tank (500 litres), a centralized WWHP with a heat capacity of 11 kW is connected to the low-temperature distribution loop, using the preheated water as its heat source. The heating energy for SH is provided by 25 water-to-air heat pumps (WAHP), which are located within the dwellings and collectively offer a total heat capacity of 99 kW. They can also provide cooling. The existing gas boiler from the previous heating system remains in place and serves as a backup system. During the cooling seasons, the heat recovered from SC is primarily reused by the DHW HP, while any surplus is discharged through the centralized AWHPs. On the electrical side, a PV system with a peak output of 10 kW_p have been installed on the roof of the building, alongside a battery system with a capacity of 22 kWh.

LIEZEN - Austrian demo site

Figure 2.4 presents a simplified hydraulic schematic of the HAPPENING system installed at the Austrian demo site, detailing the positions of the thermal energy meters:

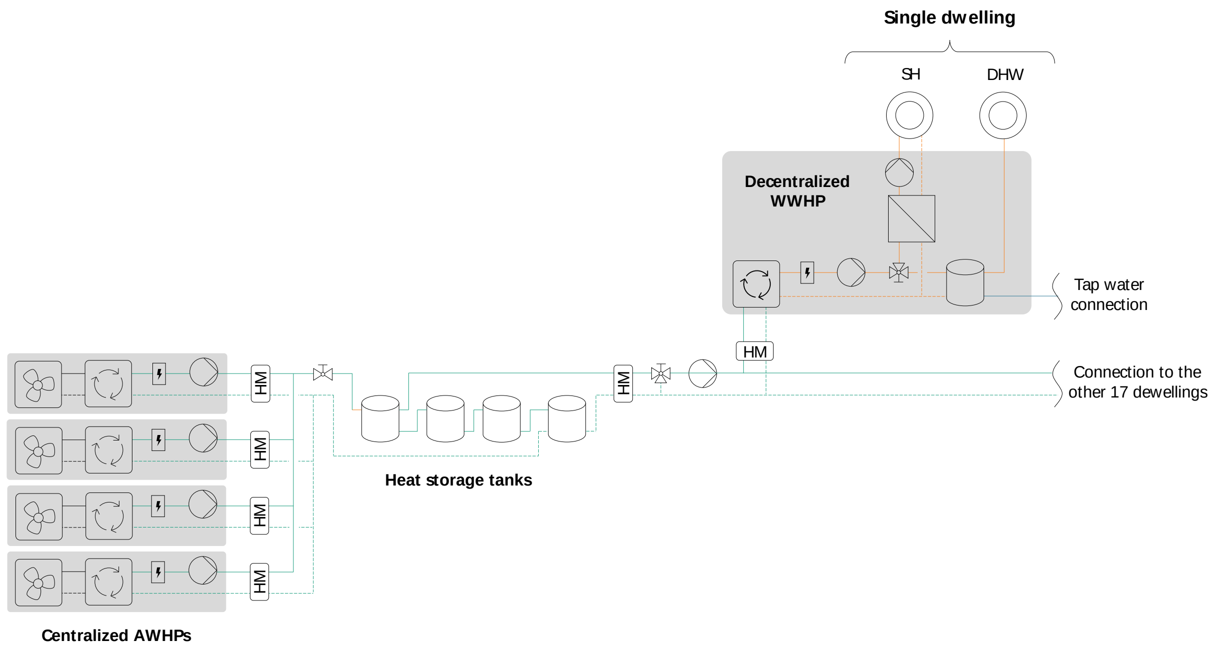

Figure 2.4: Simplified hydraulic schematic for the Austrian demo site, illustrating the position of the thermal energy meters

The system comprises four centralized AWHPs each with a total heat capacity of 31 kW. These four HPs are located outside the building. The outdoor units, which contain the entire refrigerant circle, are connected to the indoor unit via hydraulic pipes. The indoor unit links the AWHPs to the low-temperature distribution loop for the downstream HPs. The low-temperature distribution loop is equipped with four 800-liter heat storage tanks. For each dwelling, a HP with heat capacity of 7 kW provides SH and DHW. These decentralized HPs for the dwellings are equipped with a heating rod as a backup system, providing an additional 2 kW of heating energy, and an integrated 170-liter DHW storage tank. On the electrical side, PV panels with a peak power output of 28 kW_p have been installed on the roof of the building. There is no battery in the PV system.

2.3 Availability of Measured Data

All relevant thermal energy fluxes at the three demo sites have been measured using the thermal energy meters, as illustrated in the hydraulic schematics in Figure 2.2, Figure 2.3,and Figure 2.4. The main electrical components have been measured with dedicated electricity meters. All the sensors, including those for the HPs and room and ambient temperature, are connected to a centralized building management system. The energy performance assessment period which is considered for this study is for the Italian and the Austrian demo sites from 01.08.2023 until 31.07.2024. For the Spanish demo site data was only available from beginning of November 2023, so the period which is considered for this demo site reaches from 01.11.2023 until the 31.08.2024.

The measurement interval at the Austrian and Spanish demo sites is 60 seconds while the measurement interval at the Italian demo site is 300 seconds.

3. Energy Performance Assessment

This chapter presents the results of the energy performance assessment for the three demo sites equipped with HAPPENING systems. The evaluation focuses on KPIs that provides insights into the building energy use, HP efficiency and weighted energy performance.

3.1 Building Energy Use

Figure 3.1 illustrates the specific thermal energy use per heated floor area for DHW, SH and SC at the three demo sites. The annual heating energy use for DHW at the Italian and Austrian demo sites is comparable, with each measuring 47 kWh/m². In comparison, the specific heating energy use for DHW at the Spanish demo sites is only 25 kWh/m² over a 10-month assessment period, approximately half that of the other two demo sites. Differences in user behaviour regarding hot water usage may lead to the lower DHW use at the Spanish demo sites. Additionally, the average floor area of the dwellings at the Spanish demo site is significantly larger than that of the other two demo sites, resulting in a lower specific heating energy use.

The annual specific heating energy use per heated floor area for SH at the Austrian demo site is 66 kWh/m², which is 25% higher than the 50 kWh/m² measured at the Italian demo site. The heating degree days for the Austrian demo site are also 32% higher than those for the Italian demo site. In comparison, the specific heating energy use for SH at the Spanish demo site is only 12 kWh/m² over a 10-month assessment period, falling below the heating energy use for DHW. The milder climate in Pasaia contributes to a reduced heating demand. The annual specific cooling energy use per cooled floor area for SC is 14 kWh/m² at the Italian demo site, while there is no SC at the other two demo sites.

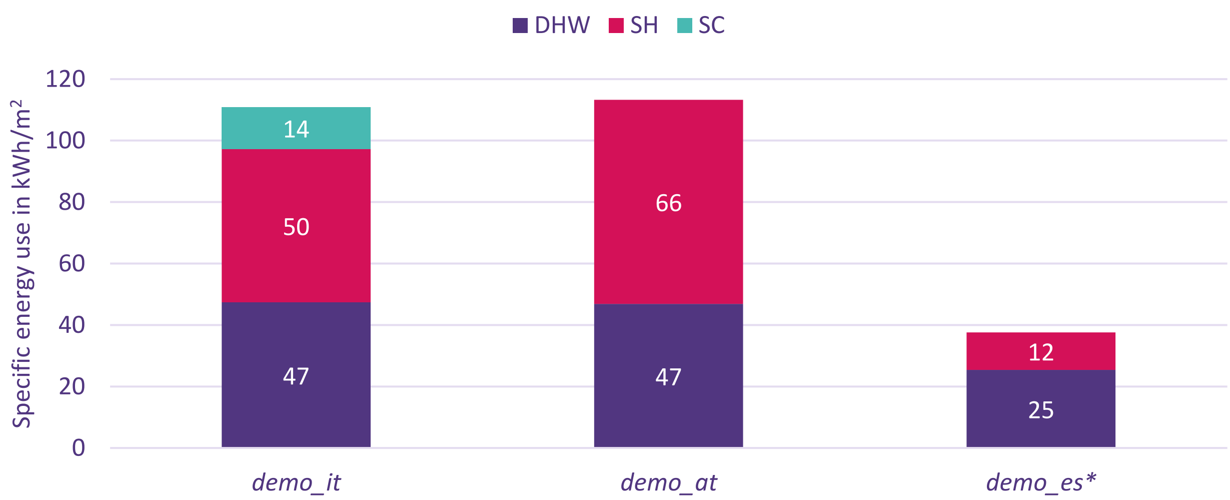

Figure 3.1: Specific thermal energy use of the three demo sites. demo_it and demo_at: measured data for 12 months from August 2023 to July 2024; demo_es: only measured data for 10 months from November 2023 to August 2024*

Figure 3.2 shows the specific grid electricity use and the specific on-site generated PV electricity use per heated floor area for the HAPPENING systems across the three demo sites. The annual total electricity use at the Austrian demo site is

63 kWh/m^2, with a self-sufficiency ratio (SSR) of 20%. The self-sufficiency ratio represents the percentage of used electricity that is supplied by the on-site generated PV electricity, indicating that 20% of the total electricity used for the HAPPENING system at the Austrian demo site is derived from the PV system. The Italian demo site exhibits a slightly lower annual total electricity use of 51 kWh/m^2 for SH and DHW and 4 kWh/m^2, while 43% of the total electricity use for SH and DHW is derived from the PV system. When accounting the electricity use for SH, the SSR increases slightly to 47%. The Spanish demo site demonstrate a significantly lower specific electricity use of 17 kWh/m^2 over a 10-month assessment period, mainly due to lower heating demand. Additionally, the PV system at the Spanish demo site was activated on July 9, 2024, while the PV system at the Italian and Austrian demo sites operated during the whole assessment period. To ensure comparability among the three sites, the PV electricity supply before the activation was simulated [D4.7]. The SSR at the Spanish demo site increases from 4% without simulated PV before the PV system activation to 45% with simulated PV. The systems equipped with battery modules at the Italian and Spanish demo sites have significantly higher SSR compared to the system without batteries at the Austrian demo site.

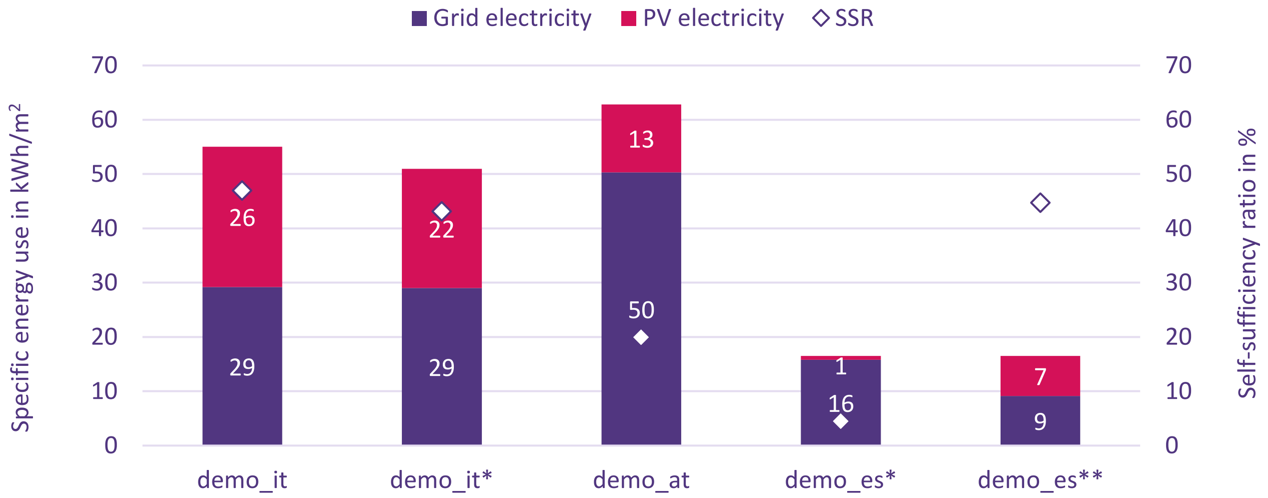

Figure 3.2: Specific electricity use and self-sufficiency ratio (SSR) of HAPPENING systems at the three demo sites. demo_it, demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_it: with energy use for space cooling; demo_it*: without energy use for space cooling. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

3.2 Efficiency of the Heat Pumps

The seasonal performance factor (SPF) and the corresponding operation temperature (OT) are used for evaluating the efficiency and performance of HPs. The SPF of electric HPs is the ratio between the annual heat energy output Q_{HP} and the annual electricity input $W_{el;HP}$:

$$SPF = \frac{Q_{HP}}{W_{el;HP}}$$

In this study, the OT of HPs is calculated as the energy-weighted average temperature on either the source or sink side of the HP, evaluated over an annual basis. The average temperature is defined as the arithmetic average of the inlet and outlet flow temperatures of the heating medium. The daily average temperature $T_{avg,dly}$ during the operation time of the HP is multiplied by the daily thermal energy input or output of the HP $Q_{HP,dly}$. This product is then integrated over the assessment period and divided by the total energy value for this period. This method ensures that temperatures at which significant amounts of energy are supplied are weighted more heavily than temperatures at which only minimal energy is supplied by the HP.

$$OT = \frac{\int (T_{avg,dly} \cdot Q_{HP,dly})}{\int Q_{HP,dly}}$$

Both the SPF and the OT can be calculated for the entire assessment period as well as separately for the different operation modes.

Centralized air-to-water heat pumps

The total heating and cooling energy output of the four centralized AWHPs at the Italian demo site are measured using a single thermal energy meter. In contrast, the heating energy output of each HP is measured individually at the other two demo sites. Additionally, the electricity input for all four centralized AWHPs is recorded by one electricity meter at the Italian demo site, whereas at the other two demo sites each HP's electricity input is measured separately. Notably, only the electricity input for the compressor is measured at the Spanish demo site, while the electricity input for all components within the HPs, including compressors, fans, heating rods, water pumps and control elements, is measured at the other two demo sites. To ensure the comparability across the three demo sites, the electricity use of fans and water pumps is calculated based on the operation time and the power consumption provided in the manufactures' datasheets. For the centralized AWHPs at all three demo sites, only the inlet air temperature is measured on the source side. Therefore, the inlet temperature is used for calculating the OT.

Figure 3.3 presents the SPF and OT of the centralized AWHPs at the three demo sites. The SPF of the centralized AWHPs at the three demo sites ranges from 4.0 and 5.1 in heating mode. The Austrian demo site exhibits the lowest SPF as well as the lowest OT on the source side in comparison to the other demo sites. The OT depends on climatic conditions at the location. Additionally, the share of SH in total heating energy use at the Austrian demo site is significantly higher than that at the other two demo sites, resulting in a greater emphasis on lower temperatures during the heating season. The temperature lift between the heat source and the heat sink at the Austrian demo site is 13.4 K, which is lower than the 14.4 K at the Italian demo site and the 14.7 K at the Spanish demo site. In addition to the variations in types, refrigerants, and manufacturers of the HPs at the three demo sites, the low evaporation temperature may also negatively impact the SPF of the HPs.

The SPF of the centralized AWHPs at the Italian demo site in cooling mode is 4.0, while the temperature lift is 8.8 K. It is important to note that the SPF in heating mode is calculated based on the heating energy output at the condenser, whereas the SPF in cooling mode is based on the heating energy input at the evaporator. Therefore, these two values are not directly comparable.

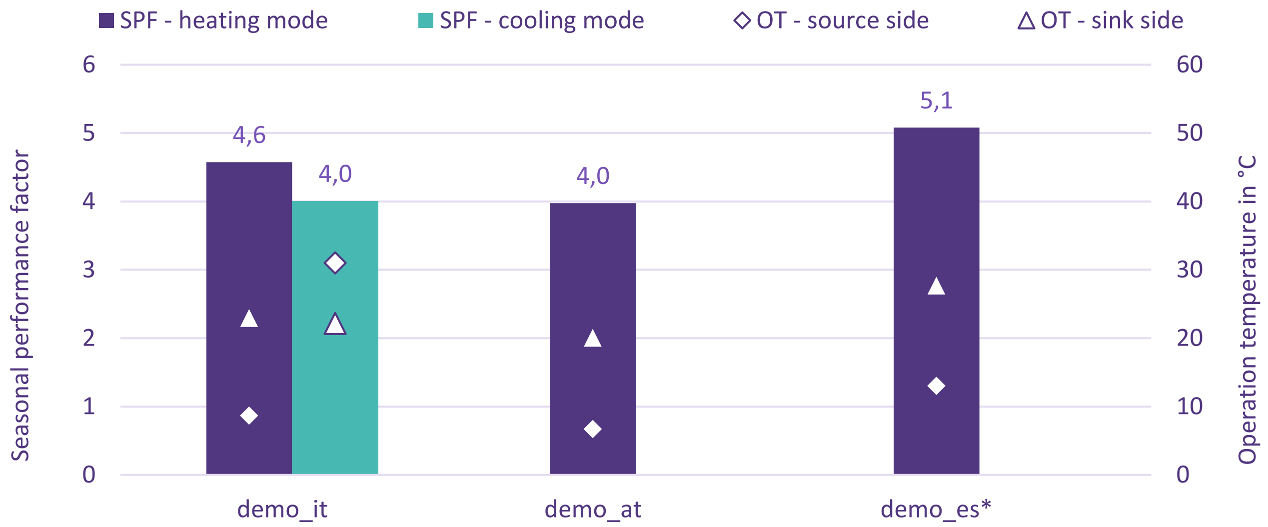

Figure 3.3: Seasonal performance factor (SPF) and the operation temperature (OT) of the centralized air-to-water heat pumps at the three demo sites. demo_it and demo_at: measured data for 12 months from August 2023 to July 2024; demo_es: only measured data for 10 months from November 2023 to August 2024*

Water-to-water heat pumps for domestic hot water

At the Italian demo site, the DHW is supplied by a centralized DHW HP coupled with an intermediate DHW storage tank, whereas at the other demo sites, each dwelling is equipped with a decentralized HP with an integrated DHW storage tank. For all demo sites, the heating energy used on the source side of each HP is measured. However, there is no measurement on the sink side of the HPs. Each HP has an individual electricity meter that measures the total electricity use of all components within the HPs, including compressors, heating rods, control elements and the water pump on the sink side. At the Spanish demo site, the measured electricity use also includes the electricity use of the source-side water pumps. The total heating energy output of the DHW HPs is calculated as the sum of the source-side heating energy use and the measured electricity energy use, which is measured under different measurement boundaries. Additionally, the calculated heating energy output includes the heat losses in the refrigerant cycle.

Figure 3.4 shows the SPF and OT of the WWHPs for DHW at the three demo sites. The SPF at all demo sites ranges from 3.3 at the Austrian demo site to 3.9 at the Italian demo site. The OTs and the temperature lifts at all demo sites are similar, with an average temperature lift of 28.7 K. The decentralized HPs at the Austrian demo site were experimental prototypes that used heating rods instead of HPs to primarily supply the DHW during the earlier months, until a firmware update on March 12, 2024 [D4.9]. In addition to the variations in types, refrigerants, and manufacturers of the HPs at the three demo sites, the different measurement boundaries and the control issues of the prototypes may also impact the SPF of the HPs.

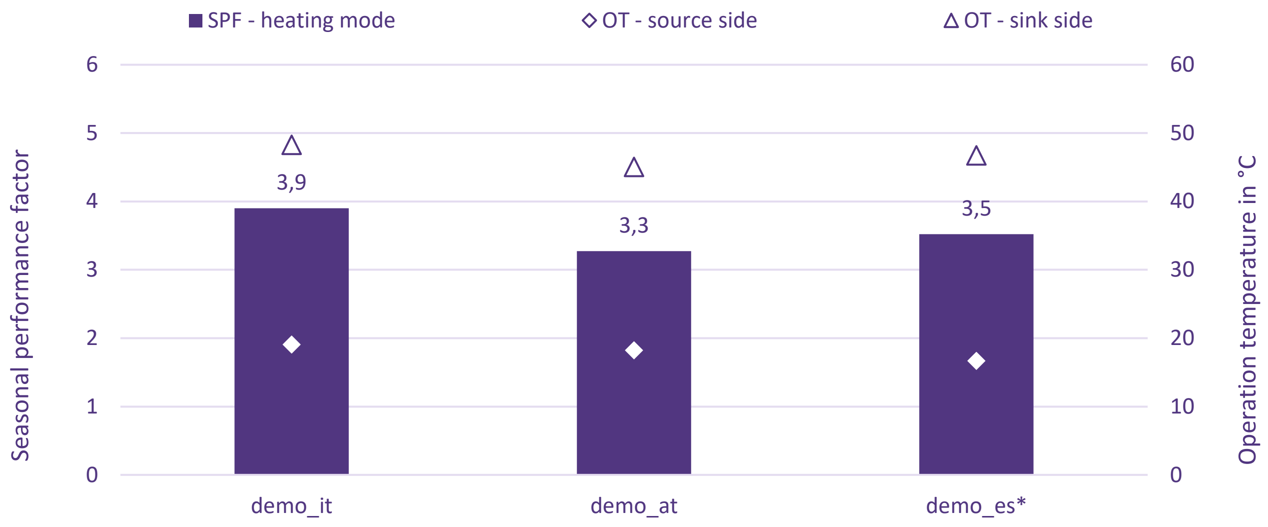

Figure 3.4: Seasonal performance factor (SPF) and the operation temperature (OT) of the centralized or decentralized water-to-water heat pumps for domestic hot water at the three demo sites. demo_it and demo_at: measured data for 12 months from August 2023 to July 2024; demo_es: only measured data for 10 months from November 2023 to August 2024*

Decentralized heat pumps for space heating

At the Italian demo site, each room in the dwellings is equipped with a WAHP for SH and SC, whereas at the other demo sites, the decentralized WWHPs are used for both DHW and SH. The decentralized WAHPs at the Italian demo site do not employ thermal energy meter on either the source or sink side. However, the HPs internally calculate the source-side thermal power input. The total thermal energy inputs are determined based on the thermal power measurements taken every 5 minutes. The total electricity use of all decentralized HPs in a single dwelling is measured using an electricity meter. The measured air inlet temperature is inaccurate due to the influence of the closely located heat exchanger. Consequently, the sink-side OT of the decentralized HPs is calculated based on the room temperature.

Figure 3.5 illustrates the SPF and the OT of the decentralized HPs for SH and SC across the three demo sites. Due to incomplete data, the SPF and the OT for the Italian demo site can only be determined for one dwelling over a 12-month assessment period, as shown in Figure 3.5 . The SPF of the WAHPs at the Italian demo site is 4.0 in heating mode and 3.1 in cooling mode, while the temperature lift is 2.6 K in heating mode and 3.5 K in cooling mode. The SPF of the decentralized WWHPs for SH at the Austrian and Spanish demo sites is 3.5 for both, whereas the temperature lift of 35.8 K at the Spanish demo site is slightly higher than the 27.3 K measured at the Austrian demo site.

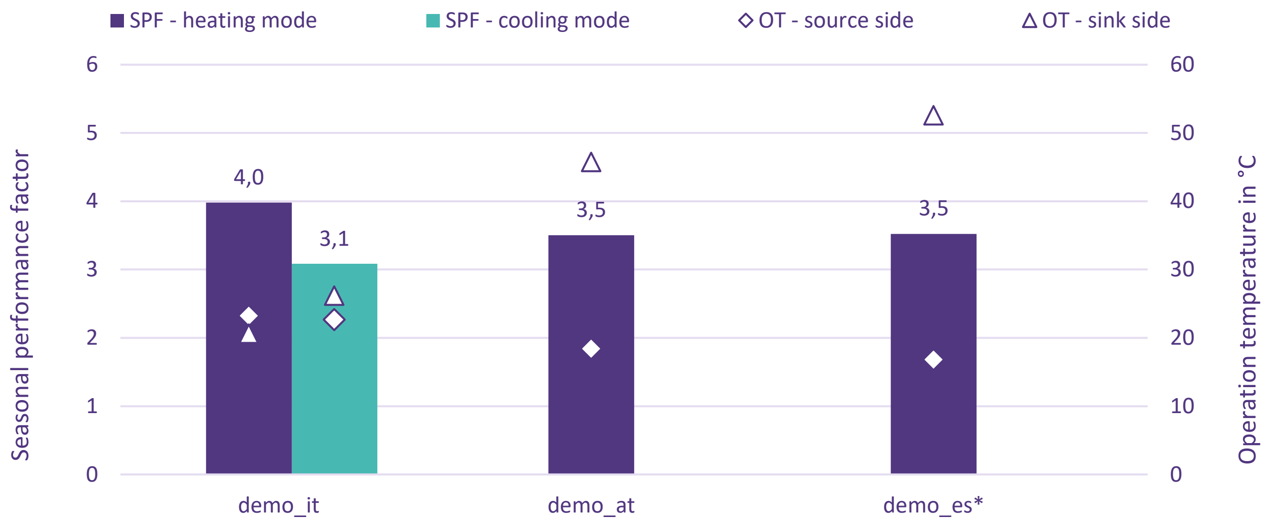

Figure 3.5: Seasonal performance factor (SPF) and the operation temperature (OT) of the decentralized heat pumps for space heating at the three demo sites. demo_it and demo_at: measured data for 12 months from August 2023 to July 2024; demo_es: only measured data for 10 months from November 2023 to August 2024*

3.3 Weighted Energy Performance

In this chapter the results of the weighted energy performance for the three demo sites are presented. The weighted energy is calculated based on weighting factors, such as primary energy factors and CO_2 equivalents, per energy carrier according to [ISO 52000-1].

3.3.1 Primary Energy Use

The primary energy refers to the energy embodied in energy resources that has not been subjected to any conversion or transformation process. The total primary energy use of buildings includes both non-renewable and renewable primary energy use across all observed energy flows that cross the balance boundaries. Consequently, all conversion and transformation losses within the energy balance boundaries are included. The primary energy use for the EPB assessment PEU_{EPB} is calculated according to [ISO 52000-1] as the difference between the delivered and the exported energy from the perimeters:

$$PEU_{EPB} = PEU_{PV;selfcons} + PEU_{el;grid;del} + PEU_{th;aero;del} - PEU_{PV;exp}$$

The delivered energy comprises the self-consumption of the on-site generated PV electricity $EU_{PV;selfcons}$, the grid electricity use $PEU_{el;grid;del}$, and the aerothermal energy use of the centralized AWHPs $PEU_{th;aero;del}$. The exported PV electricity $PEU_{PV;exp}$ encompasses both electricity fed into the public electricity grid and the electricity used within the building for non-EPB services, such as appliances and elevators. The primary energy use of the three demo sites is calculated based on the national primary energy factors; the values of these factors are listed in Appendix - Table A2.

Figure 3.6 illustrates the annual specific primary energy use per heated floor area for the three demo sites. The Italian demo site exhibits an annual total primary energy use of 138 kWh/m^2 for SH and DHW, alongside 11 kWh/m^2 for SC. At the Austrian demo site, the total primary energy use for SH and DHW is 153 kWh/m^2, which exceed that of the Italian site by 15 kWh/m^2. However, the specific non-renewable primary energy use at the Austrian demo site is 34 kWh/m^2, lower than the 49 kWh/m^2 measured at the Italian demo site. This discrepancy primarily arises from the differing renewable energy ratio in their respective national electricity grid; the Austrian gird comprises 56% renewable energy, while the Italian grid only contains 17%. In contrast, the Spanish demo site demonstrate a significantly lower total primary energy use of 49 kWh/m^2 during a 10-month assessment period, mainly due to the reduced heating demand in the mild climate of Pasaia. When accounting for the simulated PV electricity supply prior to the activation of the PV system, the non-renewable primary energy use during the assessment period appears negative, attributed to substantial PV electricity exports. This indicates that the PV electricity exports result in greater avoided non-renewable primary energy use compared to imports. The total primary energy use for the Spanish demo site with simulated PV electricity supply prior to PV system activation is 20 kWh/m^2, which is 29 kWh/m^2 lower than without the simulated PV electricity supply.

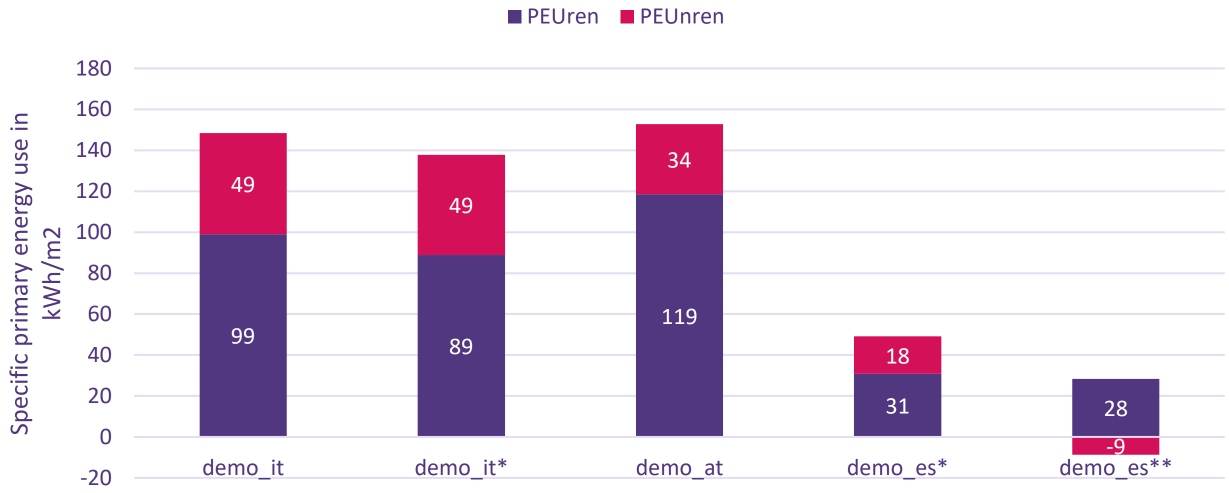

Figure 3.6: Specific renewable and non-renewable primary energy use (PEU_{ren} and PEU_{nren}) for the HAPPENING systems at the three demo sites. demo_it, demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_it: with energy use for space cooling; demo_it*: without energy use for space cooling. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

3.3.2 Renewable Energy Ratio

The renewable energy ratio RER is defined as the ratio of renewable primary energy use PEU_{ren} to total primary energy use PEU_{tot}:

$$RER = \frac{PEU_{ren}}{PEU_{tot}}$$

Figure 3.7 shows the RER for the three demo sites. The Italian demo site demonstrates a RER of 64% for SH and DHW, indicating that 64% of the total primary energy use is derived from renewable sources. When accounting for SC, the RER at the Italian demo site increases to 67% due to the high SSR during the summer months. At the Austrian demo site, the RER stands at 78%, while at the Spanish demo site, the RER is 63% without simulated PV electricity supply until the PV system activation and 145% with simulated PV electricity supply. Due to substantial PV electricity exports, the renewable primary energy use exceeds the total primary energy use resulting in a RER that surpasses 100%. Compared to the other two demo sites, the installed PV capacity in Spain is higher relative to the electricity demand of the heat pumps. The target of the HAPPENING project is a 70% renewable energy ratio, meaning that the demo site are aligned to this target. As mentioned in D4.8, the installed PV capacity at the Italian demo site is constrained due to the limited availability of roof surface with suitable exposure for this application.

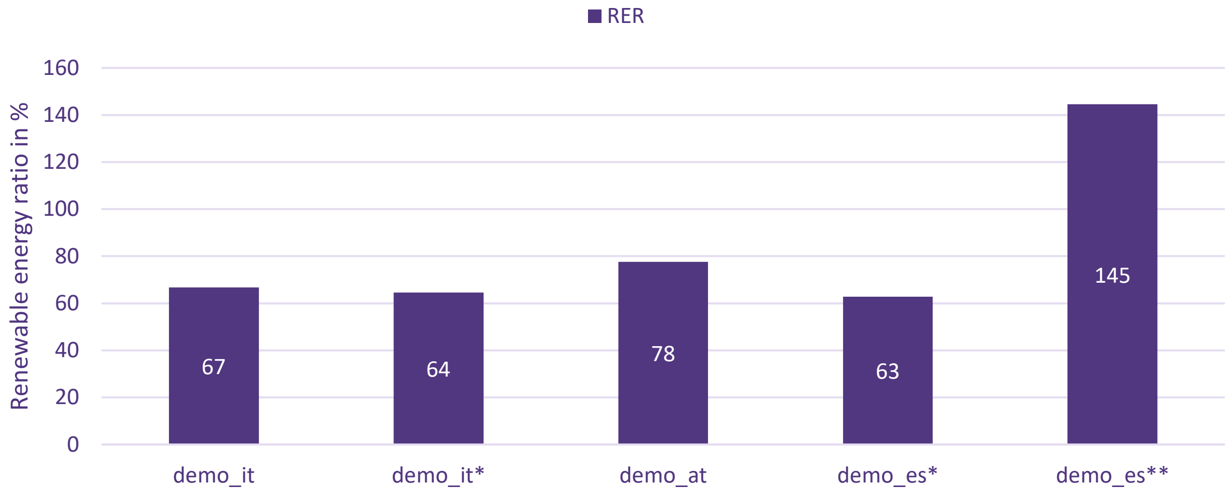

Figure 3.7: Renewable energy ratio (RER) for HAPPENING systems at the three demo sites. demo_it, demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_it: with energy use for space cooling; demo_it*: without energy use for space cooling. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

3.3.3 Primary Energy Saving

The primary energy saving $d_{EP;PE}$ is defined as the difference between the overall energy performance based on primary energy use of the HAPPENING system $EP_{PEU;HAPPENING}$ and the previous system $EP_{PEU;ref}$, as specified in [D3.1]:

$$d_{EP;PE} = EP_{PEU;HAPPENING} - EP_{PEU;ref}$$

The overall energy performance based on primary energy use EP_{PEU} is the ratio of the thermal energy used on site EU_{th} to the non-renewable primary energy use PEU_{nren}:

$$EP_{PEU} = \frac{EU_{th}}{PEU_{nren}}$$

To assess the primary energy savings of the HAPPENING system in this project, the previously installed heating supply system at each demo site is defined as the reference system and is described in Appendix - Table A1.

Figure 3.8 presents the overall energy performance based on the non-renewable primary energy used of the HAPPENING system and the previous system for SH and DHW at the three demo sites. The energy performance based on primary energy use for the HAPPENING system at the Italian demo site is 2.0 kWh/kWh indicating that to supply 2.0 kWh heating energy, 1 kWh non-renewable primary energy is required. A high energy performance reflects improved energy efficiency. In contrast, the previous system requires 1 kWh non-renewable primary energy use to provide only 0.5 kWh useful heating energy, resulting in a primary energy saving of 1.4 kWh/kWh. At the Austrian demo site, the energy performance based on primary energy use for the HAPPENING system is 3.3 kWh/kWh, corresponding to a primary energy saving of 2.3 kWh/kWh. At the Spanish demo site, the energy performance based on primary energy use for the HAPPENING system is 2.1 kWh/kWh without simulated PV electricity supply prior to PV system activation but appears to be negative at -4.3 kWh/kWh when considering the simulated PV electricity supply. This negative value is attributed to the substantial amount of PV electricity exports, resulting in negative non-renewable primary energy use, as shown in Figure 3.6. The primary energy saving for the Spanish demo site is 1.3 kWh/kWh without simulated PV electricity supply and -5.1 kWh/kWh with simulated PV electricity supply. It is important to note that this negative value of the primary energy saving does not indicate a reduction in the energy efficiency of the HAPPENING system; rather, it is caused by the negative non-renewable primary energy use due to substantial PV exports.

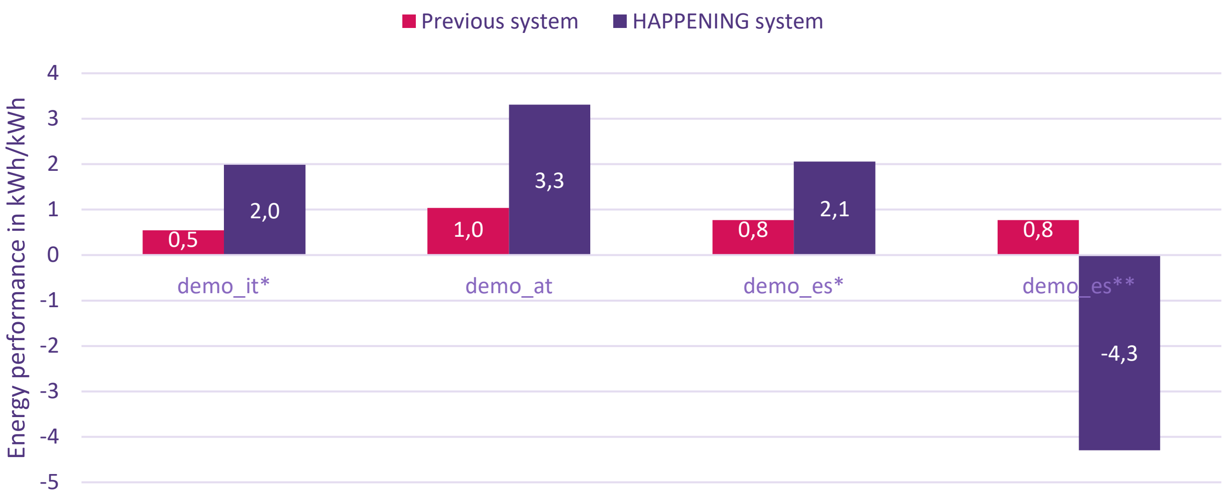

Figure 3.8: Overall energy performance based on non-renewable primary energy use of the HAPPENING systems and the previous systems for heating energy supply at the three demo sites. demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

3.3.4 Greenhouse Gas Emissions

Figure 3.9 illustrates the specific greenhouse gas (GHG) emissions per heated floor area of the HAPPENING systems at the three demo sites. The GHG emissions are calculated based on national CO_2 equivalents, which are detailed in Appendix - Table A2. The annual specific GHG emissions for the Italian and Austrian demo sites are comparable, each measuring 7 kg/m^2. In contrast, the Spanish demo site exhibits a specific GHG emissions of only 1 kg/m^2 for a 10-month assessment period without simulated PV electricity supply, and -1 kg/m^2 with simulated PV electricity supply. This negative value indicates that the avoided GHG emissions due to substantial PV electricity exports exceed the GHG emissions from energy use within the building.

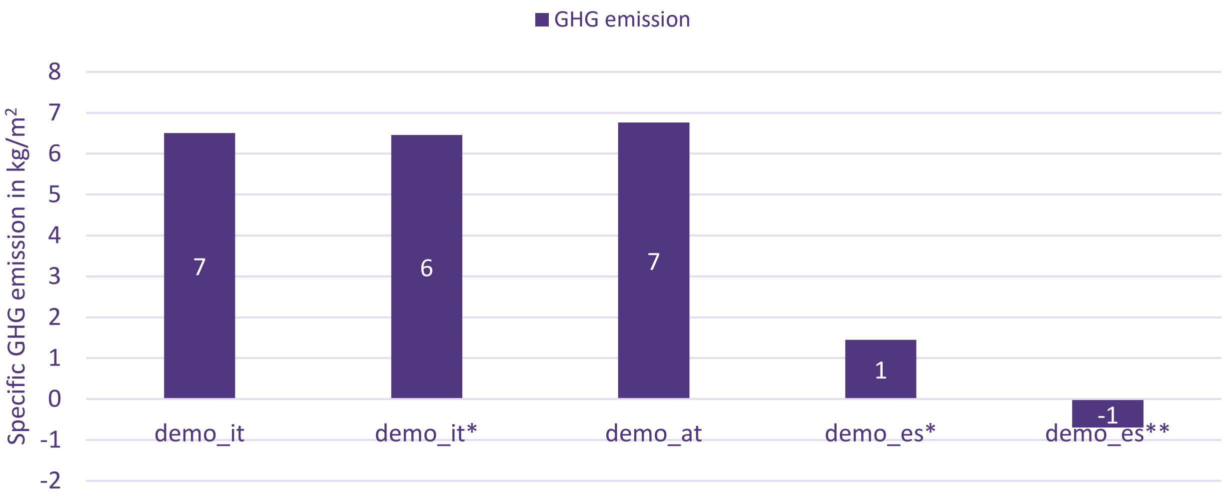

Figure 3.9: Specific greenhouse gas (GHG) emissions for HAPPENING systems at the three demo sites. demo_it, demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_it: with energy use for space cooling; demo_it*: without energy use for space cooling. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

3.3.5 Greenhouse Gas Saving

The GHG saving, denoted as $d_{EP;GHG}$, is defined analogously to the primary energy savings as the difference between the overall energy performance based on GHG emissions of the HAPPENING system $EP_{GHG;HAPPENING}$ and the reference system $EP_{GHG;ref}$:

$$d_{EP;GHG} = EP_{GHG;HAPPENING} - EP_{GHG;ref}$$

The overall energy performance based on GHG emissions EP_{GHG} is calculated as the ratio of thermal energy used on site EU_{th} to the GHG emissions at the demo sites m_{CO_2}:

$$EP_{GHG} = \frac{EU_{th}}{m_{CO_2}}$$

Figure 3.10 shows the overall energy performance based on the GHG savings of the HAPPENING system and the previous system for SH und DHW at the three demo sites. The energy performance based on GHG emission for the HAPPENING system at the Italian demo site is 15.1 kWh/kg indicating that to supply 15.1 kWh heating energy, only 1 kg of GHGs is emitted. A high energy performance reflects improved energy efficiency. In contrast, the previous system produces 1 kg of GHG emissions to provide only 2.8 kWh useful thermal energy, resulting in a GHG saving of 12.3 kWh/kg for the Italian demo site. At the Austrian demo site, the energy performance based on GHG emissions for the HAPPENING system is 16.8 kWh/kg, corresponding to a GHG saving of 11.5 kWh/kg. At the Spanish demo site, the energy performance based on GHG emissions for the HAPPENING system is 25.9 kWh/kg without simulated PV electricity supply prior to PV system activation but appears to be negative at -54.0 kWh/kg when considering the simulated PV electricity supply. This negative value is attributed to the substantial amount of PV electricity exports, resulting in negative GHG emissions, as shown in Figure 3.10. The GHG saving for the Spanish demo site is 20.9 kWh/kg without simulated PV electricity supply and -59.0

kWh/kg with simulated PV electricity supply. It is important to note that this negative value of the GHG saving does not indicate a reduction in the energy efficiency of the HAPPENING system; rather, it is caused by the negative GHG emissions due to substantial PV exports.

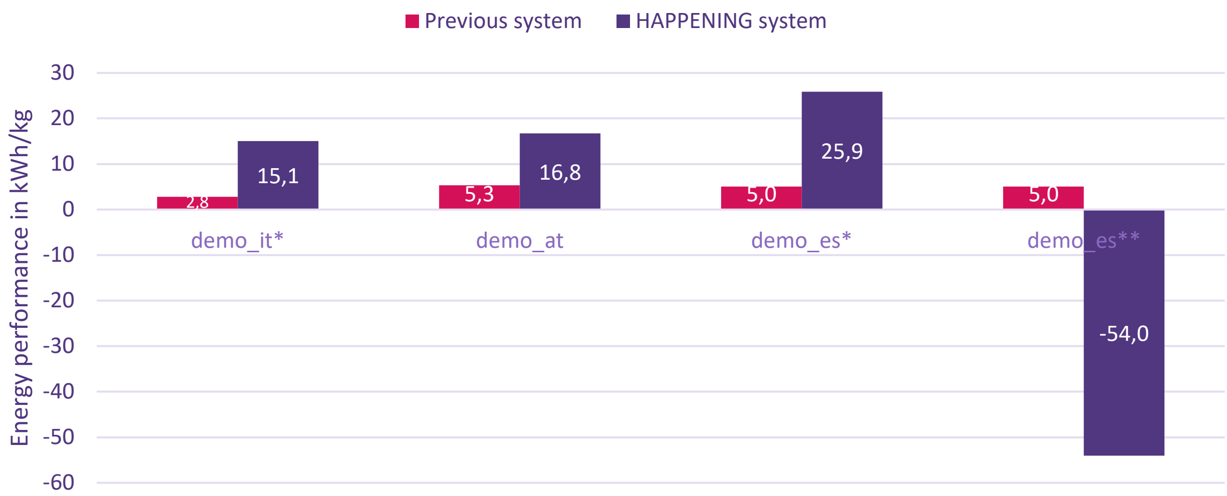

Figure 3.10: Overall energy performance based on greenhouse gas emissions of the HAPPENING systems and the previous systems for heating energy supply at the three demo sites. demo_it and demo_at: 12-month assessment period from August 2023 to July 2024; demo_es* and demo_es**: 10-month assessment period from November 2023 to August 2024. demo_es*: without simulated PV electricity supply; demo_es**: with simulated PV electricity supply before the activation of the PV system on July 9, 2024*

4. Limitations of the cross comparison

This study recognizes several limitations that may impact the results and interpretations of the KPIs related to HAPPENING systems:

- **Sensor Position**: Constraints related to sensor positioning affect the accuracy of KPI calculations. Measurements are not available on the sink side of the decentralized HPs. Consequently, the heating energy use of the Spanish and Austrian demo sites is calculated as the sum of the heating energy measured on the source side of the decentralized HPs and the total electricity use of the decentralized HPs. These calculations account for heat losses in the refrigeration cycle and the integrated DHW storage tank, as well as the electricity used by water pumps and control elements. Therefore, they are higher than the actual heating energy supplied to the dwellings.
- **Data Availability**: Several factors have repeatedly resulted in data gaps during the monitoring process, including HP malfunctions, intermittent data transfer and organizational issues. The calculation of the performance factor for decentralized WAHPs at the Italian demo site can only be performed for a limited number of dwellings and for part of the entire assessment period due to missing data. At the Spanish demo site, the PV system was not operational until July 2024 due to administrative issues. During the pre-commissioning period, where measurement data was unavailable, simulated PV data was used for KPI calculations.
- **Device Construction and Control Faults**: The decentralized HPs at the Italian demo site were experimental prototypes developed within this project. The prototype status has significantly impacted their functionality and user experience, as detailed in D4.8. In addition to data gaps caused by HP malfunctions, the measured air inlet temperature is inaccurate and is significantly affected by the temperature of the heat exchanger. Consequently, the sink-side OT of the decentralized HPs is calculated based on room temperature.
- **Standardization**: All results presented in this study do not incorporate corrections for standard climate conditions and user patterns.

5. Conclusions

This study assesses the energy performance of HAPPENING systems across three demo sites over a 12-month assessment period, apart from a 10-month period for the Spanish demo site. All demo sites are equipped with centralized AWHPs, low temperature distribution loops and decentralized HPs to provide the required heating supply temperature. At the Italian demo site, heat recovered in summer from space heating is reused for domestic hot water supply by a DHW-HP.

The analysis indicates a close correlation between the heat used for space heating and the outside temperature. The Austrian demo site shows an annual specific heating energy use for SH at 66 kWh/m^2, which is 25% greater than the 50 kWh/m^2 at the Italian demo site and 82% greater than the 12 kWh/m^2 at the Spanish demo site. This can be the higher heating degree days in Austria compared to Italy, while the Spanish site benefits from a milder climate that reduces heating demand. The annual specific heating energy use for DHW at the Italian und Austrian demo sites is comparable, both measuring 47 kWh/m^2. In contrast, the Spanish demo site exhibits a significantly lower specific heating energy use of 25 kWh/m^2 for DHW. This discrepancy can be attributed to differences in user behaviour regarding DHW use and the larger average dwelling size at the Spanish demo site, which contributes to a lower value per heated floor area.

The Austrian demo site demonstrates an annual electricity use of 63 kWh/m^2 for SH and DHW, achieving a self-sufficiency ratio (SSR) of 20%. The Italian demo site, on the other hand, displays a slightly lower total electricity use of 51 kWh/m^2 for SH and DHW, with a higher SSR of 43%. When accounting for the entire electricity use for SC, the SSR increases to 47%. The Spanish demo site stands out with a significantly lower specific electricity use of 17 kWh/m^2 over a 10-month assessment period, primarily due to its reduced heating demand. The activation of the PV system in Spain further enhances its SSR, demonstrating the contribution of the renewable energy integration.

The heating supply temperature in the distribution loop varies with the outside temperatures to optimize the efficiency of the ASHPs. The SPF of the HPs ranges from 3.3 to 5.1 in heating mode and from 3.1 to 4.0 in cooling mode. The AWHPs at the Austrian demo site presents the lowest SPF, which can be linked to both climatic conditions and the higher share of the SH in total heating energy use.

A significant portion of the total primary energy use, between 63% and 78%, is derived from renewable energy sources. When considering the simulated PV electricity supply prior to the PV system activation at the Spanish demo site on July 09, 2024, the renewable energy ratio increases from 63% to 145% for an assessment period from November 2023 to August 2024. The renewable energy ratio exceeds 100% due to substantial PV electricity exports at the Spanish demo site, indicating greater avoided non-renewable energy use compared to imports. In terms of greenhouse gases emissions, the Spanish demo site achieves remarkable GHG savings, with emissions dropping to -1 kg/m^2 due to substantial PV electricity exports.

The study acknowledges limitations related to sensor positioning, data availability, and the experimental nature of some systems, which may affect overall accuracy.

In conclusion, the findings demonstrate the technical feasibility of retrofitting HAPPENING systems in existing multi-family buildings across various countries and climates, enhancing energy efficiency and sustainability. Notably, at the Spanish demo site, where substantial PV electricity exports result in greater avoided non-renewable primary energy use and GHG emission than those associated with energy use within the building.

Appendix

Energy carriers of previous systems			Share of heating energy in %
demo_it	SH and DHW	Gas	100
demo_at	SH	Gas	28
		Electricity	28
		Oil	11
		Coal	6
		Split wood	17
		Wood pellets	11
	DHW	Gas	28
		Electricity	72
demo_es	SH and DHW	Gas	100

Table A1: Energy carriers of previous heating systems

Energy carriers		f_{Pnren}	f_{Ptot}	CO2-eq in g/kWh
Grid electricity	IT	2.0	2.4	257
	AT	0.8	1.8	156
	ES	1.5	2.0	120
PV electricity		0	1	0
Aerothermal		0	1	0
Exported electricity	IT	2.0	2.4	257
	AT	0.8	1.8	156
	ES	1.5	2.0	120
Gas	IT	1.1	1.1	207
	AT	1.1	1.1	201
	ES	1.2	1.2	182

Table A2: National values of primary energy factors and CO_2 equivalents

DATA SOURCES:

Italian demo site:

- Primary energy factors: Italian Ministry of Economic Development, "Decreto interministeriale 26 giugno 2015 - Adeguamento linee guida nazionali per la certificazione energetica degli edifice" and "Decreto Ministero dello Sviluppo Economico - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizione e dei requisiti minimi degli edifici" - Annex 1. Available in: https://www.gazzettaufficiale.it/atto/serie_generale/caricaDettaglioAtto/originario?atto.dataPubblicazioneGazzetta=2015-07-15&atto.codiceRedazionale=15A05198&elenco30giorni=false
- CO_2 equivalents: Istituto Superiore per la Protezione e la Ricerca Ambientale "ISPRA" (Higher Institute for Environmental Research and Protection), "Italian Greenhouse Gas Inventory 1990-2021 National Inventory Report 2023", Available in: https://www.isprambiente.gov.it/files2023/pubblicazioni/rapporti/rapporto_383_2023.pdf

Austrian demo site:

- Primary energy and CO_2 equivalents: OBI-Richtlinie 6, Ausgabe Mai 2023 (OIB-330.6-036/23)

Spanish demo site:

- Primary energy factors: REE, "Electricity system report", 2024 [online]. Available : https://www.sistemaelectrico-ree.es/en.

CO_2 equivalents: REE, "CO_2 EQ. emission factor and GHG emissions regarding non-renewable generation", 2024 [online]. Available in: https://www.ree.es/en/datos/generation/non-renewable-detail-CO2-emissions

References

[D3.1] Deliverable D3.1 Monitoring concept definition of the HAPPENING system. Available at: https://www.happening-project.eu/wp-content/uploads/2022/06/14_happening_d3-1_definition-of-monitoring-concept_20220228.pdf

[ISO 52000-1] ISO 52000-1:2017(E): Energy performance of buildings — Overarching EPB assessment — Part 1: General framework and procedures

[D4.7] Deliverable D4.7 Techno economic assessment – Spanish demo

[D4.8] Deliverable D4.8 Techno economic assessment - Italian demo

[D4.9] Deliverable D4.9 Techno economic assessment - Austrian demo