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District heating substations integrating heat pumps: opportunities and experiences with hardware-in-the-loop testing procedures.

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Abstract

This paper presents a comprehensive overview of a Hardware-in-the-Loop testbed and testing procedure applied for developing district heating substations integrating heat pumps. The study highlights the distinctive features of the testbed, offering an in-depth analysis of its capabilities to support the design and performance evaluation of the considered district heating substations.
The paper delves into four different configurations demonstrating the flexibility of the Hardware-in-the-Loop approach, ranging from substations that include all components to those with some components emulated. The first case is a substation that includes heat pumps and two thermal energy storages while the second case includes a heat pump and a storage. The remaining two hybrid configurations both employ a real bidirectional substation: in the first, the heat pump is emulated based on numerical models, while in the second, real-time monitoring data are used from a heat pump located in a different facility.
The described testing procedure emulates both the district heating network and thermal load according to realistic profiles, enabling the analysis of the district heating substation's operation under dynamic conditions that mimic real-world applications. The study involved a series of experiments designed to simulate real-world operational conditions, including peak load demands and partial load operations.
Within this framework, various control methodologies, such as Rule-Based Controls and Model-Predictive Controls, were tested, analyzed in detail, and compared. Furthermore, the paper discusses the technical challenges encountered during the integration process, including system compatibility, control strategies, and maintenance requirements. Solutions, improvements, and best practices derived from these experiences are also presented, providing valuable insights for future implementations of similar systems.
Overall, the laboratory tests underscore the potential of the implemented testing procedure in advancing sustainable energy solutions and improving the overall efficiency of district heating networks, particularly through the integration of heat pumps and the application of advanced control strategies.

Keywords: Hardware-in-the-Loop testbed;Heat pump: District Heating substation;Dynamic testing;Control strategies.

1. Introduction

The decarbonization of the heating sector is a critical pillar of the global energy transition, with district heating (DH) systems playing a significant role in enabling the integration of renewable energy sources (RES)

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and improving energy efficiency in urban environments. Among the technologies driving this transformation, heat pumps (HPs) have emerged as a cornerstone due to their ability to utilize low-grade heat sources and operate efficiently across a wide range of temperatures [1-2]. Their integration into DH systems—both centralized and decentralized—offers significant potential for reducing greenhouse gas emissions and primary energy consumption [3]. Recent studies have demonstrated the feasibility and benefits of retrofitting existing third-generation DH systems, traditionally reliant on gas-fired boilers and combined heat and power (CHP) units, with medium-scale HPs. For instance, Požgaj et al. (2025) demonstrate that retrofitting existing gas-fired DH systems with medium-scale HPs can reduce primary energy consumption by over 50%, with favorable payback periods under optimal electricity pricing [4]. Similarly, Soleimani et al. (2025) found that hybrid HP-DH systems can achieve operational cost savings of up to 27% and CO_2 reductions of over 32% [5].

A promising configuration involves integrating HPs at the substation level, where thermal source networks [6] are found feasible, operating at ambient loop temperatures. These systems rely on building-level HPs to meet specific heating and cooling demands, often supported by thermal storage and smart control systems [7], [8]. Other configurations consider the integration of the HP in DH substation coupled with local energy sources such as RES or waste heat (WH) [9]. In this case, the HP acts as a booster for local energy production, aiming to increase the self-consumption of RES. Advanced control strategies, such as model predictive control (MPC), have been shown to improve energy efficiency and grid flexibility in these configurations significantly [10].

A series of studies on the operational efficiency of heat pumps, based on monitoring data, has revealed significant discrepancies between the operational data and the predicted data derived from standard steady-state and quasi-steady-state tests [11]. These notable deviations are primarily due to several factors: i)the neglect of the dynamic behavior of heat pump systems [12]; ii)the failure to consider the influence of control strategies within the heat pump's internal controller [13] on the transient behavior of the systems [14]; iii)the omission of additional heat loss elements during testing, such as the efficiency of storage tanks [15], thermal losses from connecting pipes and improper hydraulic configurations. These factors contribute to a gap between expected and actual performance, highlighting the need for a more comprehensive evaluation of heat pump systems by adopting a dynamic performance testing procedure.

Testing control strategies under realistic conditions is critical for optimizing system performance. Advanced algorithms, including MPC and reinforcement learning, are increasingly applied to DH systems to improve energy efficiency and operational flexibility [16-17] .These strategies must be validated not only through simulation but also through experimental testing.

Hardware-in-the-Loop (HiL) testing has emerged as a powerful tool for this purpose. HiL platforms enable real-time interaction between physical controllers and simulated DH environments, allowing for the safe and repeatable testing of control algorithms under a wide range of scenarios. Recent studies have demonstrated the effectiveness of HiL in replicating the dynamic behaviour of HPs [18-19] and of DH substations [20-21] and validating control strategies prior to field deployment.

This paper builds upon these advancements by presenting a dynamic test procedure tailored for various configurations of DH substations integrating HPs. The procedure employs HiL techniques and is designed to evaluate the performance of control strategies under transient conditions, ensuring that the system maintains stability and efficiency across a range of scenarios. The paper is organised in several sections: section 2 showcases the HiL testbed, the testing procedure and the tested DH substation configurations; section 3 presents the main results deriving from applying the testing procedure, while section 4 provides a summary of the conclusions.

2. Method

2.1. Description of the testbed

The testbed considered in this study is the Energy Exchange laboratory of Eurac Research. It is located in Bolzano, in northern Italy. The lab's layout is shown in Figure 1. It consists of three main parts: energy production systems comprising a gas boiler coupled with a solar thermal system, an Organic Rankine Cycle (ORC) unit, and an absorption chiller. This combination enables a grid-connected trigeneration system to be replicated and tested, allowing the study and optimisation of the use of non-programmable thermal and electrical energy sources. The second part is the energy distribution system, a small-scale district heating network (DHN) that can emulate both conventional and low-temperature networks by integrating multiple heat sources and users. Lastly, the user substation consists of two electric HP, which allow simulating the behaviour of prosumers who take heat from the DHN or feed heat into the low-temperature DHN, with excess heat rejected through a dry cooler. In this way, it is possible to investigate interfaces where end users can extract energy for space heating (SH) and domestic hot water (DHW) production and feed energy back into the grid when the heat pump is inverted. Moreover, the heat pumps can be bypassed, providing a direct connection between the DHN/energy production system and the dry cooler, which is managed via flexible pipes, allowing for easy integration of the system for testing, such as DH substations. Three-way mixing valves, variable-speed pumps, flow rate and temperature sensors are installed along the hydraulic circuit to independently control operating conditions (temperature, flow rate, thermal power) at the different interfaces, with PID control.

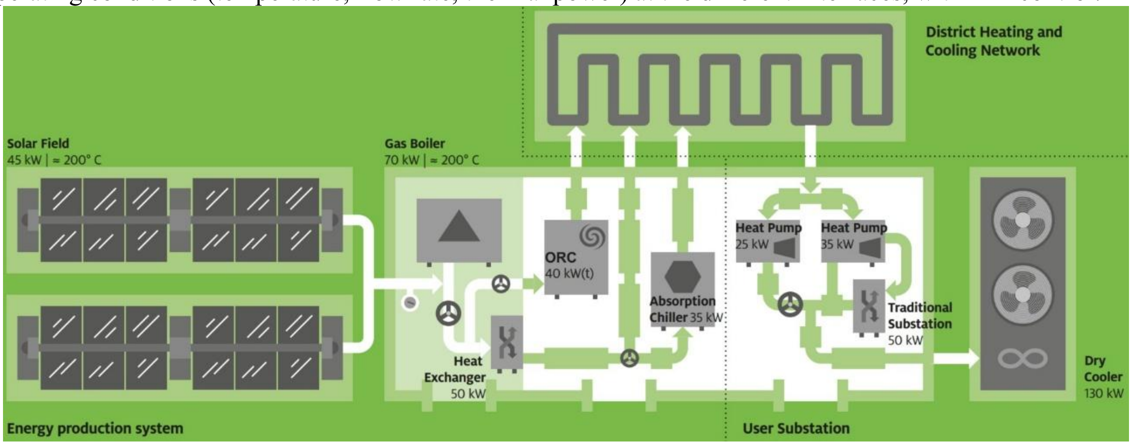

Figure 1. Energy Exchange laboratory layout

LabVIEW and various electronics (e.g., National Instruments, SENECA) at Eurac Research are used to implement the testbed's control and data acquisition systems, based on in-house expertise. This allows easy adaptation of the laboratory Plant Control Software (PCS) to integrate a unit under test (UUT) and exchange data. To test the unit under realistic operating conditions, a basic HiL infrastructure, called TiLoop (TRNSYS-in-the-Loop), has been developed and integrated into the Energy Exchange PCS to connect TRNSYS dynamic simulation software to the laboratory's real-time plant controller. One benefit of this framework is that the PCS maintains complete control over the simulation's progress, avoiding all synchronisation issues when the simulation step is sufficiently short. Another benefit is that it enables the overall control system to sustain a sampling time of about 2 seconds. This is achieved because the connection to the TRNSYS kernel is not established via file I/O (which would be slow), but solely through in-memory operations. Specifically, TiLoop adopts a client-server architecture, where the PCS serves as a communication client, and the server is an in-house-developed application that enables running a TRNSYS simulation within a controlled environment (OS process) over a communication channel (currently TCP/IP; other protocols are theoretically feasible). Data transfer between the PCS domain (written in LabVIEW) and the TRNSYS domain (written in Fortran and C++) is managed using in-memory buffers. It is decoupled via a TCP/IP communication framework, ensuring high performance for local connections.

The laboratory's flexible infrastructure (hardware and software) supports testing a variety of systems, including low-temperature district heating networks powered by multiple energy sources, as well as district heating substations integrating heat pumps and control strategies. This makes it an ideal setup for experimentally exploring the operational range and performance of heating and cooling systems.

2.2. Testing procedures

Apart from standard stationary tests, which help assess the system's performance under stationary conditions, it is possible to conduct more dynamic, realistic tests using predefined or real-time emulated profiles in a HiL manner on both the generation and user sides.

The dynamic test performed under predefined stated boundary conditions consists of emulating a time series of inlet water temperatures, water flow rates, or load at the connection point of the UUT. For predefined emulated loads, the UUT supply temperature and flow rate are measured, and the return temperature is calculated and provided as a set point to the laboratory. The predefined boundary conditions can be customised according to the UUT's functionality (e.g., a step change in temperature to test the operation of a control), or defined through numerical simulation by modelling and simulating the whole system and then extracting the boundary conditions from the simulation results, to be used as input in the laboratory as predefined time series.

Dynamic tests under predefined boundary conditions enable the verification of controller operations, the definition of a performance map and a numerical model, and the development of advanced control that accounts for the UUT's dynamic behaviour.

The system test in a TiLoop manner involves extracting a short sequence of boundary conditions from a climatic file and emulating loads, generations, and components in real time. Although the TRNSYS-in-the-loop testing procedure covers all the outcomes mentioned for the predefined boundary condition tests, it is primarily used to characterise the system under realistic boundary conditions and to assess performance over the year. This is done by extrapolating results from specific test days, as described in [22]. The number of test days considered is typically 6, representing the variability of climatic conditions throughout the year. This number allows for a relatively short test duration, ensuring sufficiently precise extrapolation of the yearly behaviours of the studied system. In a test in TiLoop mode, a numerical simulation is run in parallel with the laboratory controller. For a simulated load, the supply temperature and flow rate are measured in the laboratory and provided as inputs to a simulation model. The simulation model's output, e.g., the return temperature, is communicated to the laboratory, which uses it as a reference for its controller. A dedicated circuit reproduces the emulated component in this way.

2.3. Tested configuration description

A description of the four configurations of the DH substation integrating HP, as tested in the described testbed, is presented in the following sections, in accordance with the proposed testing procedure. Configurations 1 and 2 are specifically designed to be coupled with low-temperature district heating networks (LTDHNs), being essential components for the distribution of thermal energy, as they adjust the temperature of the energy distributed in the network to meet the specific heating (SH and DHW) or cooling needs of each building, acting as a prosumer.

Configurations 3 and 4, instead, consider a bidirectional DH substation connected to the DHN, to a distributed generation (DG) system, and to the user. In this configuration, the DG acts as a source for the HP, whose energy produced satisfies the load or is injected into the DHN.

2.3.1. Configuration 1

In the REWARDHeat project, Danfoss A/S and Eurac Research developed a prefabricated substation for residential and tertiary applications, in which the HP is hydraulically connected to the DH and the building via pipes and valves in a way to enable optimal utilisation of the HP, hence the system's coefficient of performance (COP), for given DH supply and building load temperatures. Figure 2 shows a simplified conceptual flow diagram representing the main components of the substation: main water-to-water high temperature HP (70 kW capacity, 55°C as maximum evaporator inlet temperature and 90°C as maximum condenser outlet temperature), thermal energy storage (TES) for SH/SC circuit (1000 l), DHW storage (1000 l) and dedicated DHW circulation booster HP (2 kW, outlet temperature up to 55°C). This combination particularly aims to enhance the concept's adaptability for operation over a relatively wide range of network temperatures.

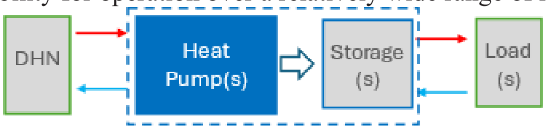

Figure 2.General concept of DH substation (blue dashed line box) considered for configurations 1 and 2, and connections with the Energy Exchange lab (green boxes)

Two main concepts are remarked in the design:

- Split-flow layout for the HP connection. This enables an efficient operation of the HP under certain temperature conditions of the network and the demand-side distribution system by dividing the fluid flow rate from the network into two supply streams: one to the evaporator and one to the condenser. The supply to both heat exchangers minimizes the temperature lift and improves the HP COP. Moreover, by reducing the temperature lift in the HP condenser, this configuration enables the exploitation of the temperature level of the network at its maximum and reduces the share of the heat demand that should be covered by the HP. At the same time, the hydraulic layout allows for operating the HP with a standard connection (i.e., evaporator with DHN and condenser with TES) or bypassing it by having a direct connection between DHN and TES to satisfy the load.

- Circulation booster for DHW recirculation dedicated management. It aims to cover the heat demand from DHW recirculation with a dedicated small HP unit. The circulation booster avoids DHW circulation from impacting the DHW storage by means of rapid discharge and loss of thermal stratification. Thanks to the separate small HP, the DHW circulation temperature is maintained.

The substation was tested in the Energy Exchange Lab before being installed at a demonstration site. It was hydraulically connected to the lab through flexible pipes. The connection points are the DH supply and return, the SH supply and return, the DHW supply and return, and the recirculation.

The lab infrastructure allows for control of the inlet temperature to the substation in the DH supply, SH return, and DHW recirculation, as well as the flow rates. The DHW return is instead directly connected with the water main. The laboratory's monitoring system can also monitor all temperatures and flow rates at the connection points. The substation has built-in monitoring and control systems comprising temperature sensors, flow meters, heat meters, electric meters, motorised valves, and electronic controllers. The controllers include web-based communication, remote control options and data acquisition. A dedicated bidirectional communication with the testbed control software has been implemented.

2.3.2. Configuration 2

The second DH substation considered in this work has been designed to have the same split-flow layout for the HP connection as the first substation and a comparable conceptual scheme, as described in Section 2.3.1 and Figure 2. The main components of the substation are a water-to-water HP and a SH TES (1250 l). The HP has a nominal heating capacity of 25 kW, a maximum allowed evaporator inlet temperature of 55°C, and a maximum condenser outlet temperature of 80°C. The substation is connected to a circuit that emulates the DHN and a circuit that emulates the SH load.

An in-house developed LabVIEW software is dedicated to overseeing the substation operation modes and the HP status, which affects the SH tank's charging and discharging. This software interacts in real-time with the Energy Exchange lab software through text files, exchanging variables in both directions. This control is defined as Rule-Based Control (RBC). The substation software has also been designed to interact with a third software, namely a MPC simulation compound elaborated in Python, aimed at mimicking the operation of each system component and optimising the TES set point in a future receding horizon of up to 24 hours. In this method, a RBC manages the operation of the substation, while the MPC adjusts set temperatures to trigger TES charging. This adjustment expedites or delays the HP activation. The interaction with the substation control software is through text files, and variables are exchanged in both directions. The MPC software emulates the lab architecture and evaluates different control options. The most favourable TES set point temperature is then fed back to the substation control software. Figure 3 summarizes the interactions between the three software and includes the predefined inputs used during the tests. In particular, SH_load is the SH load reference profile, T_DHN is the DHN supply temperature reference profile, T_out is the outdoor temperature reference profile and El_price is the electricity price profile. The first two are used as input for the MPC and the Energy Exchange lab software, where they are emulated. Moreover, the figure also shows the execution time of each software during the tests, which is 10 minutes for the MPC, 1 minute for the substation and 2 seconds for the Energy Exchange Lab.

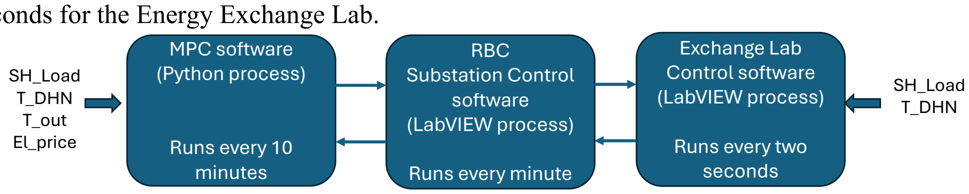

Figure 3.Summary of the interaction between the three software

2.3.3. Configuration 3

The third configuration considered and tested comprises a bidirectional DH substation acting as a thermal prosumer. The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) designed the substation in collaboration with Eurac Research. Figure 4 illustrates the conceptual scheme of the substation (blue boxes) and its connections with the testbed, which emulates the loads (SH and DHW), the DHN, and the DG system (solar field, solar TES, and HP).

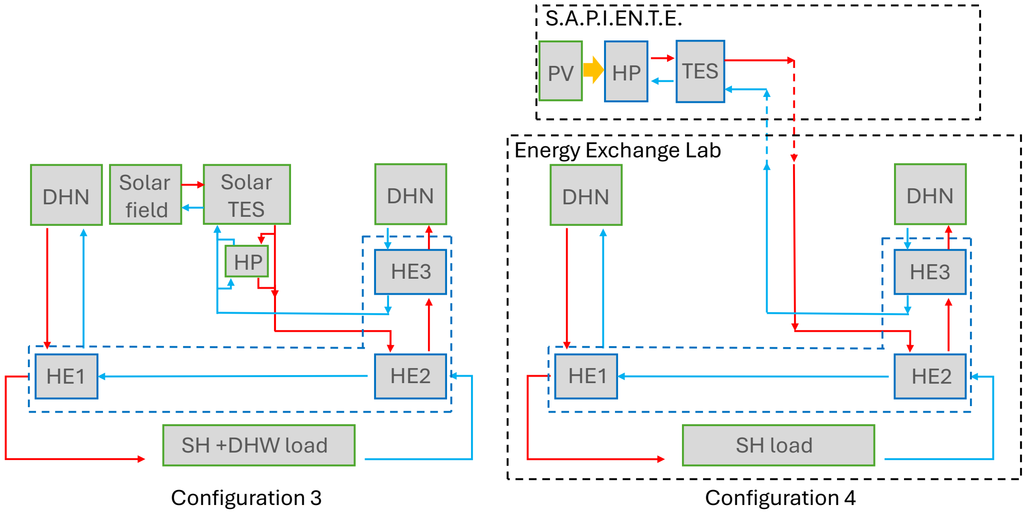

Figure 4.General concept of bidirectional DH substation integrating HP and HiL set up for configuration 3 (left) and 4 (right)

The substation is designed to optimise the utilisation of locally generated heat, prioritising coverage for user demand (through heat exchanger HE2). In detail, the user's thermal load is satisfied by the DHN and/or by the DG system through HE1 and HE2, respectively. If the DG system fulfils the user's load, then HE1 does not work; otherwise, it integrates HE2. Without DG heat production, HE2 does not work, and the DHN fulfils the total user's load. Regarding the heat fed into the DHN, if the DG production exceeds the user's needs, then HE3 feeds the excess thermal power into the DHN in a return-to-supply configuration. The prosumer substation feeds heat in the DHN only if the DG can raise the fluid temperature from the DH return pipe up to the DH supply level.

LabVIEW and National Instruments electronics are used to implement the control and data acquisition systems of the substation. The software controlling the substation interacts in real-time with the Energy Exchange lab PCS via LabVIEW network streams connection. For the tests, the TiLoop technique is employed, allowing numerical models to dynamically emulate the user's thermal load and the DG heat production profiles. The schematic view of the hardware-in-the-loop implementation is shown in Figure 4. In the same figure, a blue-dashed line indicates the installed substation boundary, while the green boxes indicate the emulation boundary. The DG system includes a water-to-water HP emulated and connected to the solar TES. The HP has been designed to increase the self-consumption of solar energy for space heating loads and ensure stable, continuous operation. The HP typology, in terms of size and operating conditions, is not designed to feed the DHN. Two different working logics are implemented to manage the integration of the HP :i)HP bypass and so direct heat transfer between the solar TES and the substation; ii)HP activation so that the evaporator is connected to the solar storage and the condenser to the substation.

Regarding the HP, an ad-hoc numerical model is developed by Eurac Research by means of a dedicated TRNSYS type, aiming to meet the design objectives mentioned. Further details related to the operations and controls of the substation, as well as the numerical models, are described in [9-23-24].

2.3.4. Configuration 4

The fourth configuration considers the real-time coupling of two experimental systems located in different sites. One is the Energy Exchange lab, the other one is S.A.P.I.EN.T.E. [25], installed in the ENEA Casaccia Research Centre (Rome). They are connected in real-time via Modbus protocol over an Ethernet network. Figure 4 shows a simplified diagram of the coupling between the two systems. The DH substation tested in the Energy Exchange laboratory is the bidirectional substation described in section 2.3.3 , while the relevant circuit for the considered test is shown for the S.A.P.I.EN.T.E. system. In this setup, the use of HE1 is not planned; only HE2 and HE3 are used. On the secondary side of HE2, the thermal load to be considered is emulated using a predefined profile. On the primary side of HE2, the production from HP, located in S.A.P.I.EN.T.E., is emulated.

The S.A.P.I.EN.T.E. system tested consists of an air-to-water heat pump with a nominal capacity of 30 kW and a maximum outlet temperature of 57°C. The HP is powered directly by PV or the grid and connected to a 1500 l TES. The TES is also connected to a dry cooler, which allows for the emulation of a thermal load.

The virtual connection point between the two laboratories is represented in the figure by blue and red dashed lines: the secondary side of TES in S.A.P.I.EN.T.E. is connected to the DG port of the substation feeding the HE2 and HE3. The coupling aims to have the same power and identical temperature and flow conditions at both connection points simultaneously. To achieve this, S.A.P.I.EN.T.E. emulates the return temperature value from the DG side of the substation (outlet from primary side of HE3, blue dashed line) while Energy Exchange Lab emulates the outlet temperature value from the TES (red dashed line). Eurac Research controls the start of circulation in the two branches (S.A.P.I.EN.T.E. and substation) based on the control implemented to satisfy the load or to feed the DHN, while S.A.P.I.EN.T.E. controls the HP based on the availability of electricity from PV panels or the temperature of the TES.

This Hardware-in-the-Loop set-up aims to evaluate how it can improve the PV electric tracking control of the HP by replacing or integrating the local thermal storage with the DHN via a bidirectional substation. The standard control of the HP, without the bidirectional substation, forces the activation of the HP based on PV production to store thermal energy in the TES. A PID control is implemented to track the PV energy by modulating the speed of the compressor of the HP. If the storage is fully charged, the HP is shut down, even if there is still power being generated from the PV. The integration of the HP in the bidirectional substation enables the overcoming of the TES capacity limits by feeding the DHN with thermal energy produced and not instantaneously self-consumed. This occurs only in the case of surplus energy: the priority is to satisfy the SH load, prioritising the thermal energy produced through PV energy. If there is insufficient production from PV panels to meet this requirement, the HP utilises electricity from the grid. In the considered configuration, it is not intended to use energy from the DHN to satisfy the load (HE1 off).

2.4. KPIs calculations

To evaluate the performance of the test facility in emulating the load and/or the generation system resulting from the real-time simulation or the predefined profiles, the tracking factor (F_T) is defined as

$$F_T = \frac{Reference\ energy\ (realt{-}time\ simulation\ or\ predefined)}{Laboratory\ emulated\ energy} \tag{1}$$

In order to analyze the results from the energetic point of view, the following KPIs are calculated based on monitoring data:

- COP_{sys}, that represents the coefficient of performance of the HP system;
- S_C, that represents the coefficient of self-consumption of locally produced energy;
- S_S, that represents the coefficient of self-sufficiency;

$$COP_{sys} = \frac{Energy\ inlet\ to\ the\ Storage(s)}{Electrical\ consumption\ of\ substation} \tag{2}$$

$$S_c = \frac{Energy\ produced\ locally\ by\ DG\ \ and\ sent\ to\ the\ user}{Energy\ produced\ locally\ by\ DG} \tag{3}$$

$$S_s = \frac{Energy\ produced\ locally\ by\ DG\ \ and\ sent\ to\ the\ user}{User\ load} \tag{4}$$

3. Results and discussion

3.1. Configuration 1

A first round of laboratory tests of configuration 1 described in section 2.3.1 focused mainly on verifying the proper operation of the installed components and integration with the test facility. The main features of the built-in control were also tested, with particular attention to the operation of the HP in various modes, storage management, and temperature controls, focusing specifically on the circuit dedicated to satisfying the SH and DHW loads of a potential user.

Experimental characterisation of the behaviour of the key components of the substation under different operating conditions has been performed, focusing on the main HP, the small HP, the heat exchangers, and the

TES. The primary outcomes of these activities were, on the one hand, to get experience in the management of such components and, on the other hand, to obtain a set of data on the performances to be used as inputs for numerical models of the substation for different purposes, such as fault detection analysis and developing expert controls.

Finally, dynamic tests were performed to calculate daily performance for a typical winter day and, in some cases, to compare the daily performance resulting from different controls satisfying the same load. Predefined SH and DHW load profiles are emulated during the tests. The SH load profile results from a simulation of a 10-apartment building (5 floors, 500 m²). Two types of loads, high temperature (HT) and low temperature (LT), have been considered, differentiated by the supply temperature level of the SH. For the HT load, the SH supply temperature is controlled by the climatic curve 40°C @20°C and 60°C @-7°C, while for the LT load, it is 25°C @20°C and 45°C @-7°C. The substation controls this temperature. The DHW load profile consists of six DHW draw-offs, each lasting approximately 20 minutes, distributed throughout the day. The DHW set point temperature is 55°C, and the substation controls it. Figure 5 shows the SH and DHW load profiles used for all the dynamic tests.

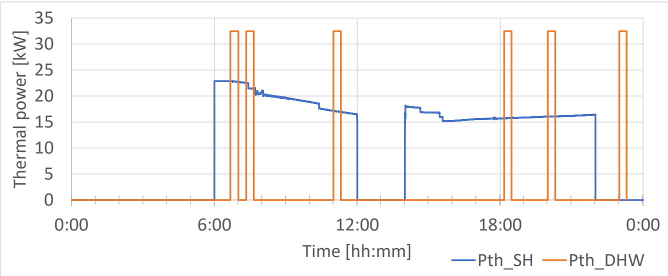

Figure 5.SH (blue line) and DHW (orange line) load profiles used in dynamic tests of configuration 1.

Two DHN supply temperature levels are considered for the dynamic tests: 38°C and 50°C. Combinations of DHN supply temperature and types of SH load have been defined to test the substation's operation and the performance of its controls. They allow two testing scenarios: a baseline case with the HP operating in standard connection with DHN and TES, and an advanced control case that includes the split flow and bypass layout.

The test results allowed evaluating the advantages of dynamic control for switching between the various operation modes from an energetic point of view, rather than a standard connection to the DH and tanks/users. The KPI considered for the comparison was the system COP. Moreover, regarding the test facility controls, the tracking factor was 98.8% for the SH emulated load and 96% for the DHW emulated load across all tests, confirming the proper operation of the emulation and its repeatability.

3.2. Configuration 2

The initial tests on the substation focused on evaluating the overall system behaviour, including controls, to ensure effective operation under dynamic conditions. These tests identify leaks and unwanted circulation, which are solved by adding some valves.

The dynamic tests aimed to verify the substation's operation under dynamic conditions, using the RBC (baseline tests) and MPC, to calculate daily performance for the tested days, and to compare the performance of different control methods in satisfying the same load while considering the same electricity price profile. A 5-day winter test sequence was devised by applying the clustering procedure described in [22]. A predefined SH load profile was emulated during the tests, as shown in Figure 6 and discussed below. The DH supply temperature was emulated as constant at 40°C.

The SH supply and return temperatures are considered constant and equal to 55°C and 45°C, respectively, and the SH storage is managed both in baseline and in MPC tests to guarantee at least 55°C to the load. By fixing the supply and return temperatures of the SH, the SH load profile is emulated by varying the space heating flow rate.

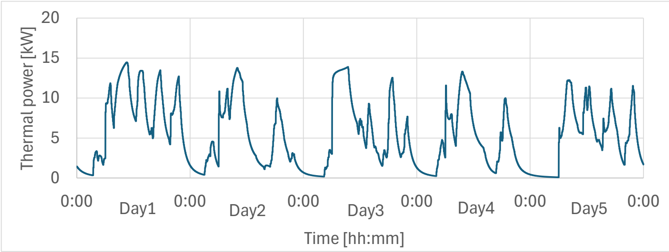

Figure 6.SH load reference profile used in the RBC and MPC tests for configuration 2.

The main KPIs considered for comparing the two controls are the COP of the HP system, the overall operating time of the HP, the differentiation between cheap and expensive periods, and the operating cost related to electricity consumption. By focusing on advanced control tests, it was found that MPC effectively utilises dynamic pricing and load shifting by scheduling heat pump operations during periods when electricity costs are lower and optimising TES charging strategies. This approach not only leverages dynamic electricity pricing to reduce operating costs but also shifts energy consumption to off-peak times. The applied test methodology enabled verification of the MPC's operation under realistic conditions, providing evidence of its potential and reliability when applied to the DH substation.

The results in both the RBC and MPC cases confirmed proper operation of the lab in emulating the SH reference load, with a minimum tracking factor of 97.5% for the load across the overall test.

3.3. Configuration 3

An extensive test campaign has been conducted on the bidirectional DH substation [9], considering cases with and without the HP integrated to evaluate its advantages. 4 case studies are investigated, whose key features are shown in Table 1. In this table, for each case, the DHN temperatures are indicated, as well as the substation temperature controls for SH and DHW, and the presence of an emulated HP, the emulated building condition, and the number of tested days. Regarding the DG system, flat plate collectors are considered for all cases, while the building model differentiates between renovated and non-renovated.

Table 1. Key features of the case studies for configuration 3

Case study	DHN supply-return temperatures	T control for SH/DHW	Emulated DG-substation coupling	Emulated Building conditions	Number of test days
A1	80 – 50 °C	Climatic curve/62°C	Solar TES	not renovated	6
B1	60 – 30 °C	Climatic curve/55°C	Solar TES	renovated	6
C	80 – 50 °C	Climatic curve/62°C	Solar TES +HP	not renovated	6
D	60 – 30 °C	Climatic curve/55°C	Solar TES +HP	renovated	6

Regarding the SH climatic curve, it is 60 °C @ -7 °C, 40 °C @ 20 °C for cases A1 and C, and 55 °C @ -7 °C, 30 °C @ 20 °C for cases B1 and D. The test sequence for each case consists of 6 days representative of the entire year, and the results have been extrapolated to the entire year, according to the procedure described in section 2.3.

Unlike the other two configurations (1 and 2) discussed in sections 3.1 and 3.2, having a real-time simulation that also includes production from RES increases the dynamicity of the variable to be emulated and, consequently, the complexity of the emulation. For the test considered, the load emulation tracking factor ranges between 88% and 97% for winter days and drops to as low as 65% for summer days. Better control occurs on days when the system operates stably and there is a high demand for SH and DHW, as is often the case in winter; poorer coupling is observed on days with less stable system operation, typically on days with only DHW demand. At the same time, the days with the worst coupling factor are characterised by lower energy exchanges compared to the others and will have less weight in the evaluation of the yearly tracking factor, resulting in 91%. The DG system emulation tracking factor (including the HP output) is lower than that for the load, which is due to the intermittent operation and high variability in operating conditions. The daily values range between 70% and 95%.

The data from the annual extrapolation confirm the trends resulting from the analysis of the single test days: thanks to the integration of the HP, both the energy produced locally and its fraction used to cover the user's demands (S_S) increases moving from Case A1 to C (considering high-temperature DHN and a non-renovated building,), and from Case B1to D (considering low-temperature DHN and renovated building,). The largest increases occur from Case A1 to C, due to the significant reduction in temperature for solar energy use in storage in Case C, compared to Case A1. As a consequence of the aforementioned effects, the share of DG energy fed into the grid decreases.

The test methodology applied supported the investigation of the integration of the HP in a bidirectional substation under realistic operating conditions, aiming to increase the share of self-consumption and optimise production from renewable sources. Moreover, it opens for future investigations focusing on optimizing the HP, specifically in terms of sizing (larger size), maximum operating temperature (high-temperature HP up to 80-90 °C) and temperature management according to load requirements: this would enhance the coupling between solar production, substation, and HP, improving overall performance; additionally, it would enable the feeding of not-used solar energy into the grid at the end of the day and increase the use of the heat pump to meet DHW demands.

3.4. Configuration 4

The primary objective of the tests is to couple the two systems (Energy Exchange Lab/substation and S.A.P.I.EN.T.E.) in hardware-in-the-loop mode and to evaluate the improvement in PV electrical tracking management of the heat pump by integrating local TES with the DHN through a bidirectional substation. A total of 12 days of testing were conducted, which included preliminary tests.

The tests for the verification of the different KPIs considered 3 cases: i)HP powered by PV energy, feeding the DHN and without considering a SH load; ii)HP powered by PV energy and grid to satisfy the SH load and without feeding the DHN; iii) HP powered by PV energy and grid to satisfy the SH load and to feed the DHN.

The SH load profile emulated is shown in Figure 7. It corresponds to the SH profile of a winter day of case study B1 in Table 1. This profile is well-suited to be coupled with the HP in question, as it corresponds to a renovated building with a maximum expected heating flow temperature of 55°C, which aligns with the maximum operating temperature of the heat pump, 57°C. As for the DHN supply and return temperature values, 40°C and 25°C were considered, respectively, based on the temperature limits of the HP. Regarding PV energy, four production profiles from predefined PV systems were considered, derived from monitoring data and representative of the four seasons.

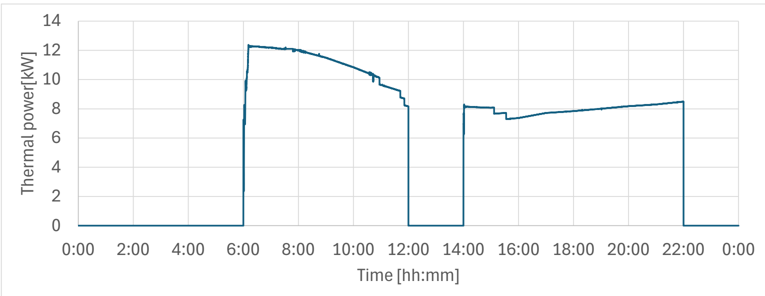

Figure 7.SH load profile used in dynamic tests of configuration 4.

The tests conducted made it possible to define the characteristics of real-time communication between the two systems in detail, to modify the software of both systems to enable such communication, and to verify this through related experimental verification. As regards the correct functioning of the emulations in both plants, the tracking factor defined in Eq. (1) has been modified by considering as reference energy the one in S.A.P.I.EN.T.E. From the tests, this value was between 98% and 100%, confirming the correct coupling of the two systems analyzed for the individual days based on the instantaneous trend. Similarly, the tacking factor for emulating SH load ranges between 98% and 102%. This successfully demonstrates the coupling of laboratories to perform types of tests that would otherwise be impossible due to the intrinsic characteristics of each plant.

The results of the final tests showed that the configuration in which the use of electricity produced by PV is maximised is the one with only injection into the DHN. In contrast, the configuration with the least power usage from PV is the load-only configuration. The lower use of PV in the case of load only is due to diverse levels of production from PV and demand by the load, as well as to the differing time distributions of the two, and to the thermal capacity of the storage. The intermediate configuration, which considers both grid injection and thermal load, determines an increase in the use of PV energy compared to the load-only case, albeit to a lesser extent than the grid-only configuration. Tests in this configuration demonstrate intermittent operation of the heat pump due to its temperature limitations under the test conditions considered. To overcome this limit and maximize the use of PV energy, possible actions are: i)the use of a HP able to work at higher temperature such that it can be fed into the grid without going into blockage; ii) sizing and management of storage to increase the accumulated thermal energy produced by PV to be used primarily to meet the load and then for injection into the grid. These interventions could lead to an increase in self-sufficiency and self-consumption, accompanied by a decrease in electricity drawn from the grid.

4. Conclusions

This study has demonstrated the versatility and effectiveness of Hardware-in-the-Loop (HiL) testing procedures for the development and evaluation of district heating substations integrating heat pumps. By employing a flexible laboratory testbed, four distinct substation configurations were analyzed, ranging from fully physical setups to hybrid arrangements with emulated components and real-time data exchange between geographically separated facilities. The results highlight the value of dynamic testing under realistic boundary conditions, enabling a comprehensive assessment of system performance, control strategies, and integration challenges.

The experiments confirmed that advanced control methodologies, such as Model Predictive Control (MPC), can significantly enhance operational efficiency, reduce costs, and increase the share of renewable and locally produced energy in district heating networks. The HiL approach proved essential for validating control algorithms and system responses prior to field deployment, bridging the gap between simulation and real-world operation. Technical challenges, including system compatibility and communication between components, were addressed, providing practical insights and best practices for future implementations.

Overall, the findings underscore the potential of HiL-based testing to accelerate the adoption of innovative, sustainable solutions in district heating, supporting the transition towards decarbonized urban energy systems through the integration of heat pumps and advanced controls.

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