HYPERGRYD

WP5 – TRL5 demonstration in living labs and virtual labs in LEC

Task 5.3 Demonstration and validation actions of RES-based Enabling technologies

D5.8 Outcomes of HYPERGRYD demonstration, lessons learnt and guidelines for replication

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DISCLAIMER

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1 Executive Summary

The goal of HYPERGRYD project is the development of a set of replicable and scalable cost effective technical solutions to allow the integration of Renewable Energy Sources (RES) with different dispatchability and intrinsic variability inside Thermal Grids as well as their link with the Electrical Grids, including the development of innovative key components, in parallel with innovative and integrated ICT services formed by a scalable suite of tools for the proper handling of the increased complexity of the systems from building to Local Energy Community (LEC) levels and beyond, and accelerate the sustainable transformation, planning and modernization of District Heating and Cooling (DHC) towards 4th and 5th generation.

HYPERGRYD also aims at developing real time management of both electrical and thermal energy flows in the coupled energy network complex, including the synergies between them. Therefore, HYPERGRYD aims at three over-arching General Objectives:

- To prove Smart Energy Networks as the future of Efficient Energy Management in DHC in synergy with the Electrical Grids in LEC/Smart Cities of the future;
- To define the roadmap to design and plan future DHC as well as the modernization of the existing ones in different climates and RES penetration levels toward 4th-5th generation,
- To demonstrate HYPERGRYD RES-based Enabling Technologies, Smart Energy Grid Solutions empowered by new ICT tools and services as the key for this evolution.

During the project, the HYPERGRYD's solutions will be implemented across four Live-In-Labs cases in three representative climates, with special consideration to their cost effectiveness and potential replicability to finally achieve these three main objectives.

The purpose of this deliverable in short is: i) to presents main outcomes of a demonstration of HYPERGRYD solutions for stakeholders, ii) set of lessons learnt, iii) guidelines for replication for three enabling technologies.

Target audience of this report is the wide group of stakeholders from district heating sectors and H&C industry.

On behalf of Authors

Michał Gliński, IMP PAN

2 Introduction

2.1 Scope

The present report is intended to present main outcomes of a demonstration of Hypergryd solutions implemented in four Live-in-Labs:

- **SONNE –** Sonnenplatz at Großschönau (Austria) - Model demonstration and validation of the ICT tools.
- **ENVI –** Envipark at Turin (Italy) - Model demonstration and validation of the multi-carrier energy dynamic model.
- **KEZO -** Jabłonna (Poland) - Demonstration of the DHC with coordinated operation of the modular Heat Pump with PCM and Sorption Storage using management algorithms driven by the ICT software tool.
- **EURAC** - Bolzano (Italy) - Demonstration of the DHC with coordinated operation of HP and storage using rule-based and model predictive controls.

The outcome of these demonstrations will be a set of lessons learnt and guidelines for the installation and operation of RES technologies in different DHC and Smart Hybrid Grids, as well as an optimized design and control of the technologies tested.

Technical results in non-public deliverables D5.4, D5.5 and D5.6.

2.2 Audience

The report is a document intended for the wide group of stakeholders: DHC operators, Energy Producers and Suppliers, Municipalities, Local and national policymakers, H&C Installers and Engineering firms, Private and public businesses.

2.3 Abbreviations

APIs: Application Programming Interfaces

BTES: Borehole Thermal Energy Storage

CHP: Combined Heat and Power

COP: Coefficient Of Performance

DHCN: District Heating and Cooling Network

DHN: District Heating Network

DHW: Domestic Hot Water

ENCO: encoord GmbH, Germany

ENVI: Environment Park

ER: Expected Result

GDHCN: Generation District Heating and Cooling Network

GET: Güssing Energy Technologies GmbH, Austria

GSY: Grid Singularity GmbH, Germany

HT: High Temperature

HMI: Human Machine Interface

HP: Heat Pump**ICT:** Information and Communication Technologies

IoT: Internet of Things

KTH: Royal Institute of Technology, Sweden

KPI: Key Performance Indicator

LEC: Local Energy Communities

LEM: Local Energy Market

LiL: Live-in Lab

LT: Low Temperature

MMI: Machine Machine Interface

MPC: Model Predictive Control

MT: Medium Temperature

PCM: Phase Change Material

PV: Photovoltaic system

P2H: Power-to-Heat

P2P: Peer-to-Peer

RES: Renewable Energy Sources

SH: Space Heating

SOC: State Of Charge

STES: Sorption Thermal Energy Storage

TTES: Thermal Tank Energy Storage

UC: Use Case

VHP: Virtual Heat Pump

WSHP: Water Source Heat Pump

WB: Water Buffer

2.4 Contributions of partners

As task leader of T5.3, IMP PAN is the editor of this report. IMP, ENVI, Sonne and EURAC are responsible for the description of outcomes, lessons learnt and guidelines for replication based on the results obtained during the demonstration in their LiL.

2.5 Structure

- **Section 1:** Executive Summary
- **Section 2:** Contains an overview of this document, providing its Scope, Audience, and Structure
- **Section 3**: Presents the outcomes and lessons learnt in all Live-In Labs
- **Section 4:** Describes the technologies and guidelines for replication of two new technologies: modular heat pump with PCM storage and sorption storage.
- **Section 5:** Conclusions and summary of the achievements

3 Outcomes and lessons learnt

As part of Workpackage 5 the demonstration and validation of the **HYPERGRYD ICT tools** took place at the **Live-in-Labs SONNE, KEZO, EURAC and ENVI,** where feedback was gathered from diverse stakeholders to identify critical user requirements for additional HYPERGRYD API development and offer practical insights for aligning technical solutions with stakeholder needs. The key findings from this demonstration and validation are summarized in the following subchapters.

3.1 SONNE

The activities described in this chapter have been carried out in Task 5.5. The objective of this task is to demonstrate and validate ICT tools developed in T3.1, T3.2, T3.3, T3.4 by applying them to the local energy community at the Live-in-lab SONNE (Austria). To achieve these objectives, data from the available DHC assets and the electricity consumption from different buildings and households in the community were used. Additional measuring points, where IoT devices were installed, were also used for modelling the DHC assets and implementing and testing the BIM-GIS, exergoeconomic tool, and AI and edge-computing algorithms. Additionally, data from generation devices such as PV systems, as well as electricity prices (including retail prices, grid fees and feed-in tariffs), were used to simulate the peer-to-peer trading. During demonstration, continuous feedback was derived and fed into WP4 “HYPERGRYD Digital Twin Platform as a service” to improve the usability and stability of different tools developed by GSY, KTH, GET and ENCO.

Figure 1 Live-in lab Sonnenplatz (Austria)

The primary objectives of HYPERGRYD ICT tools demonstrated and validated at the Live-in-Lab SONNE were to optimize energy flows and integrate renewable energy sources (RES) into coupled thermal and electrical grids, facilitating the modernization of District Heating and Cooling (DHC) systems toward 4th and 5th-generation technologies. Key insights were derived from two use cases as described in Deliverable 4.1 “Use Case definition including stakeholders and Roles for DT PaaS”:

- **Use case 1: Local energy market integrating heat and power**
  Within this use case, a local energy market was simulated for the Live-in lab SONNE to assess the benefits of local energy trading for the participating households, commercial, and public buildings. Based on historical data, GSY investigated the role of thermal assets and the impact of activating peer-to-peer trading within such a local energy market with 18 simulation scenarios (Grid Singularity, 2024). This simulation study showed that activating P2P trading improved energy cost for electricity and heating (of up to 145 %), self-sufficiency (especially in summer due to PV production which increases the amount to 124%) and self-consumption rates. Scenarios incorporating heat pumps enhanced local energy usage but were costlier due to current level of electricity prices compared to the heat price. This finding emphasizes the need for balancing economic and environmental objectives. The final scenario investigating the optimization of the trading strategy for a virtual heat pump (VHP) showed significant cost reductions and a very high self-sufficiency rate, demonstrating how smart trading strategies can lead to further economic and environmental benefits for a community that engages in P2P energy trading.

Key Performance Indicators		v.2. District heating replaced by heat pumps	v.3. P2P trading (no replacement)	v.4. P2P trading with heat pumps replacing district heating	v.7. P2P trading with heat pumps replacing district heating and an optimised heat pump trading strategy	
Scenario in comparison		v.1	v.1	v.2	v.2	v.4
Energy Cost	Summer Winter	+134% +37%	-145% -10%	-69% -7%	-75% -11%	-19% -5%
Self-Sufficiency	Summer Winter	+7% +19%	+124% +105%	+122% +73%	+132% +79%	+5% +4%
Self-Consumption	Summer Winter	+17% +23%	+124% +105%	+108% +72%	+116% +72%	+4% +0%
Energy Imports	Summer Winter	+28% +63%	-92% -37%	-78% -19%	-84% -23%	-31% -5%
Energy Exports	Summer Winter	-5% -22%	-72% -94%	-81% -100%	-88% -100%	-37% -

Key Performance Indicators		v.5. P2P trading and applied dynamic tariffs		v.6. P2P trading with applied dynamic tariffs and heat pumps replacing district heating			
		Day ToU	Night ToU	Day ToU		Night ToU	
Scenario in comparison		v.1	v.1	v.2	v.4	v.2	v.4
Energy Cost	Summer Winter	-92% -10%	-278% -62%	-49% -11%	+64% -5%	-142% -58%	-234% -55%
Self-Sufficiency	Summer Winter	-23% -73%	+64% +38%	-28% -76%	-67% -86%	+65% +54%	-26% -11%
Self-Consumption	Summer Winter	-23% -72%	+64% +38%	-32% -76%	-67% -86%	+54% +54%	-26% -11%
Energy Imports	Summer Winter	+28% +30%	-67% -65%	+24% +22%	+454% +50%	-59% -49%	+82% -37%
Energy Exports	Summer Winter	+20% +79%	-34% -28%	+25% +126%	+547% -	-40% -50%	+213% -

Figure 2 Key performance indicators, Sonnenplatz LEM study simulation scenarios and objectives, GSY simulation study for HYPERGRYD 2023-2024

KTH used real-time data to develop and demonstrate an IoT-enabled tool for the optimization of the local energy trading and demand response, improving PV self-consumption. This approach not only affects the electricity sector, but also the heating sector, particularly when heat pumps act as boosters or replacements for the DH system. The simulation of several scenarios showed that peer-to-peer trading and the coordination of the heat pump control to share PV energy optimally among the concerned buildings can improve the PV self-consumption by 60 %. However, implementing this optimal scenario requires the members of the energy community to install additional hardware so that devices such as heat pumps, PV systems, and batteries can be controlled and optimized remotely. Even though those results were obtained through a simulation study with virtual scenarios, for implementation, KTH has built and successfully tested an ICT solution based on a set of open-source software installed on a Linux virtual machine. This solution architecture facilities the deployment of the optimization driven energy trading in local energy communities, while highlighting the feature of data security and privacy concerns.

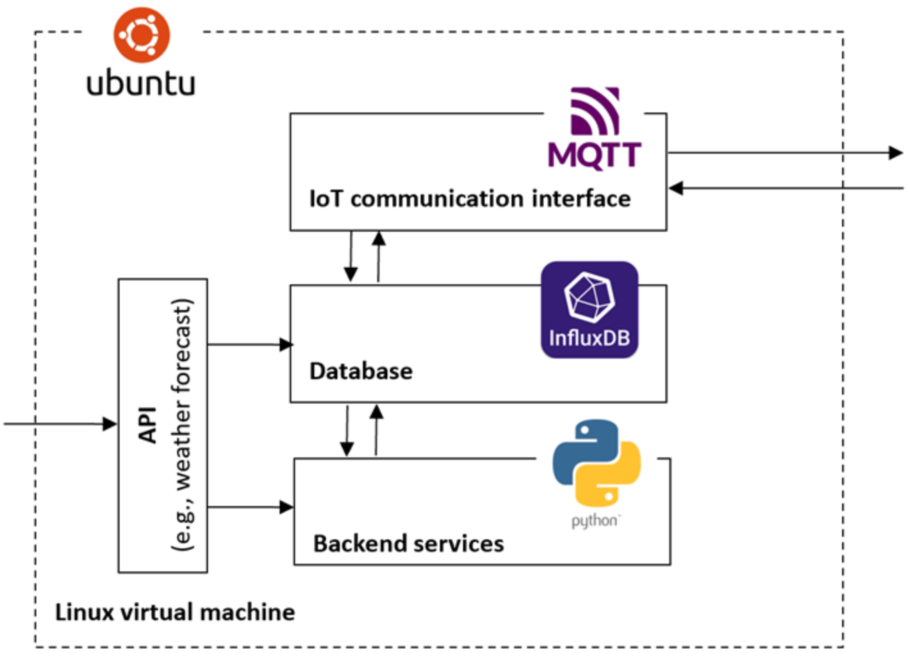

Figure 3 Proposed open-source software solution for centralized demand-side management

- **Use case 2: DHC network planning including spatial constraints**
  Within this use case, various datasets were provided to the tool developers to validate simulation models analysing different scenarios and aspects of the DHC network to:
  - integrate flexible heating systems into the electrical grid
  - explore dynamic pricing effects on flexible assets
  - reduce the exergy of DHC systems.

  ENCO used the multi-carrier energy network simulation tool called SAInt (Scenario Analysis Interface for Energy Systems) to simulate electricity, gas, and thermal networks and their flows in order to optimize or initially plan them, focusing primarily on physical simulations. As a result, the software calculates:

- the return temperature from generation assets;
- the supply temperature that reaches the users;
- the thermal losses across the pipes;
- the pressure and temperature drops for each pipe (both on the supply and return side);
- the pressure at the nodes (supply and return side);
- the flow rates in the pipes and network-side heat exchangers;
- the outlet temperature at the nodes

on the network side. The flow rate and temperature profiles on the secondary side of the heat exchangers connected to the nodes are not taken into account.

GET provides the optimization of existing or planned DHC networks as a service based on the « Exergoeconomic optimization tool for 4th and 5th generation of DHC » to optimize the operation of the DHC grid from an exergoeconomic point of view towards the 4th generation of DHC, considering investments, fuel and operation costs, and the price index, as well as flexible heat and electricity tariffs and costs for the reduction of GHG emissions. Potential use cases for this service can be:

- The simulation and calculation of the integration of decentralized production systems in order to integrate RES and P2H, which is particularly interesting in the case of variable tariffs for producers. For example, low tariffs at special time slots can be used optimally for feeding heat from a heat pump into the DHC system. Variable tariffs for heat consumers are not common yet, but this could be an interesting aspect for the future.
- The investigation of potential reductions of heat losses and pumping costs.
- An exergy-based analysis to reduce the exergy level, the temperature levels, and the heat losses.
- The comparison of different scenarios, e.g. the current situation and a scenario considering a grid extension or the integration of new consumers or of decentralized feed-in systems.
- The optimization of the DHC grid based on a pressure drop in order to pinpoint bottlenecks or locate suitable positions for booster pumps.
- The calculation of the effects of a grid extension to the whole DHC grid.

Some results from use case 1, mainly those related to the integration of flexible heating systems into the electrical grid and dynamic pricing effects on flexible assets, were used as input.

More information about the tools can be found in D3.2, D3.4, D3.6 and D3.8 of this project.

The **HYPERGRYD Project** successfully demonstrated the potential of these **advanced ICT tools to optimize and integrate renewable energy sources within thermal and electrical grids.** The validation of these tools across multiple stakeholders—including private households, municipalities, DHC operators, and electric grid operators— provided valuable insights into both technical and non-technical aspects of the implementation of the tools and services presented. The key findings of the validation process can be found in detail in D5.6 of this project and can be summarised as follows:

- **Private Households/Consumers/Prosumers**: Their primary interest lies in **being reliably supplied** with heat, hot water, and electricity at reasonable prices rather than engaging with technical details. Although the residents in Großschönau demonstrate openness to contributing to renewable energy initiatives, bolstered by a long-standing culture of sustainability, barriers such as administrative complexity and high initial investments hinder full participation in advanced energy management systems. Granting **third-party access** to **heat pumps, PV systems, or battery inverters** for coordinated energy management faced significant skepticism from local stakeholders. Concerns include potential energy unavailability and unexpected costs due to technical errors. Many residents prefer retaining full control, though voluntary recommendations instead of direct remote control could be a more acceptable alternative. Trust and transparency are crucial, as willingness to grant access depends on clear benefits. While skepticism remains, **data sharing is already practiced** in existing local and regional energy communities, where participants benefit from lower energy costs, reduced grid fees, and market independence. These insights highlight the importance of clear communication and user-centric implementation of energy management solutions.
  Also, on the subject of **flexible tariffs for electricity and heat,** local stakeholders remained cautious, while most international participants at the workshop found flexible tariffs relevant. Many local consumers may struggle to adapt to hourly price changes, preferring simpler day/night tariffs. However, some prosumers have already begun adjusting their behavior, using PV electricity for EV charging or appliances when available. Successful adoption of dynamic heating models would require gradual learning and targeted education efforts to increase acceptance.

  Thus, simplified implementation, financial incentives, and transparent communication of benefits are prerequisites for engagement. These insights emphasize the importance of aligning technical advancements with user needs and preferences for successful integration into local energy systems.

- **Municipalities:** Municipalities such as Großschönau recognize the benefits of optimizing electricity and heat supply, integrating RES, and advancing climate goals. However, financial constraints pose significant challenges. Investments in infrastructure must balance economic returns with public priorities. Municipalities require robust financial models and technical support to scale renewable energy initiatives while addressing competing local needs. Clear policy frameworks and funding mechanisms tailored to municipal budgets could enable greater adoption of innovations. Regarding DHC, municipalities rarely act as planners or operators of DHC systems directly in Austria. It is more common for a cooperative to be established for these purposes.

- **DHC Operators:** DHC operators recognize the value of innovative tools for optimizing existing and planned networks or enhancing them, whereby they prefer using a service rather than using a tool and rely on personal contact with the service-provider. Key priorities include the reduction of temperature losses and the optimization of summer operations, both of which contribute to greater operational efficiency and lower energy costs. However, broader adoption of the tools requires addressing technical and data-related challenges, ensuring the cost-efficiency of solutions, and designing user-friendly interfaces. Cost-efficiency is emphasized as a critical consideration, not only for optimizing operations, minimizing infrastructure investments, and justifying network expansions, but also for incorporating decentralized feeders and technologies into existing systems and implementing dynamic pricing strategies.

- **Electric Grid Operators**: Although the HYPERGRYD tools align with the future needs of electric grids, direct feedback from regional **electric grid operators** was limited due to collaboration challenges and regulatory complexities. Regional stakeholders reported grid overloads and restrictions on feed-in capacities because of the rapid expansion of PV systems over the last year. While tools like those developed by KTH require real-time electricity pricing for effective peer-to-peer utility trading, dynamic tariffs are still in their infancy in the region. Technical requirements like the widespread installation of smart meters are almost completed. Regulatory frameworks that accelerate the adoption of flexible tariffs and incentivize collaborative efforts with energy communities will be critical for unlocking the full potential of such tools.
  Concerning use case 2, the grid operator may not be the primary target for such tools, because it often delegates grid planning to internationally renowned companies with established expertise. These companies typically rely on their years of experience rather than using tools such as SAInt.

- **Researchers and engineering offices** on the other hand, prefer the usage of tools over services. The most notable engineering office in the Großschönau area, which also planned the DHC network of Großschönu, is "innoVAT GmbH". This office has many years of experience and started planning grids before specialized software was available. During a site visit, the engineer of this company could describe numerous details about the network design based purely on experience. This is why they are still refusing to use a software and continue planning grids or grid extensions only, relying on the 2D and 3D computer-aided design software application « AutoCAD » and Microsoft Excel for calculations. The validation of the SAInt tool by engineering offices would require more detailed training on the tool. Language barriers might also pose a problem, as German-language tools tend to be preferred.

In summary, the validated tools can guide sustainable energy transition strategies and support modernization towards the 4th and 5th-generation of DHC systems. The integration of flexible assets, such as heat pumps and decentralized RES, combined with advanced ICT solutions, has demonstrated clear potential to improve energy efficiency, reduce costs, and enhance grid stability. Future efforts should address regulatory barriers, user education, and cost-sharing mechanisms to ensure wider adoption and long-term success.

3.2 KEZO

The KEZO Live-in lab is located in KEZO Research Centre in Jabłonna near Warsaw. KEZO is one of the most modern research complexes dealing with the use of renewable energy in Poland. Constructed in 2015, it was meant to combine the function of research centre, conference centre and living laboratory. KEZO has a number of heat sources, renewable energy sources, energy storage units for both electricity and heat. Stakeholders are IMP PAN and companies working in the field of heat pump, energy storage, EV, PV, and other institutes conducting experimental research in Reseach Center.

Figure 4 KEZO Reseach Centre, view on L5 building.

The KEZO Research Center consists of three buildings: 2 laboratory buildings (B1, B2) and one main building L5 that houses offices, additional labs, a conference room and guest rooms. The cooling and heating system consists of four main lines that connect all buildings with heat and cold sinks, and sources placed along the way of the main lines. Each building has its own ventilation, fan coils, radiators and floor heating unit in which heat exchangers are supplied from the main heating and cooling lines. There is no connection with the DHN of the city. KEZO possesses over 180 kWp of PV in various systems including on carports, trackers, building integrated photovoltaics, as well as a 12 kW wind turbine and over 60 m^2 of solar collectors. Smart electricity meters have been installed in each laboratory to measure and log energy consumption.

Within the HYPERGRYD project, many modifications were made to the KEZO energy and H&C systems for preparation to connection the new Enabling Technologies. For determination H&C characteristics of KEZO building and performance maps of existing and new technologies, additional ultrasonic heat meters and energy meters with MODBUS communication have been installed there. Two of the new Enabling Technologies developed within the framework of Task 2.2, i.e. the modular Heat Pump with PCM storage and sorption storage, have been delivered to KEZO LiL for testing. The first step was to integrate the technologies and software developed in WP2 and WP3 respectively with the existing energy system in KEZO Living Lab and with the already installed selected technologies for heat and cold generation. The works were carried out based on the detailed strategy for tests and validation developed in Task 5.1.

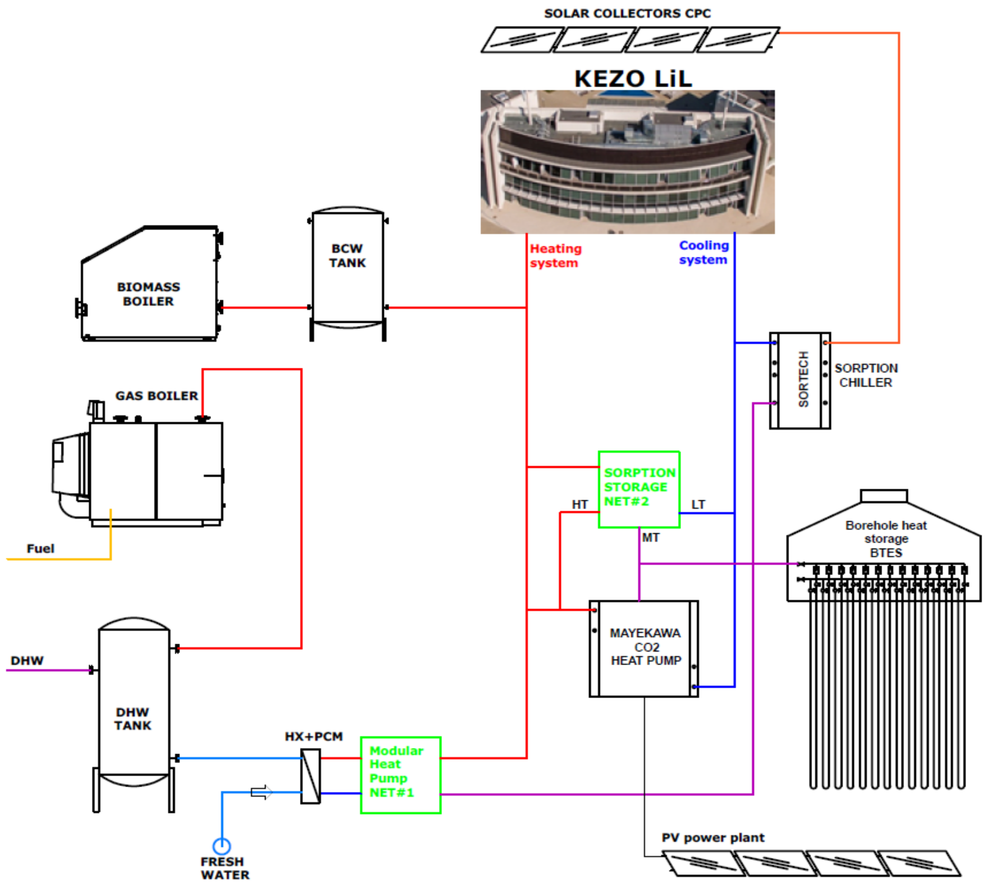

Figure 5 Simplify scheme of H&C systems in KEZO LiL

This demonstration activities have been carried out in **Task 5.3**, with focus on the determination of KPIs for benchmarking of the HYPERGRYD solutions and to validate developed models and control strategies.

The first tested device was the modular heat pump with PCM storage for heating and DHW purpose, it was developed by Ochsner and AIT. The second device is the sorption storage developed by SORTEC in cooperation with CNR. Both devices were very advanced, but also very complicated in both technical dimension and management.

The modular heat pump with PCM storage was supplied from BTES storage as the lower heat source in 5th GDHC system (Fig.6). The device was tested in two modes: DHW production and heating mode, for which the heating efficiency and COP was calculated. The characteristics of charging and discharging the PCM storage were determined. Based on the obtained results, the technologic specific KPIs were calculated, which were then compared with those values for traditional heat pumps. The calculated KPIs are worse in comparison, which is due to too a high temperature on supply side of PCM storage. For a full phase transition of RT57 in the PCM storage, there should be an inflow temperature over 60°C; such temperatures are on the border of what modular heat pump can provide with minimal efficiency. For the whole charging process of the PCM, the total COP is below 1.5.

In the construction of the modular heat pump, 2 additional plate heat exchangers were used. These were meant to protect the water installation of KEZO against leaks and against seeping of the RT57 into the circuit. Unfortunately, those plate heat exchangers were causing additional resistance in transferring heat which caused worsening of the operational parameters of the modular heat pumps. For the heating mode the maximum COP was around 2. The PCM storage has an average degree of compactness of 56% and a energy storage capacity of 4.17 kWh. The energy storage efficiency was ca. 85%.

Figure 6 The modular heat pump connected to KEZO system.

The **sorption storage** was supplied with water of 80-85°C from the high temperature CO_2 heat pump (Fig.7). For proper operation of this device, there has to be an additional circuit for consuming heat, i.e. the average temperature circuit MT, with a supply temperature of 30-35°C from e.g. heating system, and low temperature circuit which would take cold water at 12-16°C for cooling the buildings.

The storage was tested in two modes: 1) heat storage, 2) production of heat and cold simultaneously. The energy storage capacity is 8 kWh and the maximum energy storage efficiency was about 67.3%. The time of charging the tested storage is 1 h 46 min with a charge power of 4.7 kW. A full discharge takes 1h 29 min with 5.4 kW of discharge power. The storage is based on sorption and desorption processes, so it can be used as a **mid**-term storage.

Figure 7 Sorption storage connected with Mayekawa CO2 Heat Pump in KEZO Research Centre

Technology specific KPIs for the modular heat pump with PCM storage and sorption storage were determined based on tests carried out in KEZO LiL within Task 5.3. These KPIs are listed in Table 6, the last column contains the results of the calculation based experimental data.

Table 1 Technology specific KPIs panel

Technology/ Tool	KPI	Index	Symbol	Results
Modular heat pump	COP heating	KET 4.1	COP_{heat}	1.92
	COP cooling	KET 4.2	COP_{cool}	NA
	COP DHW with PCM losses	KET 4.3	COP_{DWH}	1.44
	COP DHW without PCM losses	KET 4.4	COP_{PCM}	1.69
PCM storage	Degree of compactness	KET 5.1	Φ_{PCM}	56%
	Energy storage capacity	KET 5.2	ESC_{PCM}	4.17 kWh
	Energy storage density	KET 5.3	ESD_{PCM}	50.1 kWh/m3
	Energy storage efficiency	KET 5.4	η_{PCM}	85.5%
	DHW charging cycles per day	KET 5.5	*DHWcycles*	NA
	Charge/discharge time	KET 5.6	tch_{PCM}, $tdis_{PCM}$	1 h 6 min 15 min
Sorption storage	Operating temperature levels	KET 6.1	Tch_{SOR}, $Tdis_{SOR}$	85°C 13°C

	Energy storage capacity	KET 6.2	ESC_{SOR}	8 kWh
	Energy storage efficiency	KET 6.3	η_{SOR}	67.3%
	Charge/discharge power	KET 6.4	$Qch_{nom,SOR}$, $Qdis_{nom,SOR}$	4.7 kW 5.4 kW
	Charge/discharge time	KET 6.5	tch_{SOR}, $tdis_{SOR}$	1 h 46 min 1h 29 min

The next demonstration activities were performed tests of the existing and the new enabling technologies in variety configuration according to defined Use Cases:

- **UC1. Simulation of building, hotel and tertiary loads in small districts.**

Using historical data collected via the KTH edge panel, prediction models were developed to estimate the heating and cooling loads of the KEZO buildings. These models enable the identification of the key parameters influencing heating and cooling demands within the research facility, while also facilitating the energy flow assessment within the local sector coupling system. In this deliverable, there will be a particular focus on the heating demand since most of the data was collected in the winter season. Below, is a two-day ahead prediction of the heating load corresponding to the radiators and fan coils in the Building L5 using Gated Recurrent Unit, which is a type of recurrent neural network (RNN).

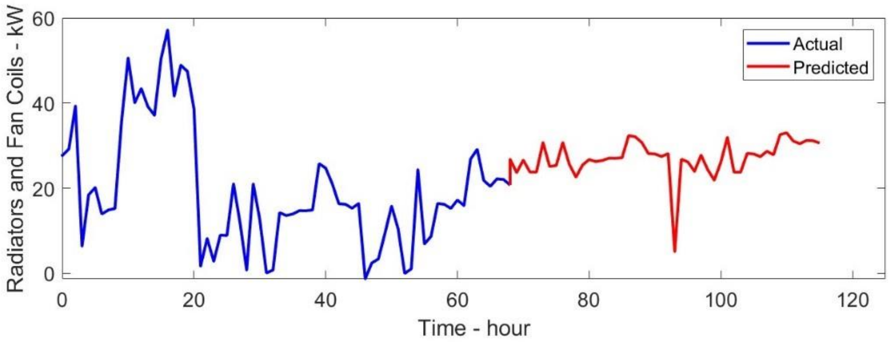

Figure 8 Two-day ahead prediction of the radiators and fan coils heating power in building L5 using GRU approach

Below, the prediction performance of the NN model for heating COP prediction are displayed, along with the prediction error metrics.

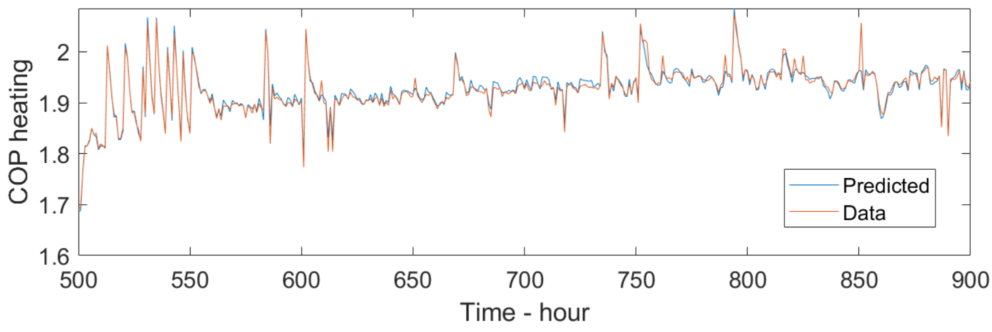

Figure 9 Temporal variation of COP heating: measurement and NN

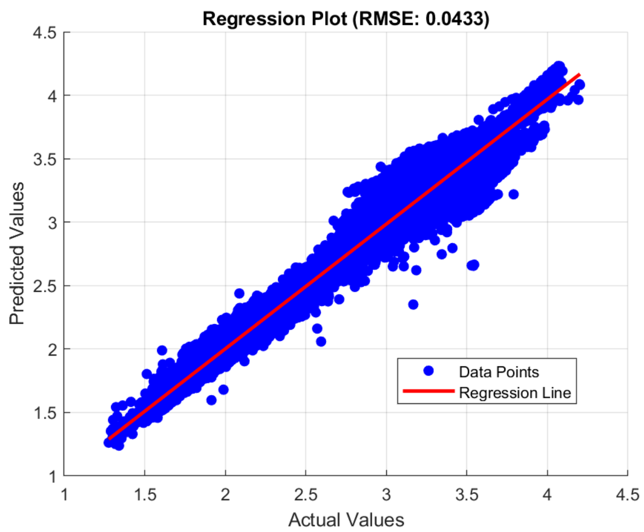

Figure 10 Regression curve of the COP heating prediction using NN

- **UC2. DHC with coordinated operation of heat pumps, sorption cooling, storages, and PV production.**

For this use case, the energy flexibility available within the KEZO emulated DHC system, enhanced by the newly installed hardware, will be leveraged to optimize energy flow management. In the demonstration phase, the sorption energy storage serves as the primary flexibility mechanism for regulating energy flows related to heating and cooling demands. Since this storage system is powered by a CO_2 heat pump during the testing phase, its sector coupling potential is also considered. To this end, the ability to perform load shifting and shaving through the charging and discharging cycles of the adsorption storage will be analyzed and simulated using load prediction data from UC1.

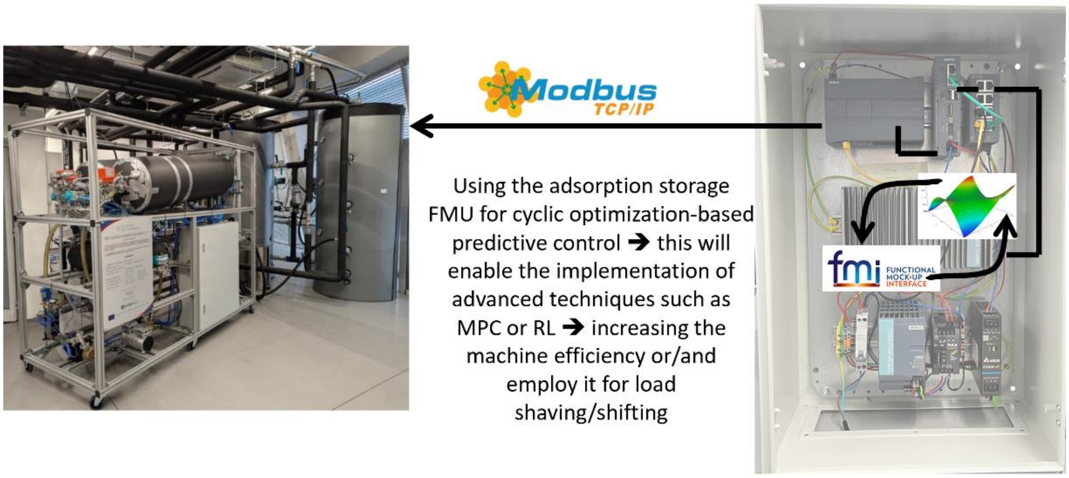

Figure 11 Model-based control of the adsorption storage using the KTH edge panel

- **UC3. Real data-driven simulation of multi-carrier DHC.**

Based on data collected via the edge panel, it was possible to develop data-driven models for the CO_2 heat pump and for the sorption storage. Later, those models, along with the heating/cooling demands and PV production, are used for the simulation of electric and thermal power flows within the coupled local grids at KEZO.

Based on the findings from UC1 and UC2, UC3 was successfully validated by integrating load prediction, system models, and control strategies into a comprehensive data-driven simulation of the KEZO emulated sector coupling network. The primary objective of this simulation was to assess the accuracy of the developed model by analyzing prediction errors, evaluating simulation computing time—reflecting the efficiency of advanced energy management algorithms—and determining the optimal costs associated with satisfying heating and cooling demands through optimal control strategies.

To achieve this, KTH conducted digital simulations of the KEZO LiL's targeted HVAC system under varying outdoor (weather) and indoor (occupant) conditions. The focus was not on simulating the KEZO emulated DHC network as a whole, but rather on evaluating the impact of optimally controlling the innovative hardware technologies developed within HYPERGRYD, particularly the sorption storage, on the energy flow within the HVAC system of Building 5 and the energy flows resulting from that. This approach enables a deeper understanding of the interaction between the optimally driven energy storage solutions and sector-coupled energy distribution.

3.3 EURAC

3.3.1 Description of the LiL and objectives of demonstration

EURAC is located in Bozen (Italy). This Live-In Lab consists of the Energy Exchange laboratory which includes equipment producing, on a lab scale, a DHCN with heat production units (gas boiler and solar collector), user substation (based on HPs) and thermal storages. The main components are shown in Figure 12. The water distribution network has connected all the heat and cold generation units on it. There is a connection to multiple points, emulating a single user. All consumers are emulated through heat pumps. The lab can be used to emulate a DHC network (about 70 m long in a 2-pipe configuration) with a storage of 2000 l. The DHN circuit can also be used in a 1 pipe configuration (150 m long). The flexible infrastructure enables testing various types of products, including DHN substations, Heat Pumps, micro-CHP systems, controls, and similar equipment. Due to its monitoring and control system and in-house experience, it is possible to easily integrate the product to be tested in the overall laboratory architecture and run a laboratory-controlled test. Moreover, apart from the standard stationary tests, which are useful for evaluating the product's performance under stationary conditions, it is also possible to conduct more dynamic and realistic tests through predefined profiles or real-time emulated profiles (Hardware-In-the-Loop).

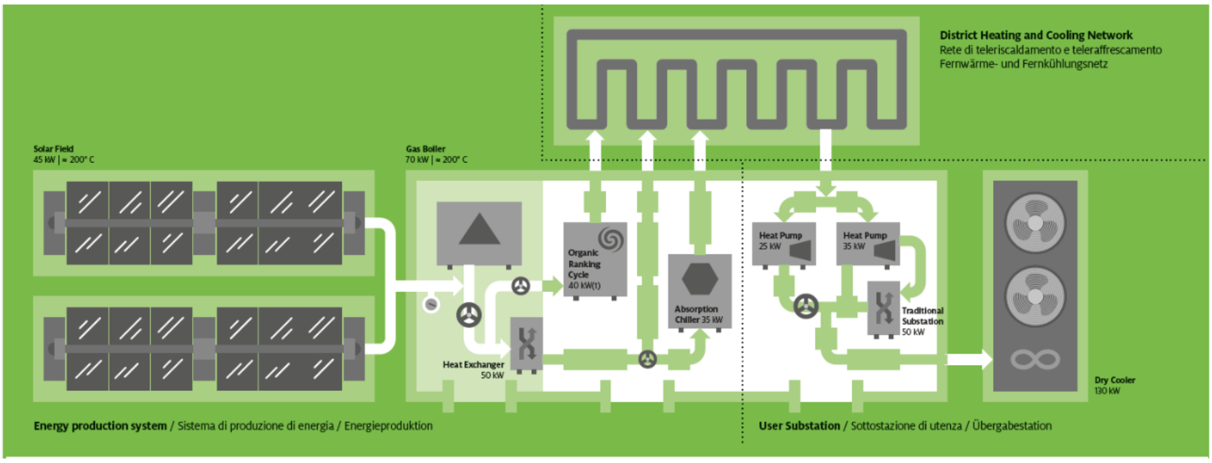

Figure 12. Energy Exchange Lab of Eurac Research schematic

Within the framework of the HYPERGRYD project and based on the aforementioned characteristics of the laboratory, tests have been conducted in the identified use case 1, "DHC with the coordinated operation of heat pumps, storage, and PV production". The main objective of this use case is to test the 4^{th}-5^{th} GDHCN coordinating the operation of user substations integrating heat pumps and storages with the thermal energy distribution along the network. In the transition from the 3rd GDHN to the 4th and 5th GDHN, the use of HPs in user substations, coupled with thermal storages and PV production is a key topic to be analysed. In such a kind of network, the supply temperature can vary depending on the specific needs; at the same time, different temperatures are required at the load side depending on the type of user needs (i.e., heating or cooling) and the building features (i.e., new building with a radiant floor or older building with radiators terminal units). In this context, a user substation integrating HP and storage for space heating was assembled at the EURAC LiL with features allowing the flexibility to match the DHN and load temperature variations. User substation control logic, including Rule-Based Controls (RBC) and Model Predictive Control (MPC), has been developed and implemented to adapt the substation's use to varying network and load temperatures, thereby optimizing overall substation energy use and costs. Experimental tests have been performed in dynamic conditions to analyse in detail the behaviour of a real-like system on a lab scale operating under different controls.

3.3.2 Substation description and controls

In the 4th and 5th GDHN, heat pumps are considered essential components, as they are used to adjust the temperature of the distributed thermal energy to match the specific heating or cooling demands of each building, which is treated as a prosumer. Multiple benefits are provided by adopting decentralized, active substations in DHC networks. First, thermal energy is distributed more efficiently, and energy losses during transmission are reduced. Additionally, greater control flexibility is offered to individual prosumers.

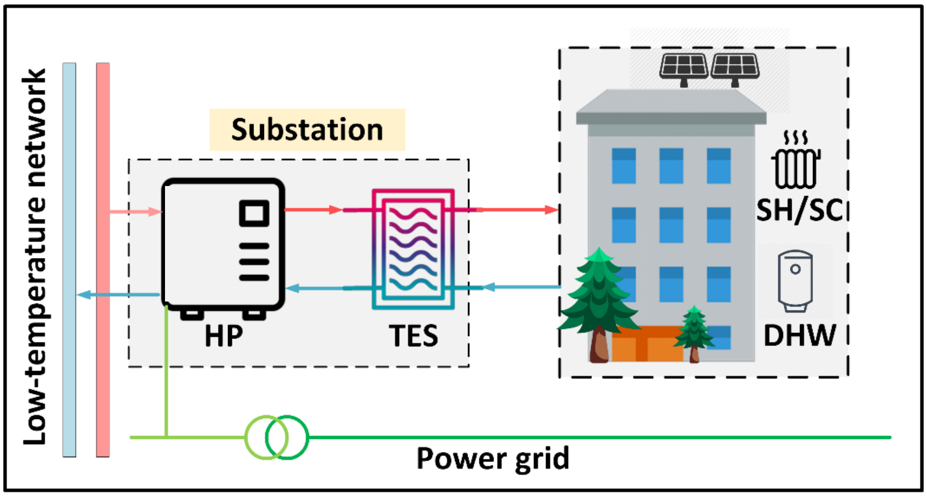

Figure 13. Overview of the substation's operation within the context of 4th and 5th GDHN.

In Figure 13 the integration of 4th and 5th GDHN with a residential building is illustrated, where the network operates at temperatures not suitable for direct heating. At the center, a common and simple substation equipped with a HP and TES is shown. The required thermal energy for space heating and domestic hot water is supplied to the residential building on the right.

In the Energy Exchange Lab, EURAC has set up a substation where the HP is hydraulically connected to circuits that simulate both the DH system and the building. This configuration utilizes pipes and valves to optimize the heat pump's performance, thereby enhancing the system's coefficient of performance (COP) based on the temperatures of the DH supply and the building load. Figure 14 illustrates the different operational scenarios. Four different operation schemes can be considered to enhance the effectiveness and efficiency of the substation, tailored to specific temperature conditions:

- If the DH supply temperature is lower than the return from the building, scheme 1 is activated.
- If the DH supply temperature exceeds the set temperature for the building, scheme 4 is triggered.
- If the DH supply temperature is higher than the return temperature from the building and lower than the supply set temperature to the building, schemes 2 or 3 are enabled. Scheme 2 maximises system COP, while scheme 3 minimises the return temperature to the DH while still enabling a high system COP.

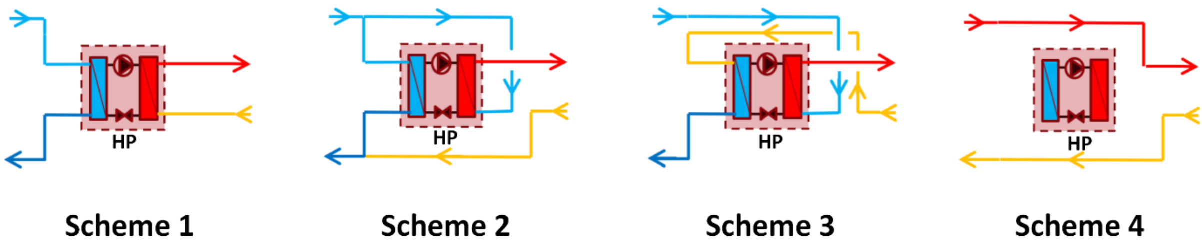

Figure 14. Overview of the four different configuration schemes considered in this study. The DH network is on the left and the building on the right side of each scheme

The main focus of this study is placed on the optimal control of a substation within a 4th and 5th GDHN, using a high-level controller based on MPC. Particular attention is given to how MPC is utilized to manage the operation of HP+TES systems in a flexible and cost-effective manner, thereby meeting varying building energy demands. In Figure 15 the MPC concept is shown: a rule-based control is used for basic substation operation, while the MPC overrides the set temperatures to trigger TES charging, thereby forcing or delaying HP activation. For this purpose, a model of the substation is applied to simulate system operation in quasi-real time over a 24-hour receding horizon, and an optimisation algorithm is used to determine the optimal set points within the same period.

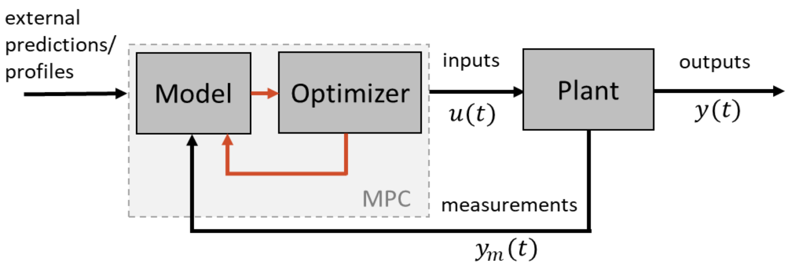

Figure 15. Schematic of MPC framework

The implementation of Model Predictive Control (MPC) necessitates the development of several models. First, creating a model that calculates the building's thermal demand based on outdoor conditions and user behaviour is crucial, as MPC relies on accurate forecasts to anticipate future energy needs. Additionally, the MPC must consider the state of charge (SOC) of the TES and the operational status of the HP, since their interaction significantly affects overall system performance. To efficiently represent the behaviour of both the HP and TES while maintaining computational feasibility, reduced-order models (ROM) are essential. Lastly, optimisation is vital for defining the best operational trajectory over a specified timeframe. To meet these requirements, this study included a range of activities:

- Building Demand Model: The objective was to develop a ROM that effectively captures the essential dynamics of thermal load variations while maintaining computational simplicity. This model is robust and adaptable across different building types, sizes, and locations. It can be trained during operation using limited monitoring data and is suitable for online execution, even on hardware with limited computational resources.
- TES model: the model developed meets three key objectives: i) simplicity by capturing the essential dynamics of TES behaviour while minimising computational demands; ii) consistent energy balance by maintaining a balanced account of all relevant energy inputs and outputs during both charging and discharging processes; iii) accurate representation of the thermocline by ensuring an accurate depiction of the thermocline, which influences both performance and the operation of the connected HP.
- Heat Pump Model: Developing a ROM for heat pumps involves several key aspects to ensure accurate and efficient operation. The primary objective is to model the modulation of compressor speed to consistently maintain the setpoint temperature at the inlet of the load side. The model calculates thermal power and electrical consumption based on the compressor speed and other operational parameters. This requires a comprehensive understanding of the heat pump's performance characteristics and the ability to simulate these characteristics under various conditions. Continuous training procedures are integrated into the model to maintain accuracy and adaptability. These procedures update the performance map using real-time data, allowing the model to adjust effectively to different heat pump configurations and operational scenarios.
- Quasi-Real-Time Optimization: it prioritised the integrated operation of the substation, taking into account the dynamic interactions among the electricity grid, thermal grid, and buildings. This comprehensive approach ensures that all components function together smoothly to achieve optimal performance.

3.3.3 Assessment of the control performance

A test campaign was carried out to compare MPC with RBC, both applied to operate the substation under the same boundary conditions in an emulated multifamily home. A performance evaluation was conducted, first to confirm the reliable and consistent operation of MPC and then to assess its effectiveness in terms of system coefficient of performance (COP) and overall energy and cost savings.

The reference building, a renovated and energy-efficient multi-family house in Stuttgart, features a total area of 300 m² with a heating demand of 70 kWh/m² per year. The HP's thermal capacity is 25 kW at 60°C, whilst the TES has a volume of 1.25 m³. The weather conditions are typical of a December week. During the work elaboration, we considered several combinations of boundary conditions, culminating in the test of a constant DH supply temperature (40°C) and a variable electricity price.

The MPC's optimisation algorithm has been allowed to adjust the TES set point, with a cost function aimed at minimising the overall operating costs (in terms of electricity).

Test 1: Performance assessment with time of use (TOU) electricity tariff

In Test 1, the performance of MPC and RBC is compared with an electricity price from the grid following a Time-of-Use (TOU) tariff: €0.11/kWh during the cheap period and €0.33/kWh during the expensive period, with a variation every two hours. The power prices span is typical of daily variations in electricity markets with significant integration of on programmable RES, while the stepwise shape was chosen as to oversimplify a real power price timeseries, aimed to allow a clear understanding of the MPC decision making process and acknowledging that it is not how a real-life price signal would look like. The DH temperature is maintained at 40°C, and the SH supply and return temperatures are 55°C and 45°C, respectively, under the climatic conditions of the first three days of December.

The first plot in Figure 16 shows the thermal load that is the same for the two cases, while the other plots display key variables for the MPC and RBC cases, respectively, in red and blue lines. The second plot displays the TES setpoints, constant at 55°C for RBC and variable for MPC. The third plot shows the TES state of charge (solid lines) and its top temperature (dotted lines), which increases when a charge is applied and exceeds 62°C in cases of overcharging during the MPC operation. Given the TES temperature stratification, this temperature also provides an indication of the supply temperature to the load: while the MPC and RBC sometimes violate the comfort condition (55°C), this effect is negligible. The fourth plot shows the electricity price and the distribution of TES charges in the two cases: while in the RBC case they are randomly distributed between cheap and expensive period and they charge the TES always in the same way (state of charge), the MPC decides to charge the TES mainly when the electricity price is low by changing the TES SP (second graph), considering the constraint on the comfort condition and the prediction of the load. Moreover, another relevant effect is the distribution of TES overcharges that occur when the electricity price is low and in anticipation of a peak in the building load (i.e. 5:00 on day 3). This allows sufficient energy to be stored in the TES by increasing the state of charge and meeting the load during the expensive period, thereby avoiding an expensive charge. However, the ability to achieve this heavily depends on the TES capacity relative to the expected load. Brief HP operations were observed during expensive hours (e.g., 19:50 on day 2). This behaviour may stem from mismatches between the thermal load peak and the TES capacity, as well as model inaccuracies. The control system relies on ROMs for predictions, which can lead to deviations between the predicted and actual system states. Consequently, the controller may underestimate the needed charge or overestimate the tank's supply capacity, resulting in occasional HP activation during high-price periods to meet demand and maintain system constraints.

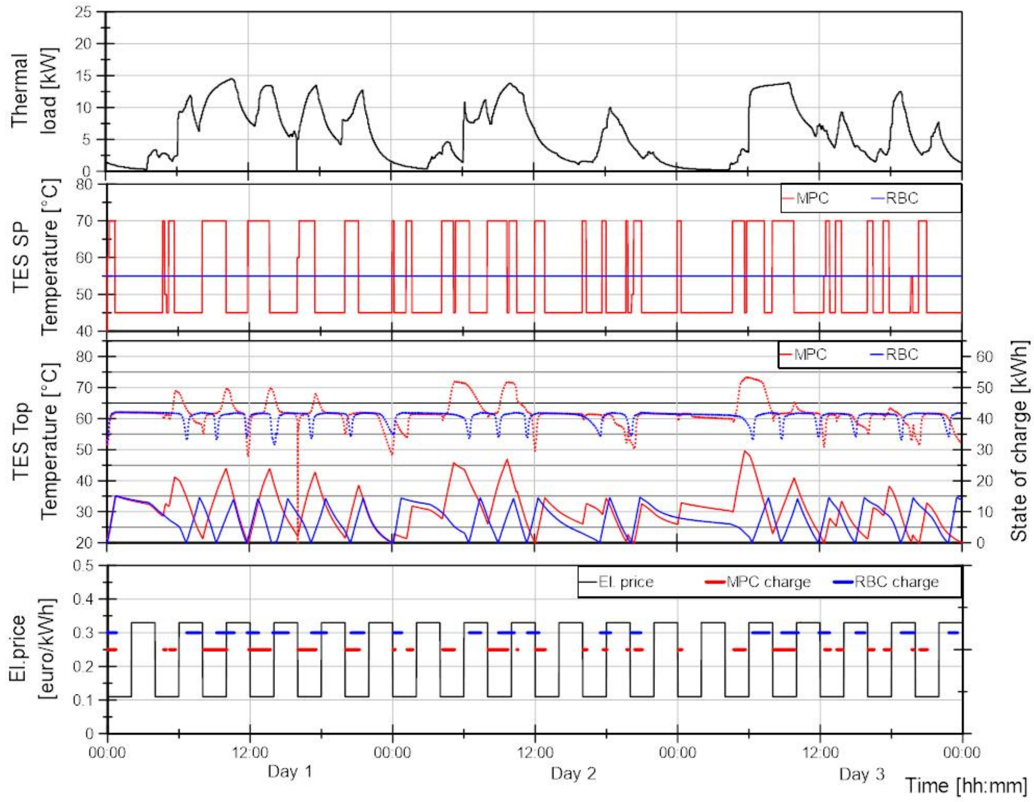

Figure 16. Result of comparison the performance of MPC vs. RBC with TOU electricity price (test 1)

The total durations of HP activation were similar in the two cases, with 1199 minutes for RBC and 1181 minutes for MPC. The main difference lies in its distribution along the tests. Firstly, there is a different distribution across the two tariff periods, as shown in Figure 17: under the RBC, 48.6% occurred during the low-cost periods and 51.4% during the high-cost ones; in contrast, the MPC optimized the activations, with 96.8% during cheaper intervals and only 3.2% during expensive ones. This highlights the effectiveness of MPC in shifting energy use to more cost-effective periods. Secondly, the number of charge cycles and energy stored in each charge significantly changed, as shown in Figure 18: under the RBC, the energy stored per cycle is mostly the same, primarily between 14–16 kWh, indicating 19 relatively long and uniform activation cycles; the MPC increased the activations up to 26 allowing the system to operate in shorter, more flexible bursts aligned with low-price periods, with energy stored per cycle mostly in the range 2–14 kWh and hence lower than RBC case. Additionally, the controller strategically utilizes favorable periods to supercharge the TES occasionally, storing energy bursts exceeding 18 kWh when inexpensive electricity is available.

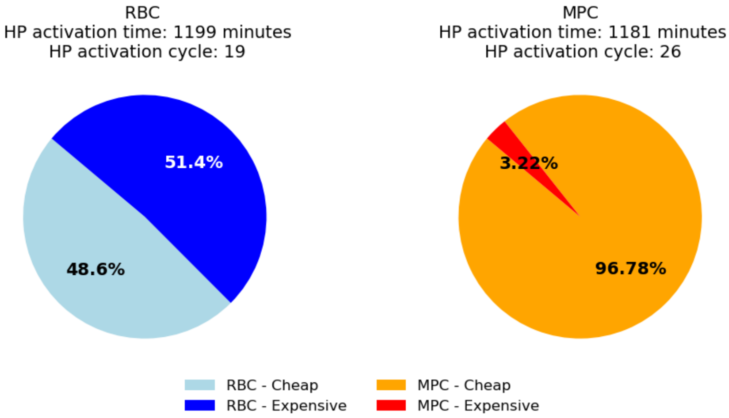

Figure 17. Distribution of HP activation durations during cheap and expensive periods under RBC and MPC with TOU electricity pricing.

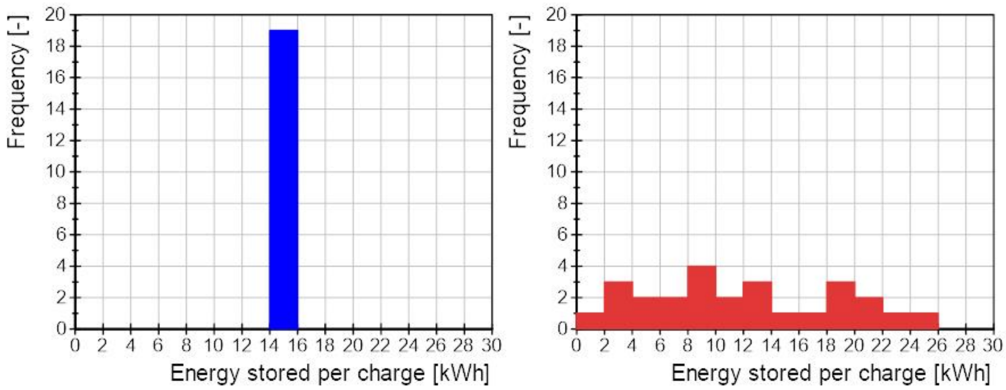

Figure 18. Comparison of energy stored per charging cycle and number of charging under RBC (blue) and MPC (red) with TOU electricity pricing

The described MPC decisions reduce dependency on expensive periods and enhance cost savings, allowing for the same load to be satisfied as the RBC. Although the overall electricity consumption increases by 2.3 kWh (2.4%) and the system COP decreases by 0.3 (5.8%), mainly due to the HP operating at lower COP during overcharges, the operating cost (electricity) significantly reduced from 18.9 € (RBC) to 10.44 € (MPC), representing savings of about 44.79%.

Test 2: Performance assessment with realistic electricity price

The test 2 conditions are the same as those in test 1, with one single difference: while in test 1, the electricity price considered is fictitious, here it is a realistic one. It varies between 0.11 and 0.27 €/kWh, according to the variation in the "PUN Index GME" (short for Prezzo Unico Nazionale, or National Single Price) over three days in December 2024 (11-14). The "PUN Index GME**"** is the reference index of the Italian electricity market, i.e. the reference index of electricity traded in the Day-Ahead Market (MGP).

Figure 19 presents the results of Test 2, which yield similar outcomes to those of the previous tests. Here, the average electricity price (0.19 €/kWh) serves as the threshold considered in the analysis to differentiate between expensive periods (prices higher than this threshold) and cheap ones (prices lower than this threshold, grey areas of the fourth plot). The MPC strategy activates the HP more frequently during periods of low electricity prices, taking advantage of lower costs. During these times, MPC extensively uses the HP to maximize TES charging. In contrast, RBC shows the highest levels of HP operation during peak electricity price periods, closely following the load pattern. This difference is due to MPC's ability to predict future trends, including electricity prices and load peaks, enabling it to make more informed and optimal decisions. An example is between 2:00 and 4:00 on day 1, when the electricity price was low, the MPC strategy predicted an upcoming thermal load peak in the early morning. Consequently, the tank setpoint was increased to its maximum value, allowing the system to supercharge the tank in anticipation of the demand. Around midday, the electricity price dropped again, prompting the MPC to charge the tank further. However, it is worth noting that the tank's thermal capacity also played a significant role in the decision-making process. For instance, the MPC activated the HP at 18:00 on the first day despite the high electricity price due to a thermal load peak and insufficient state of charge in the tank to meet the demand.

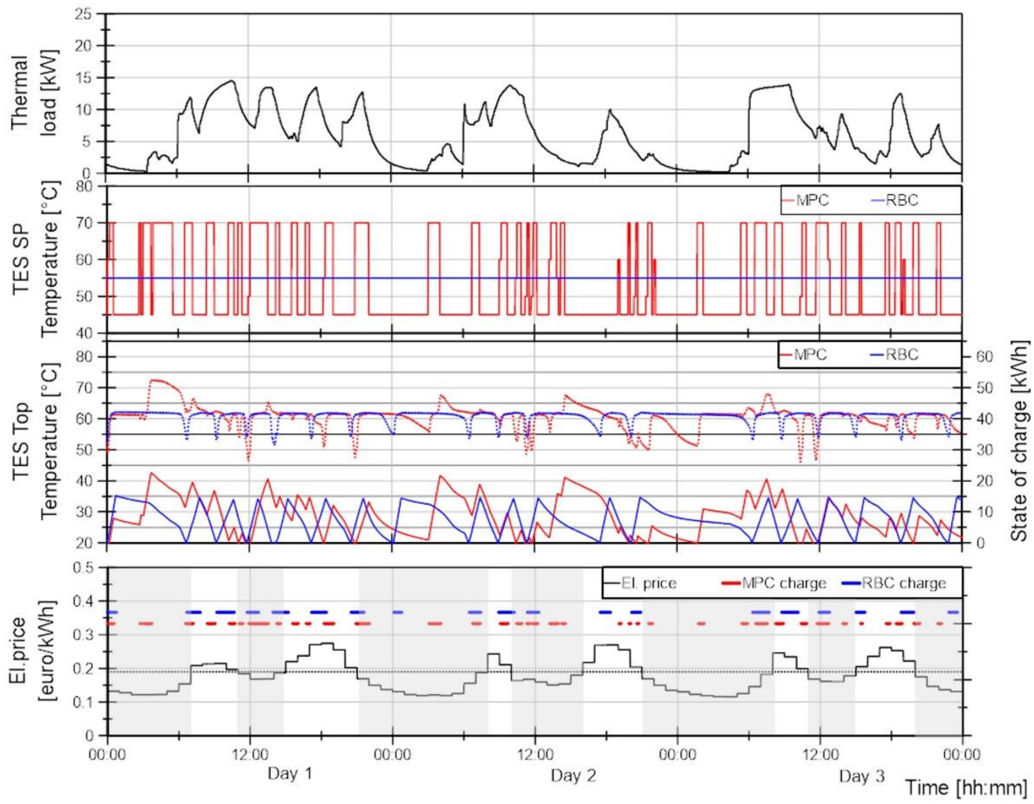

Figure 19. Result of comparison the performance of MPC vs. RBC with realistic electricity price (test 2)

The total durations of HP activation were similar in the two cases, with 1199 minutes for RBC and 1207 minutes for MPC. Figure 20 shows that under RBC, the HP activations were almost evenly distributed between cheap (48.5%) and expensive (51.5%) periods, indicating no responsiveness to price variations. The system operated solely based on thermal demand without considering electricity prices. In contrast, the MPC with a variable pricing strategy significantly shifted operations toward cheaper periods. Approximately 67.19% of the HP activations occurred during low-cost periods, while 32.81% occurred during high-cost times. Figure 21 gives an insight into the number of charges and the energy stored per charge. As in the previous test, the number of charges increased even more, reaching 37 shorter and more frequent activation periods. It should be noted that no explicit term was included in the objective function to penalize or control the number of HP activations, which likely contributed to this behaviour. This approach enables the heat pump to operate more flexibly, adapting effectively to the variable conditions of the electricity price and load by storing energy in smaller increments, mostly between 2 and 10 kWh. Overall, the MPC strategy resulted in a 6.86% reduction in operating costs, from 18.07 € to 16.83 €.

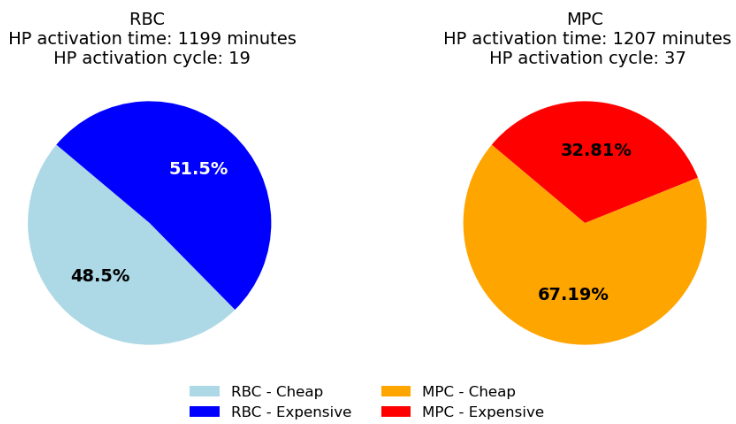

Figure 20. Distribution of HP activation durations during cheap and expensive periods under RBC and MPC with realistic electricity pricing.

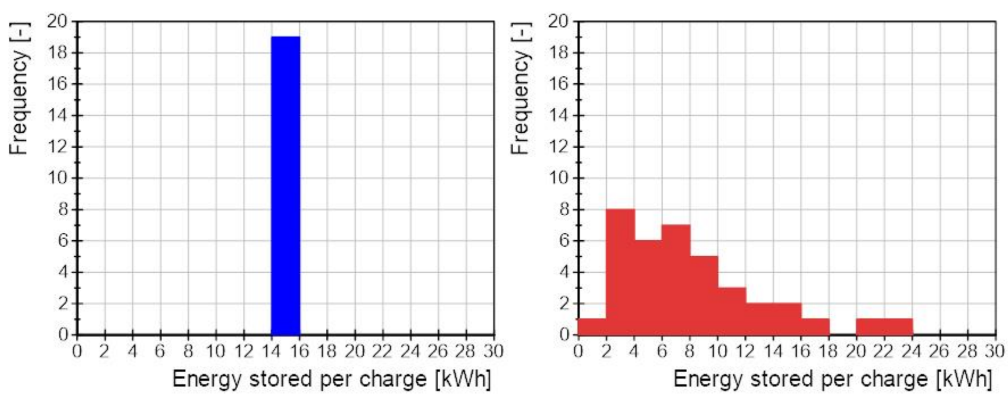

Figure 21. Comparison of energy stored per charging cycle and number of charging under RBC (blue) and MPC (red) with realistic electricity pricing

3.3.4 Lessons learnt

MPC consistently outperformed RBC by lowering electricity costs and achieving notable savings. The analysis shows that MPC effectively shifted TES charging to periods with lower prices while meeting load demands. However, the increased activation cycles suggest a dynamic response to changing conditions. To improve this, it may be helpful to add a term to the objective function to reduce these cycles.

The most critical insights derived from the research activity on the described DH substation and advanced controls are:

- MPC effectively utilizes dynamic pricing and load shifting by scheduling heat pump operations during periods when electricity costs are lower and optimizing TES charging strategies. This approach not only leverages dynamic electricity pricing to reduce operating costs but also shifts energy consumption to off-peak times. As a result, it enhances overall system efficiency and improves demand-side management.
- Continuous model training ensures systems adapt to changing conditions and remain accurate, maintaining optimal performance over time.
- Accurate thermal load forecasting is critical for effective MPC. Employing ANN to develop a ROM provides precise and adaptable forecasts, enhancing system responsiveness.
- Efficiency improvements through various substation schemes: By exploring different substation schemes, it is possible to enhance the system's efficiency. Implementing temperature-based transitions and combining hysteresis methods facilitated smoother and more effective changes between operational schemes, ultimately leading to improved substation efficiency.

Although this study has demonstrated significant benefits from using MPC in decentralized substations, there is still potential for further improvement. The following are suggestions for enhancing the system and directions for future research based on our findings:

- Longevity constraints for equipment: While MPC reduced electricity costs, it may also result in a higher HP switching rate, which can lead to increased wear on equipment over time. This could be incorporated as a constraint in the MPC's decision-making process.
- Explore advanced machine learning techniques for model training, including reinforcement learning, to enhance model adaptability and prediction accuracy across various conditions.
- Optimize the sizing and operation of TES: Analyse the effects of various TES sizes and configurations on system performance to enhance TES design for specific applications and improve energy storage utilization.
- Integrate renewable energy sources: Investigate the integration of renewable energy sources, including solar thermal and photovoltaic (PV) panels, along with battery storage, into the MPC framework to enhance sustainability and reduce dependence on grid electricity.

- Expand the study to incorporate cooling applications: This research primarily concentrated on heating applications. Future investigations could broaden the focus to include cooling operations within the district heating network. Implementing model predictive control (MPC) in cooling systems could enhance performance and efficiency throughout the year, offering comprehensive solutions for both heating and cooling requirements.
- Expand the analysis to encompass the entire heating season and consider various climates: The study focused on three typical winter days for a specific climate to experience the MPC operation and its advantages. By extending the analysis to the entire heating season and considering various climates, it is possible to investigate the operation of the MPC under different load conditions and achieve seasonal cost savings.
- Expand the study by considering variable DH conditions: the MPC resulted in the effective utilisation of electricity dynamic pricing and load shifting in cases of constant conditions at the DHN side. However, both DH thermal energy costs and temperatures can vary throughout the day and season, which affects the overall system efficiency and operating costs. Future investigations could consider these aspects and their correlation with various substation operating schemes by incorporating them into the MPC decision-making process.

3.4 ENVI

The ENVI Live-In Lab, located at Environment Park in Turin, serves as an innovation hub dedicated to ecological transition and sustainable development. Environment Park is a technology park in Turin dedicated to sustainable innovation and ecological transition. It hosts companies, research centers, and laboratories focused on renewable energy, energy efficiency, and sustainable mobility. As part of the HYPERGRYD project, its energy monitoring infrastructure supports data collection on electricity, heat, and water consumption for ICT tool development and validation.

Figure 22 Live-in lab Environment Park (Turin-Italy)

In particular, the complex consists of 10 buildings, including 5 office buildings, 4 laboratories, and a canteen, all interconnected by an internal distribution network for electricity, heating, and cooling.

Figure 23 Main buildings within Environment Park

Within the HYPERGRYD project, the lab has been utilized to validate a multi-carrier energy model aimed at integrating thermal and electrical networks with renewable energy sources. The system includes a **District Heating and Cooling (DHC)** network, heat pumps, photovoltaic installations, a hydropower system, and all crucial components for testing the effectiveness of the developed solutions. This demonstration is part of **Task 5.4**, which focuses on validating the multi-carrier energy dynamic model at ENVI.

The methodological approach was structured around several key activities to ensure a robust validation process. **Task 5.4** played a central role in coordinating the demonstration, while **Task 3.5** contributed by developing the modeling tool applied in the ENVI LiL.

The process began with **real-time data acquisition** from the SCADA system, allowing continuous monitoring of energy system performance. The integration of a **digital twin**, developed using ENCO's SAInt tool, enabled the simulation of various operational scenarios, providing detailed insights into the interactions between thermal, electrical, and renewable energy sources.

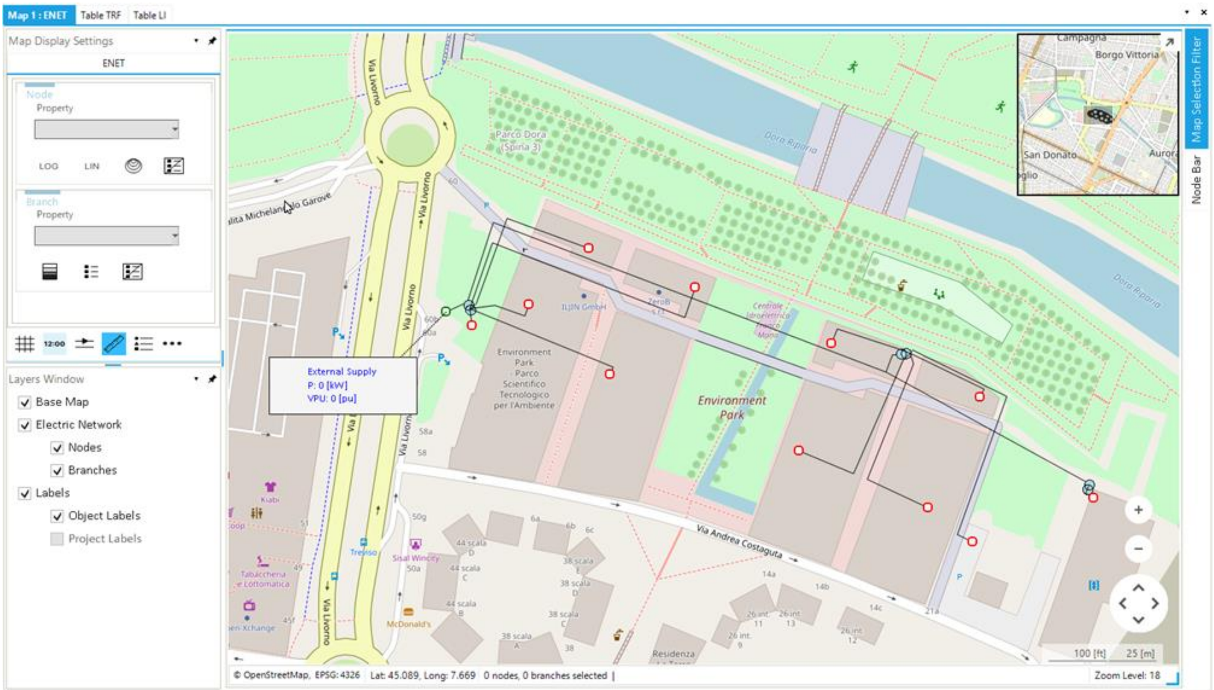

Figure 24 Model of the medium and low voltage electric distribution system of ENVI in ENCO. Red points represent nodes with electric demands

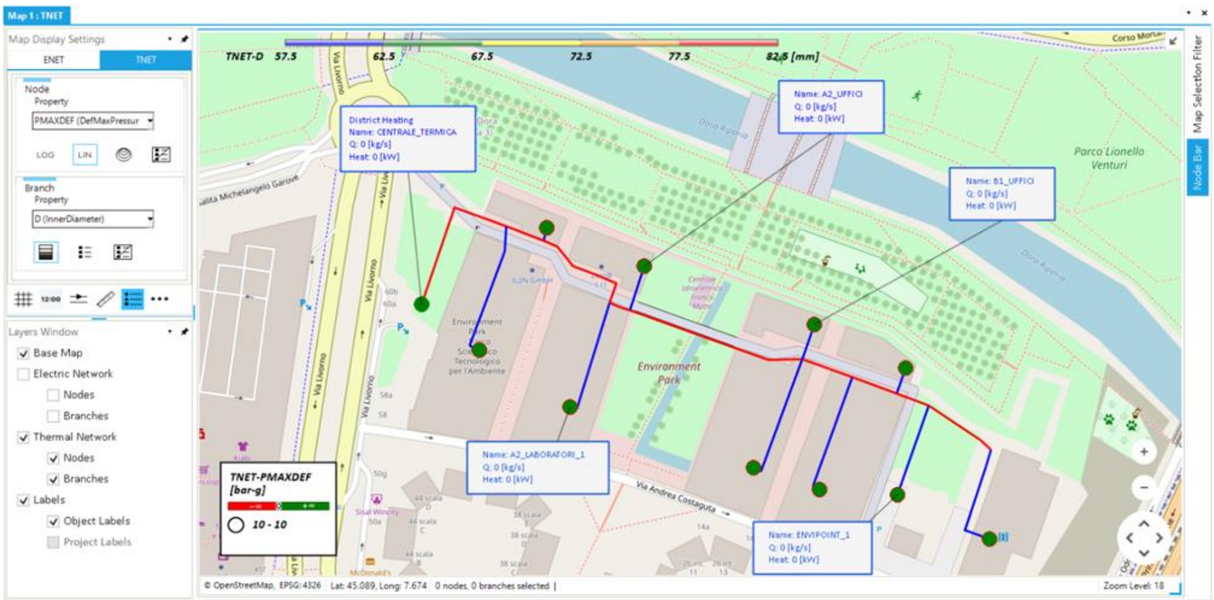

Figure 25 Mod Model of the thermal distribution network of Envi Park in SAInt. Nodes describe the supply or demand maximum hydraulic pressure

Active stakeholder involvement, including feedback from ENVI network operators and technology providers, was essential for refining the model's usability and adapting it to real-world conditions. The validation process involved multiple network configurations, stress-testing different operational strategies under varying energy demand and supply scenarios. The feedback loop with **WP4 -**

HYPERGRYD Digital Twin Platform as a Service ensured continuous improvements to the modeling tool.

The validation at ENVI LiL focused on three main use cases, each addressing critical challenges in multi-carrier energy network management:

- **Islanded Mode Operation**: this scenario tested the ability of ENVI to function autonomously, minimizing reliance on the external grid. The results demonstrated that a combination of hydropower and photovoltaics significantly contributed to self-sufficiency while ensuring grid stability.
- **Transition to 4th-generation DHC network**: the implementation of reversible heat pumps and optimized thermal distribution strategies resulted in increased efficiency and a reduction in energy losses. Lower supply temperatures improved overall system performance.
- **Integration of multiple energy carriers**: the demonstration evaluated the combined operation of CHP and thermal storage, enhancing flexibility and enabling more effective load balancing between electricity and heat networks. The results confirmed that a multi-carrier approach allows for better demand-side management and grid optimization.

The demonstration at the ENVI Live-In Lab successfully validated **multi-carrier energy models**, confirming their potential for seamless integration of renewable energy sources with thermal and electrical networks. The findings underscore the importance of **advanced ICT tools**, particularly **digital twins**, in optimizing hybrid energy grids. Collaboration among stakeholders, driven by the structured activities of **Task 5.4** and **Task 3.5**, proved essential in ensuring technical viability, economic feasibility, and overall system efficiency in modern **Smart Hybrid Grids**.

Additionally, as emphasized in deliverable **D5.5**, the availability and utilization of accurate data play a decisive role in enhancing system performance, making real-time data management an indispensable element for future energy communities.

4 Guidelines for replication

4.1 Modular HP with PCM storage (installed in KEZO LiL)

4.1.1 Purpose

The PCM-integrated heat pump system is a demonstrator for a new emerging technology aimed at small houses and apartments. The studies have demonstrated that coupling heat pumps with PCM storage can lead to significant energy savings and improved system performance, our research, for instance, indicates that integrating PCM storage with heat pumps can enhance the Seasonal Coefficient of Performance (SCOP) by up to 13%, depending on the building's heating demand. The technology demonstrator shows the technology is feasible and beneficial at the scale of households, with the following advantages and disadvantages:

Advantages

- The modular heat pump is designed to regulate power and heating capacity in a wide range, made possible thanks to the modular aspect which allows to disconnect individual heat pump modules.
- Regulation of efficiency is facilitated by the possibility to switch each compressor on and off, which eliminates the need to use expensive solutions, such as e.g. frequency inverters.
- Short-term heat storage based on phase change material RT57 (PCM) can store the heat for DHW, allowing it to be used for peak-shaving and peak-shifting when there is high heat water demand, e.g. in the evenings.
- Combining the modular heat pump with PCM storage gives more possibilities to physically fit the device in a limited space thanks to its compact format: with a base of 70 by 70 cm, the device has a height of 2.3m. In this configuration the requirement is a room of height min. 2.5m.
- Electrically, the modular heat pump uses 3 phases and is capable of equally loading phases.
- PCM storage is smaller than water TTES storage, so its main customer group are flats, small houses and offices, which have their own heating system and DHW production.
- Increased reliability and redundancy: parallel connection of the HP modules allows each module to work independently. If one unit would get damaged the others can work and ensure continuous heating or cooling.
- Scalability and flexibility: Adding additional modules in this parallel configuration is relatively easy, which allows to adjust the system to changing heating or cooling requirements without the need to do big changes to the infrastructure.
- Increased efficiency during partial loads: Working with many smaller units might be more efficient in case of partial load. The units might switch on or off depending on the needs, maintaining optimal efficiency and reducing the energy usage.

Drawbacks and barriers

- Increased initial investment: the purchase of the system is more costly considering the equipment and installation.

- Complexity of system management: coordinating the operation of multiple units needs advanced management systems to ensure equalised distribution of loads and prevent short cycles.
- Spatial requirement: each additional module takes some physical space. While each unit is rather compact, locations with very limited space may restrict the number of modules. In addition, while compact, the entire construction is still rather bulky and potentially problematic to physically fit through doors, etc. This could be mitigated, through e.g. on-site assembly, but the economic feasibility of this would need to be verified.
- Regulation issues and safety: R290 (propane) is classified as a flammable cooling agent, which requires following strict safety norms. For example, in outdoor uses the volume of the R290 agent is limited to 152 grams per 1 cooling circuit to minimize the danger of combustion.
- To summarise, the modular heat pumps in parallel configuration have many advantages, such as increased resilience, scalability and efficiency, but they also have some challenges like higher initial costs, increased complexity of the system, space limitation and elevated safety requirements. Careful planning and design are required to maximise the advantages, while at the same time reducing the problems.

4.1.2 Observed potential technical barriers for replication

During the testing phases of the demonstrator, several technical aspects and issues, some of which need to be considered while others may be a barrier for replication and need specific attention for practical implementations, were observed. These observed aspects and issues are

- PCM material and its characteristics. An appropriate PCM material should be selected depending on the heat pump and recipient parameters, because the RT 57 used here has a phase transition temperature of approx. 57 °C, which defines that the circuit has to be supplied with water of 62-65 °C. This is too high as a parameter for a modular heat pump, causing ineffective condenser cooling and thus high condensation pressure. This leads to overheating of the refrigeration compressors. Too high condensation pressure significantly reduces the efficiency of the heat pump COP.
- Heat exchanger in the PCM storage. It is necessary to select and design a suitable heat exchanger in the PCM storage made of a material other than aluminium as the aluminium plate heat exchanger poses challenges at the stage of production and operation. The process of welding plates in the heat exchanger is time-consuming, expensive, and requires a good specialist in this field. Thick aluminium sheets were used, which cause a significant increase in the weight of aluminium and a limitation/reduction of the amount of PCM material in the exchanger. During operation, the aluminium plates may also leak and PCM may leak into the water. The compatibility of the PCM material with the materials used in the heat exchanger is also important. The exchanger must be cheap at the production stage, durable during operation and compatible with the PCM material.
- Monitoring the temperature at the supply to the PCM storage. The PCM storage must maintain an appropriate temperature range to operate properly. If the system overheats or operates outside the desired temperature range, the PCM may not change phase as intended. It is

necessary to ensure appropriate temperature regulation by implementing a heat pump control system, i.e. regulating the amount of heat supplied depending on the charge level of the PCM storage, in order to reduce electricity consumption to a minimum.

- PCM storage capacity. The PCM storage size may be insufficient or of inadequate capacity for the specific needs of the customer or the heat pump capacity, which may limit the application and efficiency of the system. The capacity of the PCM storage should be adjusted to the individual needs of each customer.
- Control and monitoring system. The operation of multiple compressors requires more advanced control systems. Problems with electronic controls or sensors can cause the PCM storage system to malfunction, especially when managing phase change cycles or temperature. Appropriate quality flow meters and temperature sensors should be used to accurately estimate the state of charge of the PCM storage to ensure optimal heat pump operation. PLCs must manage inputs and outputs to control a complex system of several HP modules in parallel or serial connection feeding the PCM storage. Also, the data collection and processing speed in the PLC should be high to minimize delay.
- System complexity. The use of 8 compressor modules in the heat pump multiplies the number of connections and additional equipment, which in turn causes difficulties during assembly and implementation of system control. For this reason, the number of modules in such solutions could be limited, e.g. to a maximum of 4 modules. This should be feasible with a similar performance but requires that single modules will be more complex. For the construction and development of the demonstrator the use of simpler single modules was beneficial, for implementations this balance of complexity between the overall system and the individual modules should be evaluated.
- Heat losses. Due to the use of multiple modules/compressors, more pipes are needed to connect the heat exchangers and the modules. The larger number and greater total length of these pipes significantly increase the surface of the heat exchange with the environment, which results in increased heat losses. The number of pipes inside and outside the heat pump modules should be limited.
- Noise. In the case of multiple compressors, there may be a higher noise level compared to a single compressor unit. This can be an issue in apartments and other locations where the noise level should be limited. For such situations, tight enclosures with soundproofing mats should be considered.
- Installation and maintenance. Due to the complexity of the heat pump module system and PCM software, installation by a specialist in HVAC systems is required. In addition, it is necessary to provide detailed manual for heat pump maintenance with detailed troubleshooting. It should contain information and special instructions in case of the PCM or R290 refrigeration system leak. The modular system requires qualified technicians, which might cause more expensive maintenance.

4.1.3 Replication requirements and recommendations

Due to the unique design of the modular heat pump (propane as refrigerant) and PCM storage (RT57), operation and maintenance require special attention during both installation and ongoing operation to ensure safety, efficiency and reliability.

A site where the modular HP with PCM storage can be installed needs to fulfil a number of basic requirements:

- From connection point of view, the location needs to have a three-phase electrical connection, a freshwater connection and a cold source, in the form of local boreholes (ground-based thermal storage) or – better and more likely to be present in modern buildings – a 5th generation DHCN that has a cold source.
- It needs to be ensured that there is sufficient space for the installation of the modular heat pump and PCM storage. Proper airflow must be provided to cool the compressors housing. Access to each HP module and PCM for maintenance and repair must also be provided. Conduct a thorough site analysis to meet the requirements for 3-phase electrical power and available space.

There are however additional requirements to the location and installation as such:

- Safety related to the refrigerant used (propane). Propane (R290) is a flammable refrigerant. During installation, it has to be ensured that the heat pump is installed in accordance with the manufacturer's guidelines and local safety regulations for flammable refrigerants. All sources of ignition near the system have to be avoided.
- Ventilation. Proper ventilation is essential to prevent the build-up of flammable gases. Ensure that the installation site is well ventilated and meets R290 safety standards.
- Leak Detection. During installation, ensure that all refrigerant lines, connections and valves are checked for leaks to prevent possible leaks.
- Qualified Technicians. Only qualified technicians who are trained in the use of flammable refrigerants should install and service the system. They must be familiar with specific safety procedures for working with R290.
- The electrical connection has made in accordance with the heat pump specifications and local regulations. This includes properly sizing the cables for the load generated by all compressors and pumps.
- Water and refrigeration lines should be properly insulated and protected against damage. Check the tightness (leakproof-ness) of the installation by locating any leaks and performing a pressure test.

Prior to commissioning an installation, it is necessary to calibrate and test the various control systems:

- Advanced Control Systems. Modular Heat Pumps with Storage PCMs utilize advanced control systems to ensure optimal operation (e.g. compressor switching control and thermal storage management). Ensure that these controls are properly installed and calibrated.

- Temperature Sensors. PCM systems rely on accurate temperature monitoring. Ensure that all temperature sensors are installed in key locations to ensure proper operation of both the PCM and the modular HP.

4.2 Sorption Storage (installed in KEZO LiL)

4.2.1 Purpose

The sorption storage uses, as storage material, a composite made by impregnation of silica-gel with $CaCL_2$. The general layout consists of a reactor with the storage material and an evaporator/condenser. The working fluid is water. When heating up the material, heat is stored and – at the same time- condensation heat is released in the range of 30-50°C. When supplying the evaporator/condenser with an energy source and, at the same time, the storage material is cooled down, it is possible to release the stored heat at a temperature suitable for low-temperature heating systems (30-40°C). At the same time, the cooling effect at the evaporator can be exploited. Such features makes it useful in various applications such as temperature control (peak-shaving and peak-shifting) or energy storage. With the selected configuration for HYPERGRYD (2 reactors, separate condenser and evaporator), it can also be used to generate heat and cold simultaneously. As such, it can operate in summer and winter periods. Therefore, integrating sorption heat storage (Sorption Thermal Energy Storage – STES) into heating systems offers many advantages, enabling efficient heat storage with minimal losses; the demonstrator generally revealed the following advantages and disadvantages.

Advantages

- **Compact.** The compact design of the SORTEC heat storage with dimensions of length 2.5m, width 1m and height 1.9m provides many application possibilities, e.g. in single-family houses, industrial plants, office buildings, wherever garage or industrial space will be available.
- **Scalability.** The storage can be scaled with the required needs, it however needs proper planning – see the related drawback design further on.
- **Long term storage.** Sorption materials can store thermal energy for a longer period of time with little heat loss, which makes it possible to use them as weekly or monthly energy storage.
- **Integration with RES sources.** STES systems can effectively store energy from renewable sources such as solar collectors, increasing the sustainability of heating systems. This is especially beneficial during the period when they can provide chilled water to the cooling system of the building.
- **Cooling production.** The design of the sorption storage provides the ability to produce cold for the cooling the facility, and while at the same time the heat sink can be used to heat water.

Drawbacks and barriers

- **Complex design.** Implementing STES requires complex system configurations, including reactors and heat exchangers, which can complicate design and maintenance and affects different aspects.
    - **Connection.** Connection to 1 high-temperature source supplying STES (heating device or waste heat) and 2 receivers, i.e. low-temperature heating and cooling installations of the building, is required
    - **Restrictions on the storage supply.** The SORTEC storage must be supplied with a medium at a temperature of 70-90°C from a high-temperature source, which significantly limits its field of application in traditional heating systems: it cannot be supplied from typical heat pumps or condensing gas boilers.
    - **Scalability.** With an increase in the capacity of the heat storage, the design of an efficient heat exchanger becomes more complex, since it needs to provide fast heating/cooling of the storage material. For an increasing amount of storage material, this requirement can lead to the need for bulky and heavy heat exchangers.
    - **Necessity of working in a vacuum.** The operation of the storage requires a cyclic generation of vacuum using a vacuum pump. It is therefore necessary to ensure super-tight connections between components and to provide automatic valves controlling the flow between the circuits, so that the vacuum pump does not turn on frequently (the operation of the vacuum pump uses electricity, which decreases efficiency of the device).
- **Cost.** Materials and technologies used in STES can involve higher initial investments compared to conventional heat storage methods. However, the possibility of mid-term heat storage provides some additional advantages that should be taken into account.
- The complex design comes with a need for high quality components.
    - **Construction.** High-quality corrosion-resistant materials should be used, especially for the materials that need to be resistant to the sorption material used in the reactor, to high negative pressure, etc. The appropriate type of sealing of connections between components and measurement and control equipment should also be selected.
    - **Material durability.** The performance/efficiency of sorption materials can deteriorate over time during use, which can affect the performance and life of the system.
    - **Control and regulation.** Dedicated activities to control sorption systems have not yet been targeted in the literature/market, which means there is limited information on how to properly control the storage.
- **Installation planning.** A detailed plan for installation and integration with the existing heating system needs to be developed, taking into account the available space, energy capacity and safety regulations.

4.2.2 Observed potential technical barriers for replication

The testing phases of the demonstrator revealed several technical aspects and issues, some of which need to be considered while others may be a barrier for replication and need specific attention for practical implementations. These observed aspects and issues are:

- **Adsorption material and its characteristics.** An appropriate adsorption material with appropriate sorption capacity and charge/discharge temperatures should be selected so that the heat adsorption process is effective and to accumulate as much heat as possible.
- **Heat exchanger in the sorption storage.** The heat exchangers used in the reactor must have a large heat exchange surface area throughout the reactor volume, and, to ensure effective operation, non-corrosive materials should be used.
- **Tightness of the construction.** Leaks should be reduced to a minimum by using appropriate seals in each element of the storage. Micro leaks cause the inflow of outside air, which disrupts the processes occurring in the reactor. This increases the need to turn on the vacuum pump, which causes a larger electrical energy consumption and thus reduces the efficiency of the system.
- **Storage capacity.** In order to increase the economic viability and use STES for as long-term as possible, the storage capacity should be increased several times compared to what was available in the demonstrator.
- **Control and monitoring system.** The inherently transient operation of the sorption storage requires 1-2 s intervals for speed of data collection and processing in the PLC.
- **Cavitation phenomenon.** The hydraulic system should be carefully calculated and designed in terms of phenomena occurring in high vacuum conditions, including cavitation. The occurrence of cavitation should be avoided because it can contribute to the rapid degradation of water pump impellers and thus to their damage. An appropriate type of circulation pumps with increased durability should be selected. This is a characteristic specific to the patented design from Sorption Technologies.
- **Noise.** Higher noise levels may occur during operation of the vacuum pump. This may be a problem in rooms with limited noise levels. Tight enclosures with soundproofing mats should be considered in such situations.
- **Installation and operation.** Due to the complexity of the sorption storage system, installation by a specialist in HVAC systems is required. It is also necessary to provide a detailed operating manual along with a troubleshooting guide. It should also contain additional information or special instructions in the event of a leak in the installation. The complex design requires qualified technicians familiar with more the complex operation, control systems and diagnostics, which may result in higher service and possible repair costs.

4.2.3 Replication requirements and recommendations

Due to the very complex design of the sorption heat storage, operation and maintenance require special attention both during installation and ongoing operation to ensure safety, efficiency and failure-free operation.

A site where a sorption storage can be installed needs to fulfil a number of basic requirements:

- Connection-wise, the location needs to have a three-phase electrical connection, and connections to the three required hydraulic systems: the high temperature (HT) supply, the heat collection (MT) and the cooling collection (LT).

- There needs to be enough space for the sorption storage installation. Access to both the automation system, the reactors, the heat exchangers, and the pumps must be provided to allow for maintenance and repair work.

There are however additional requirements to the location and installation as such:

- The electrical connection has made in accordance with the heat pump specifications and local regulations.
- Water pipes should be properly insulated and protected against damage. Appropriate insulation should be used for the pipes at temperature to prevent heat loss and condensation of water vapor from the environment. The tightness of the installation should be ensured by locating any leaks and conducting a pressure test.
- The sorption storage makes use of advanced control systems to ensure optimal operation, e.g. to control of 3-way valves, and to manage the adsorption and desorption process in two heat storage reactors. These controls need to be properly installed and calibrated.
- The heat storage systems rely on accurate monitoring of temperature and pressure. Ensure that all temperature and pressure sensors are installed in key locations to ensure proper operating parameters.

Prior to commissioning an installation, the various systems need to be tested and calibrated

- Before starting the system, all connections, pressure levels, working fluid quantity and control system settings need to be inspected.
- Check the parameters and performance of the sorption storage during operation. The performance of the system depends to a large extent on maintaining correct operating conditions. Make sure that the system operates within the designed temperature and pressure range, avoiding extremes that could affect the system's performance or lead to system failure. Check the frequency of the vacuum pump use: its frequent operation may indicate a leak in the system. Any alarms displayed on the device controller should be read and the cause should be eliminated. High-risk alarms should be appropriately resolved immediately.
- Servicing of the sorption storage service should occur at regular intervals to check the general technical condition of the system, detect irregularities in the refrigeration system or in the storage, check the system's operating parameters based on historical data, and ti make any changes to the control system. Any identified failures or elements requiring replacement in the near future should be taken care of to prevent a larger failure, e.g. of the entire system.

5 Conclusions

This deliverable presents the main results of the research work carried out in the four Live-in-Labs in three different climate zones within the HYPERGRYD project. These activities aimed to demonstrate new technologies for heat generation and storage, and to demonstrate and validate ICT models and tools for the management and optimization of integrated heat and electricity networks in Local

Energy Communities (LECs), which supports the modernization of district heating systems to 4th and 5th GDHC.

Demonstration and validation of the ICT tools for the management of heat and energy networks in the local energy communities were carried out at the Live-in-Lab SONNE in Austria. The main objectives were to optimize energy flows and integrate renewable energy sources (RES) into integrated heat and electricity networks. The key points and benefits resulting from the implementation of ICT tools and the analyses performed are as follows:

- The use of ICT tools such as BIM-GIS, exergoeconomic tools, AI, and edge-computing algorithms enabled accurate modeling of the DHC network and RES. Thanks to simulations using ICT tools, real-time data from PV systems, and energy prices, peer-to-peer (P2P) trading tests were conducted. These showed significant benefits for local market participants.
- The simulation of the local energy market showed that the activation of P2P trading contributed to improving the electricity and heat costs by 145% and also increased self-sufficiency (up to 124% in summer due to PV production). The use of intelligent trading strategies, such as virtual heat pumps, yielded reduced costs and significantly improved self-sufficiency rates.
- The use of ICT tools enabled the analysis of various scenarios in electricity, gas and heat networks, which contribute to the reduction of heat losses, the costs of using devices and facilitates the integration of distributed RES systems.
- Continuous feedback from project participants, including households, municipalities, DHC operators and electricity grid operators, has allowed for the improvement of HYPERGRYD tools and services. Collaboration with different stakeholders has revealed important technical and non-technical aspects related to the implementation of solutions.
- The results indicate that, despite the interest in sustainable initiatives, there are barriers such as administrative complexity and high upfront costs that can hinder full participation in advanced energy management systems. Understanding user needs, simplifying implementation and transparent communication of benefits are key to engaging local communities.
- Addressing regulatory barriers, user education and cost-sharing mechanisms are essential to ensure wider adoption and long-term success of innovative energy solutions.

The conclusions of work carried out within Task 5.6 at ENVI Live-In Lab in the Turin Environmental Park underline the importance of innovation in sustainable development and ecological transition. The project validated the effectiveness of energy models and tools based on multiple energy carriers, which enable the integration of renewable energy sources into thermal and electrical networks. The analysis carried out at ENVI LiL provided valuable information on three key operational scenarios: autonomous system operation, transition to a fourth generation heating network and integration of different energy carriers. The results showed that the appropriate combination and mix of PV and hydropower with energy storage contributes to the system's self-sufficiency, while the use of heat pumps and heat distribution optimization strategies increases efficiency and reduces energy losses.

Within the HYPERGRYD project, a Digital Twin Platform was implemented for SONNE and ENVI LiL. It was developed by IDP to improve the usability and stability of different tools developed by GSY, KTH, GET and ENCO. The platform is a digital twin of real heating and electrical grid with historical data, real-time data and continuous feedback for simulation of the LEC.

Demonstration activities were carried out within in Task 5.3 at KEZO Live-in-Lab in Jabłonna in Poland, focused on defining KPIs for benchmarking new technologies and validating developed models and control strategies. The tested technologies, including a modular heat pump with PCM storage, and sorption storage, showed many possible applications. The main conclusions from these studies are as follows:

1. Modular heat pump with PCM storage:

- The water source heat pump (WSHP) should have the borehole storage (BTES) as the lower heat source. Such a solution is proposed in the new generation 5th GDHC systems.
- The tests of modular HP showed a low efficiency due to: i) additional heat exchangers causing heat losses; ii) high inlet temperature at the PCM storage (above 60°C) which is at the maximum temperature achievable with the heat pump with R290; the maximum value of COP achieved during heating mode was approximately 2.0, and the total COP during charging mode of PCM obtained below 1.5.
- It was shown that the PCM storage is charged with relatively low power and for a long period of time of approx. 1 hour, but it has the ability to quickly discharge to provide DHW at up to 15 l/s. The maximum energy storage efficiency in the PCM reached around 85.5%.

2. Sorption storage:

- The sorption storage must be supplied from a high-temperature source HT with a temperature around 70-90°C (in the KEZO case the supplied temperature was 80-85°C. It is also necessary to provide the possibility for the discharge of medium-temperature heat MT, e.g. to the building heating system with fan coils or floor heating, and ensure a feed to the low-temperature system LT, e.g. in order to cool the facility. This is because the HT and MT circuits must operate during the charging of the storage (when the sorption process occurs), while during discharging phase it is necessary to operate the MT and LT circuits (desorption process).
- The sorption storage has 2 operating modes: i) as a thermal storage, ii) simultaneous as a heat storage and heat and cold production.
- The storage capacity was 8 kWh, and the maximum energy storage efficiency reached 67.3%. It was shown that the time of fully charging the sorption storage is approx. 1.5 hours with a power of approx. 5kW; similar parameters were obtained during the discharging phase.
- The ability to store thermal energy both short-term and long-term was demonstrated.

ICT tools to manage and optimize the operation of the modular heat pump of the PCM storage and the sorption storage enables greater flexibility in energy and heat management. Such actions significantly contribute to reducing CO2 emissions and increasing energy efficiency, which supports sustainable development goals. Test results and obtained KPIs indicate areas for further optimization, which may lead to improving the technologies and increasing their efficiency in the future. In summary, the demonstration activity conducted at KEZO LiL provided valuable information on the performance of modern solutions in heating and cooling systems, highlighting both their potential and the challenges that need to be overcome to maximise the benefits of their application in integrated energy systems.

Based on the analyses carried out at the Eurac Live-in-Lab in Bolzano, Italy, within the framework of Task 5.3, key information on the performance and potential improvements of Model Predictive Control (MPC) for decentralized District Heating (DH) substations was provided. The main conclusions drawn from the analysis are as follows:

- MPC outperformed the conventional Rule-Based Control (RBC) approach by reducing electricity costs and achieving significant savings. This was achieved by shifting Thermal Energy Storage (TES) charges to periods of lower electricity prices while still meeting power demand. MPC effectively uses dynamic pricing and load shifting to optimize the operation of heat pumps and TES. This reduces operating costs and shifts energy consumption to off-peak periods, improving overall system efficiency and streamlining demand-side management.
- Continuous substation component's model training ensures the system adapts to changing conditions and remains accurate, maintaining optimal performance over time. Additionally, accurate thermal load forecasting is crucial for effective MPC operation. Using artificial neural networks (ANN) to develop a reduced-order model (ROM) enables accurate and adaptive forecasts, thereby improving system responsiveness and efficiency.
- Research suggests that exploring different substation schemes, such as temperature-based transitions and the use of hysteresis methods, improves system efficiency by facilitating smoother operational transitions. These improvements contribute to better substation efficiency and reduced operating costs.
- There is a need to optimize the size and operation of thermal storage to improve the system efficiency and performance. Moreover, integrating renewable energy sources with thermal and electrical storage in MPC can increase sustainability and reduce the dependence on grid electricity.

In summary, the study highlights the significant benefits of MPC in DH systems, especially in terms of cost reduction, efficiency and adaptability. However, there are several areas for improvement, including equipment durability, renewable energy integration, and expansion into cooling applications, suggesting that future research should focus on these aspects to further enhance system performance.

The HYPERGRYD project has successfully demonstrated the potential of advanced ICT tools for the optimization and integration of renewable energy sources in heat and electricity networks. Validation of these tools contributed to a better understanding of the challenges and opportunities related to the implementation of modern energy solutions. The involvement of stakeholders and continuous exchange of information played a key role in improving the models and adapting them to real conditions. Collaboration between project teams, as well as the use of advanced ICT tools such as digital twins, were essential to achieve technical feasibility and economic viability of the solutions.

The conclusions from this project provide a solid basis for future actions aimed at transforming energy systems towards greater efficiency, cost reduction and improved grid stability.

6 References

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