D4.1 – Configuration and sizing of packaged substations

Renewable and Waste Heat Recovery for Competitive District Heating and Cooling Networks

REWARDHeat

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REWARDHeat

Table of Contents

List of acronyms

COP	Coefficient of Performance
DHC	District Heating & Cooling
DHW	Domestic Hot Water
HBS	Heat Booster Substation
HE	Heat Exchanger
HP	Heat Pump
LTDH	Low-temperature District Heating
NTDH	Neutral-temperature District Heating
R&D	Research and Development
SH	Space heating
SC	Space cooling
TES	Thermal Energy Storage
WSHP	Water-source Heat Pump

1 Summary

This deliverable reports on the main outcomes of REWARDHeat activity focused on the definition of suitable packaged substation concepts for buildings connected to low- and neutral-temperature DHC networks.

The core part of the document presents the task progress and knowledge generated in the first part of the project, including a brief review of current trends and best practices leading to the proposition of design concepts that build the REWARDHeat vision on packaged building substations. This addresses a flexible integration of HP units to enable the adaptation to different network temperatures and load conditions with increased expected efficiencies.

Moreover, a focus on suitable reference integration of thermal storage systems to complement the HP operation is presented, based on the experience from individual H&C supply solutions.

The content of this report will be complemented with more detailed simulation-based analyses in a later stage of the project according to properly calibrated and validated models thanks to lab testing results. This will provide suitable instruments to support the design phase as well as replication assessments adapted to a wider size and type ranges of target applications.

2 Introduction

2.1 Objectives and methodology

The heating and cooling sector is facing important challenges in the framework of the global energy transition towards sustainability and mitigation of climate change; in particular, District Heating and Cooling (DHC) systems are requested to move from traditional, high-temperature fossil-based thermal grids, to sustainable low- and neutral-temperature ones based on a dominant energy supply from distributed renewable and waste heat sources.

One of the main challenges to be solved is how to cover DHW needs (at 50ºC-60ºC) and space heating loads in existing buildings (typically designed for supply temperatures >60ºC) from distribution networks operating at very low temperatures (15-35ºC). Novel concepts of substations are needed integrating booster HP solutions to address the required temperature lift.

This report aims at supporting the development of novel substation concepts for low- and neutral-temperature DH networks, with the ambition of creating a knowledgebase for the development of standardised solutions including HP units for applications at building level. To this purpose, first, a short review of state-of-the-art R&D activities on building substations for low- and neutral-temperature networks is compiled in **Section 2**, which provides the background where REWARDHeat vision and concepts have come to live from.

Then, a dedicated focus on substations configurations and thermal storage use is included in **Section 3**. It is remarked that the definition and assessment of a wide set of different potential substation concepts for multiple applications based on generic models has been intentionally avoided. Instead, an approach to modularity and flexibility has been pursued, leading to the definition of a "all-purpose" configuration, which can be reduced to specific configurations based on piping configuration and operation modes. The substation concept development is following the next steps:

- Step 1: Gathering inputs from previous projects and experiences, selecting specific target application/s and creating a REWARDHeat own vision on flexible and modular substation concepts to be materialised into one unique complete prototype design
- Step 2: Detailed engineering of a skid in a collaborative design process leading to a prototype
- Step 3: Laboratory testing of the prototype
- Step 4: Generating models (calibrated and validated with lab tests) of the proposed prototype and possible variants adapted to some different market segments/needs and providing reliable simulation-based design and operational recommendations.

The first step is covered in this report, which will be later updated with the outcomes from the simulation-based analyses to fulfil the complete ambition of the proposed task.

Finally, **Section 4** collects a set of conclusions and next steps summarizing the different designs integrated into the REWARDHeat approach and opening the door to the development of tools and methods for sizing of packaged substations. This will ensure validated and reliable design-support models that will be used to analyse the replicability and scalability of the proposed packaged substation concept and identify suitable design rules for a relevant range of residential and commercial applications. The results of this analysis will be made openly available, complementing the knowledge base presented in this report and triggering replication outside the consortium limits.

3 Packaged substation concepts for low- and neutral-temperature DH networks

3.1 Review on LTDH / NTDH substations knowledge

REWARDHeat's vision on packaged substations for buildings connected to LTDH / NTDH networks stems from the knowhow mainly generated within FLEXYNETS H2020 project [1] and the industrial experience from providers of DHC solutions in the Project. In addition, other relevant findings and trends are briefly reviewed in this section. Some of the core concepts to be integrated in the REWARDHeat's substation approach for neutral temperature DHNs are remarked in bold.

In traditional DHC networks, substations refer to units where energy is transformed from a higher to a lower-level temperature (in analogy with the substation concept used in electrical power engineering). Key elements are given by heat exchangers, combined with mixing and control equipment. Substations are typically placed at each building connected to the network, even though some other solutions can be found (e.g. area substations, to serve local distribution networks, or apartment substations, to allow for specific regulation and billing at each flat in a building) [2].

Lowering the supply temperature to reduce heat losses, as well as increasing the supply-return temperature difference to improve the generation efficiencies and reduce pumping costs are sought as the main desired improvements in these networks; however, this goal is obviously affected by the temperature levels that are required on the end-user side, what unavoidably affects the design of the building substations by even taking it out of the pure traditional concept mentioned above.

Additionally, **hydraulic separation** of the building circuit from the network is also a typical requirement favouring safety and comfort performance and reducing maintenance issues.

Nevertheless, substations in modern DHC networks that are conceived to pursue their operation at lower supply temperatures (even below those end-use required levels), do not need to transform the energy from high to low temperature levels anymore; on the contrary, they need to wisely **integrate boosting solutions** to provide the needed temperature lift.

REWARDHeat continues the trend initiated in FLEXYNETS project, which addressed the development of a new generation of intelligent DHC networks that reduces energy transportation losses by working at "neutral" (15-20°C) temperature levels. Reversible HPs are proposed to be used to exchange heat with the DHC network on the demand side, providing the necessary heating and cooling supply for the buildings. Figure 1 shows the building substation layout resulting from FLEXYNETS simulation analyses.

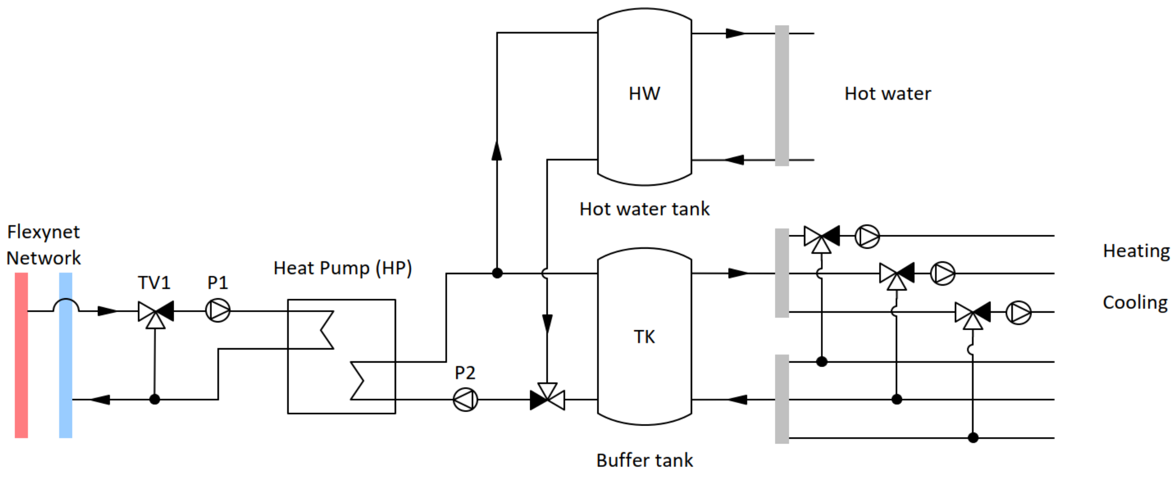

Figure 1. FLEXYNETS residential substation. Source: [3]

This design aims to cover DHW, SH and SC from a neutral-temperature network as a source for a reversible water-to-water HP. Both a storage tank for DHW and a buffer tank for the H&C supply are included (more details on this are discussed in Section 3). One of the most relevant lessons learnt refers to the proposal of using a **recirculation loop** on the network side of the HP in order to accommodate different grid temperatures to the operational limits of the unit [4].

Moreover, the **use of reversible HPs** to enable the operation of the substation in cooling mode is a key aspect for flexibility and adaptability of the design to a wider range of applications. This, however, involves some technical limitations in 2-pipe networks that are also discussed in [4].

Buffa et al. [5] also compiled the most representative features and best examples of "prosumer" substations; term that is adopted for building substations in NTDH networks since each customer may operate as a "consumer" or a "producer" of thermal energy when the network is designed to address both heating and cooling needs. Different versions of building "prosumer" substations have been encountered in the reported survey. Figure 2 represents three of the most relevant substation configurations.

Substation A is the simplest solution because contains the direct connection of the water-source HP (WSHP) to the network for active heating/cooling. Moreover, two 3-way diverter valves allow the connection with a heat exchanger, installed in parallel with the WSHP, for free-cooling operation. In system retrofitting projects, **a backup unit can be maintained to operate in bivalent mode**. Sometimes, it can be connected in series to lift the supply temperature from the WSHP especially for DHW production or when a high-temperature water distribution is needed. This permits to operate the WSHP with a lower supply temperature and to increment its own COP.

Substation B adds some complexity by including a redundant heat exchanger (HE) between the WSHP and the network, providing the hydraulic **separation** to protect the WSHP from fouling risks. However, this increments costs and thermodynamic irreversibility: since a temperature difference is needed to exchange heat through the HE both in heating and cooling modes, the intermediary circuit between the WSHP and the redundant HE will operate at a temperature lower and higher than the network one, respectively. This penalises the WSHP performance. According to the surveyed cases, including this HE is often mandatory, but may be optional in some other cases depending on specific local regulation and/or engineering practice.

Substation C is the most advanced solution. It includes **two diverter 3-way valves installed on the primary loop** of the WSHP between the hydraulic pump and the network. This enables to reject separately hot water (in active or free-cooling mode) in the warm pipeline and cold water (in heating mode) in the cold pipeline, what avoids thermal mixing within the network so that the exergy content of the DHC transfer fluid is not lost. Therefore, the set of HPs along the network can operate with the most efficient boundary conditions. This kind of solution has been implemented in the NTDH system in Herleen also to preserve the exergy content of the water reservoirs.

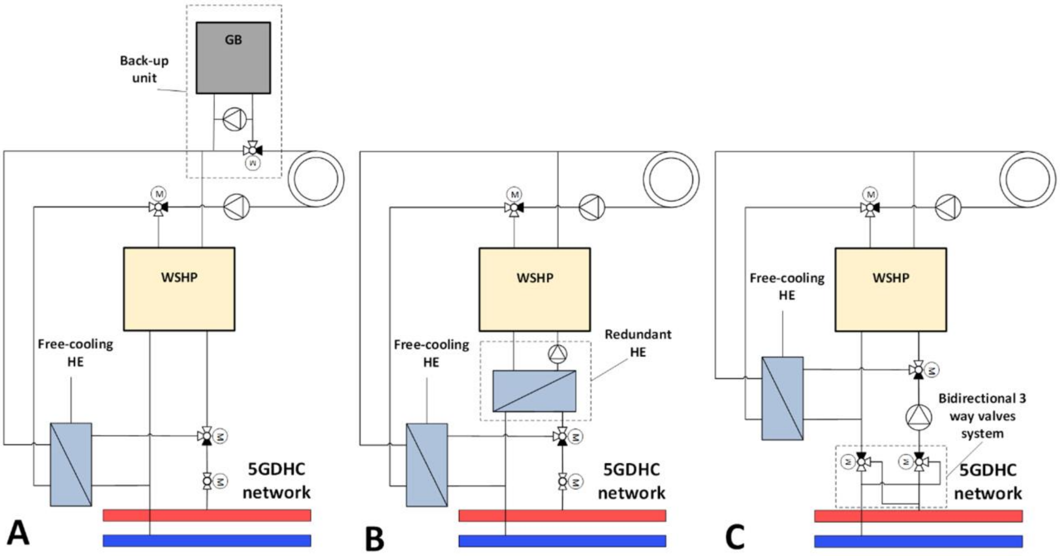

Figure 2. Different types of prosumer substations. Source: [5]

REWARDHeat's vision capitalizes the industrial experience from partner technology providers. In line with the previous concepts, field experience with building substations for very low-temperature networks by Danfoss is reported in [6]. Particularly, the heat booster station (HBS) shown in Figure 3 was proposed and installed in a multifamily residential building in Havnehuset (Copenhagen).

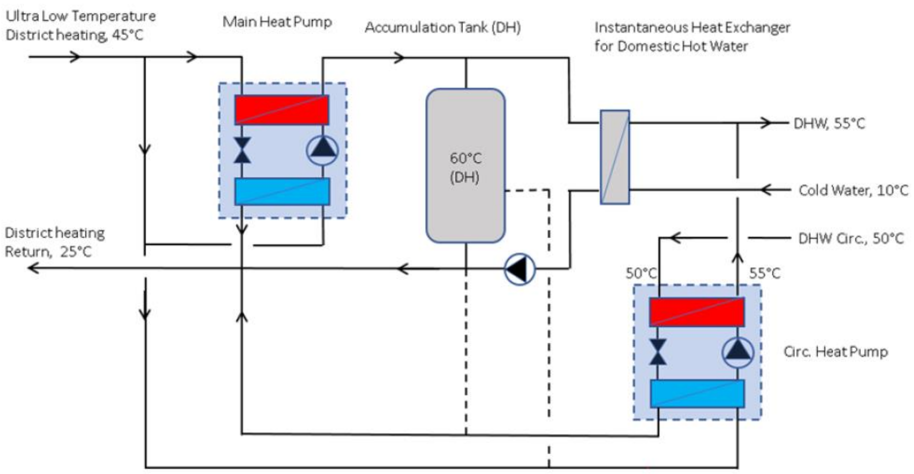

Figure 3. Basic scheme of heat booster substation installed in Havnehuset. Source: [6]

Two main concepts are remarked and recovered from this design, thus contributing to build the present vision within the REWARDHeat project:

- **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 to exploit the temperature level of the network at its maximum and reduce the share of the heat demand that should be covered by the HP.
- **Circulation booster for DHW recirculation dedicated management**. Covering the heat demand from the DHW recirculation with a dedicated small HP unit has proven to provide good results. The circulation booster manages to avoid the DHW circulation impacting the DHW storage by means of fast discharge and loss of the thermal stratification. Thanks to the separate small HP the DHW circulation temperature is maintained.

  The backup of this circulation booster is shown in both Figure 3 and Figure 4, with slightly different connection designs and the possible combination with a direct heat exchanger (HE) when adapted to 'high' temperature DH networks. Moreover, the heat source could be chosen between the DH network and the bottom of the DHW storage tank depending on the suitability of the available temperature levels.

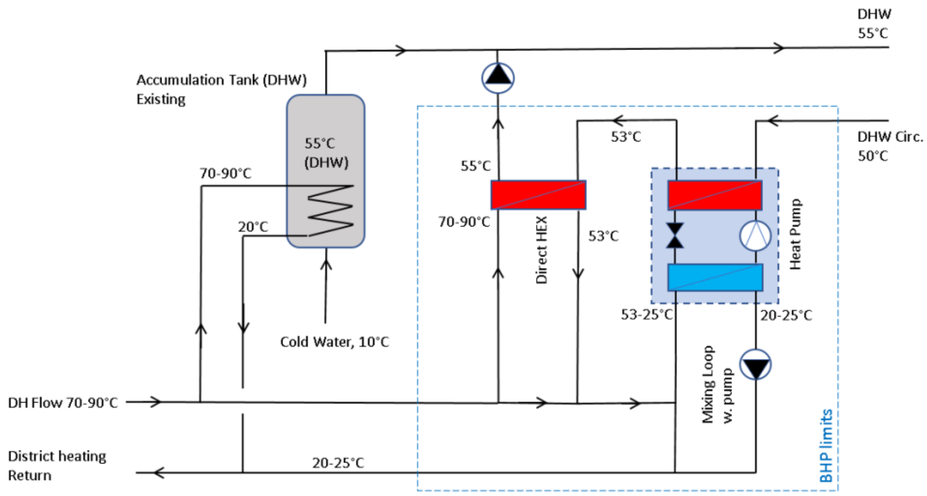

Figure 4. Basic principle of Circulation Booster. Source: [7]

It is relevant noticing that these experiences addressed energy boosting for DHW purposes. The space heating (SH) circuit was designed and operated in parallel and is not part of the HBS. The ambition of the substation concepts proposed in REWARDHeat (as explained later) is to integrate modular designs addressing DHW, SH an SC services depending on the end-user needs.

The integration of individual booster HPs at building level is also a key feature of the NTDH network implemented at Mijnwater in Heerlen [8].

Figure 5 represents the functionalities enabled by the HP substation connecting the DH network (on the left side of the pictures) to the building heating systems (on the right side of the pictures) under different network temperature operation conditions.

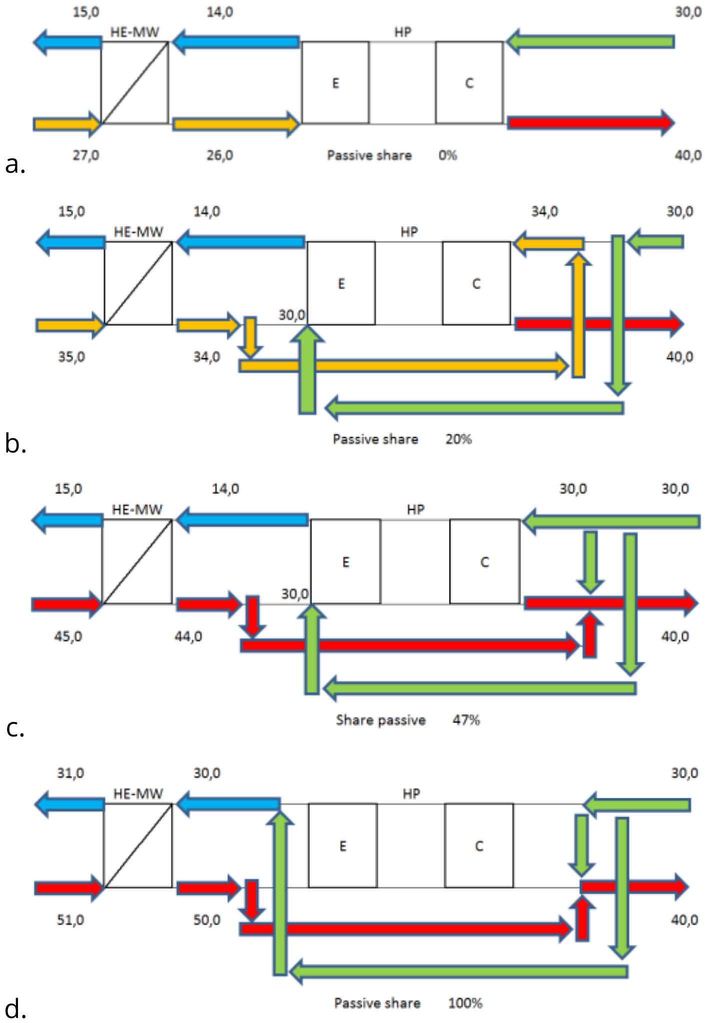

Figure 5. Mijnwater's substation smart hydraulic design, enabling DH energy use under different temperature boundary conditions. Source: [8]

It can be observed that when the network supply temperature is lower than the building return temperature, the HP must cover the overall lift from DH network- to building load temperature (see Case a).

However, when the network supply temperature is higher than the building return temperature part of the heat load can be directly provided by the network: the HP condenser only needs to partially cover the temperature lift. A hydraulic switch between the network supply flow (at inlet of the HP condenser) and the building return flow (at inlet of the evaporator) enables this working mode (see Case b).

The substation operation can be even more effective when the network supply temperature is also higher than the required building supply temperature. Under such circumstance, heat is distributed directly from the network to the load. If the return to the network needs to be cooled to lower than return temperature from the building, the building return flow is both fed to the HP evaporator and condenser; the required cooling effect is obtained and part of the heating load is provided by the HP, operating at very high COP values (see Case c).

Finally, when higher return temperatures to the DH network are allowed, the booster HP can be fully by-passed (see Case d).

REWARDHeat also leverages on this concept which integrates a **smart hydraulic design**: depending on the variable network temperature operation conditions and the thermal level required by the end-users at any point in time, part of the supplied heat can be directly provided, thus reducing or eliminating the instantaneous boosting capacity requested to the HP. This approach can be used either to reduce the HP rated capacity during substation design or to lower the electricity consumption during substation operation.

As a conclusion to this review, several design best practices and lessons learnt have been identified. The challenge in this Project has been related to integrating the different visions as much as possible into a common approach and to proposing complementary design improvements for **enhanced flexibility:**

- Flexibility in terms of **adaptation** to different network and demand temperature boundary conditions. This is required since many low- and neutral-temperature DH systems can be seen as free-floating temperature systems with different operating temperatures depending on the energy balance, and they may also need to meet different temperature requirements of the load along the year depending on the specific types of services implemented.
- Flexibility in terms of **modularity** to easily adapt to different configurations/characteristics of the target energy demand, depending on whether a specific substation will be required or not to provide different end uses: SH, SC and DHW.

4 REWARDHeat applications

4.1 REWARDHeat targets

In addition to the reference trends and best-practice example layouts, it is to be noted that the target applications ambitioned by the REWARDHeat design approach is oriented to a wide range of **residential and light commercial applications**. As previously remarked, modular design is considered in any case, so that the concept can be easily adapted to different scales of SH/SC and DHW demands.

Moreover, despite the flexibility and wide scope of the REWARDHeat vision, the concept development process has been also adapted to business and market drivers under the perspective of the industrial partners. The following strategic considerations regarding market-attractive concepts are accounted for:

- By "only" boosting a minor part of the energy extracted from the network, the HP costs and capacity can be kept low, and as little as possible electricity consumption at building level is used.
- The role of DHC networks in the transition to smarter energy systems is maintained by enabling a 'central system optimization' principle capable of exploiting local central and local energy resources and synergies.
- Cooling service represents a growing market, still smaller than the heating one. With a vision in future integrated, combined H&C systems, the REWARDHeat vision (enabled by potential integration of reversible WSHP units) keeps the concept open for integration of cooling capabilities, thus providing a relevant added value when compatible with the rest of design drivers.

Additionally, the market demand for booster substations makes the concept focus on:

- New buildings/existing "newer" buildings (low-energy intensive with low-temperature heat emitters, e.g. radiant floor system):
  - DH network temperatures: 20~50°C; End-use temperatures: 40-50°C,
  - Network temperature might be sufficient for space heating (SH) but needs boosting (e.g. by a HP unit) for DHW.
  - Storage tank for SH and/or DHW
  - Cooling may be considered
  - HP for DHW circulation is relevant in some cases
  - Targeted reference building: single-family house (SFH) to 3-4 apartments residential (small multi-family houses, s-MFH)
- Older buildings in low temperature networks (medium-/high-energy intensive with radiator terminal units):
  - DH network temperatures: 20~50°C; End-use temperatures: 40-70°C
  - DHW needs boosting (e.g. by a HP unit) and space heating needs boosting in cold periods by a HP unit.

- Storage tank for SH and/or DHW
- HP for DHW circulation is typically relevant
- Cooling may be considered
- Targeted reference building: Multi-family residential buildings (MFH).

A typical HP capacity needed for these applications is in the range of 50 kW – 70 kW, even though the design drivers and recommendations collected in this document aims to adapt to a scalable and modular concept.

4.2 REWARDHeat vision on packaged substations

After consideration and discussion of several substation layouts, based on the above-mentioned background knowledge and market-oriented proposals, REWARDHeat provides a general concept for flexible and modular packaged substations capable of integrating and being adapted to the set of best-practice design aspects previously referred in this document, while it provides a novel vision on the integration of the main water source HP as the core element enabling the required booster effect, when needed.

Figure 6 shows a simplified conceptual flow diagram representing the main components of the proposed design reference: main HP, buffer tank for SH/SC circuit, DHW storage tank and dedicated DHW circulation booster HP. This combination particularly aims at the adaptability of the concept for operation with a relatively wide range of network temperatures.

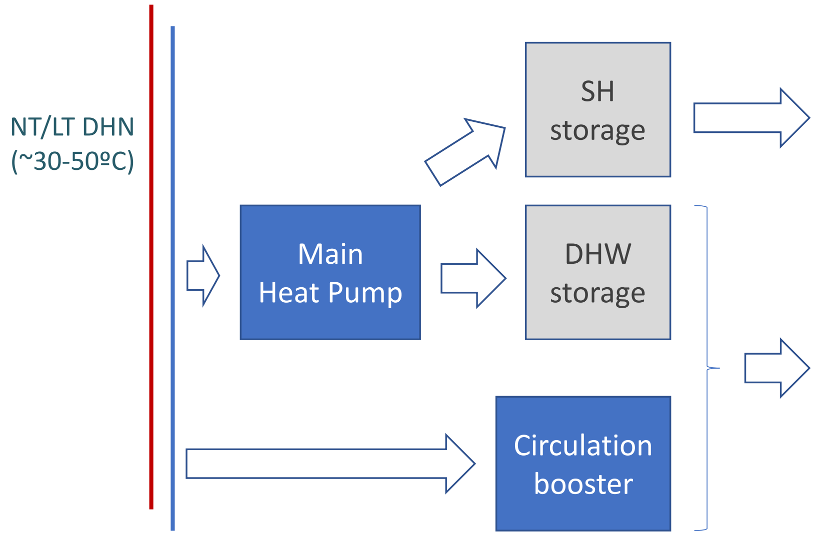

Figure 6. General concept of a flexible packaged substation

Focusing on the 'heart' of the substation layout (i.e. the main HP), REWARDHeat proposes a specific novel integration scheme that seeks the most efficient connection of the HP unit to the network and the demand-side facilities (to favour high operational COPs) depending on the specific boundary conditions at every moment.

Figure 6 to Figure 10 shows a set of simplified HP connection diagrams where the main 4 different operating modes are reflected. The relevant temperature boundary conditions are indicated as follows:

- T_DH_F: District Heating network FORWARD temperature

- T_DH_R: District Heating network RETURN temperature
- T_HE_F: HP demand-side / secondary loop FORWARD temperature
- T_HE_R: HP demand-side / secondary loop RETURN temperature

First, it can be observed that high flexibility on the flow path for the network forward flow and the demand-side return flow is prioritized by the hydraulic design. The network forward flow into the packaged substation can be driven:

- To the evaporator inlet
- To the condenser inlet
- Directly to the secondary loop with a HP by-pass

The demand-side return flow reaching the main HP unit can be driven to:

- To the condenser inlet
- To the evaporator inlet
- Directly to the network return pipe with a HP by-pass[1]

In addition, it is assumed that the return temperature from the demand-side heating system (T_HE_R) will be always lower than the maximum admissible evaporator inlet temperature (T_EVAP_IN_MAX). If this were not the case, a critical operation might arise to be managed through a shunt valve or recirculation loop; according to the consulted HP manufacturers this limit is not too restrictive and for HPs specifically thought for this operation it would be possible to face the boundary condition. For this reason, this has not been included in the diagrams, even if it is considered as a possible operation option.

Besides, the forward network temperature (T_DH_F) is assumed to be always lower than the required forward temperature in the demand-side energy system (T_HE_F), except within the Operation mode IV, where the opposite condition occurs and the HP can be by-passed.

Based on these assumptions, the 4 main expected Operation Modes are represented and described as follows:

1. Operation Mode I (T_DH_F < T_HE_R)

This is the basic operation in building substations connected to DH networks when T_DH_F < T_HE_R, high thermal loads and/or high temperature lifts are required for DHW production or space heating. The network forward flow is connected to the evaporator inlet, the HP unit thus extract the energy from the network low-temperature level and boosts it to the demand-side temperature required. In this configuration, the highest electricity consumption among all Operation Modes is encountered since all the energy transfer to the distribution needs to go through the use of the HP compressor.

[1] Or to the secondary inlet connection of a redundant HE when a hydraulic separation is provided between the network and the HP unit

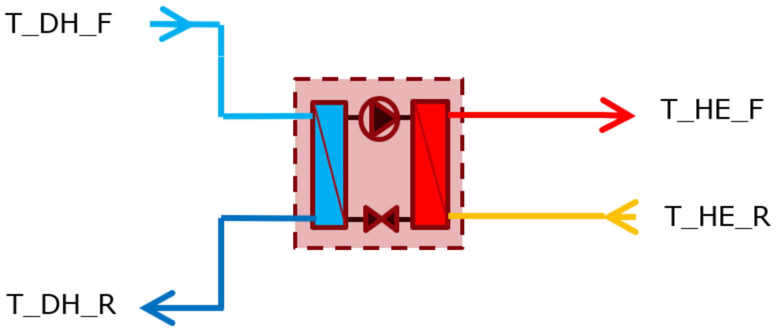

Figure 7. Operating mode I: T_DH_F < T_HE_R

2. Operation Mode II (T_EVAP_IN_MAX > T_DH_F > T_HE_R)

When the network temperature is higher than the return of the building heating circuit (but lower than its required supply temperature), the network cannot directly cover the load at the desired temperature level but still attains certain capacity to 'pre-heat' the demand-side return flow. Therefore, instead of providing all the required capacity through the HP unit (as in the former operating mode), a split-flow connection is used by driving the network forward flow to both the HP evaporator and condenser inlets. This reduces the thermal power to be provided from the HP condenser, since its inlet flow comes at a higher level than in the previous case. Moreover, the split-flow configuration makes the HP work to provide a reduced temperature lift, meaning that higher COP values are expected. Finally, the building return flow is directly driven to the network return pipe; mixing return flow from the building and from the HP increases the overall DT insisting on the DH network pipes.

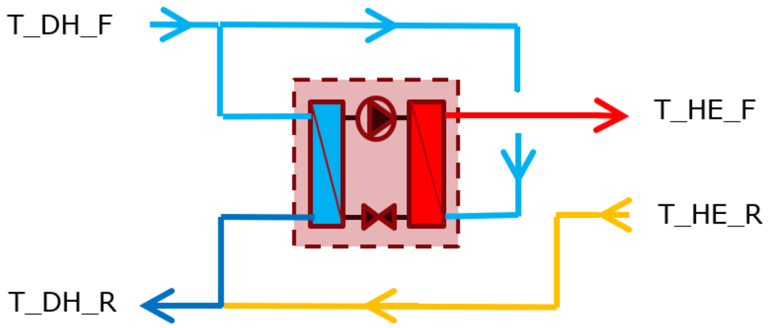

Figure 8. Operating mode II: T_EVAP_IN_MAX > T_DH_F > T_HE_R

3. Operation mode III (T_DH_F > T_EVAP_IN_MAX > T_HE_R)

This mode plays a role when similar conditions to those in mode II occur (T_DH_F > T_HE_R) but the network forward temperature is also higher than the maximum evaporator inlet temperature accepted by the unit; the split-flow connection is not allowed, and the evaporator inlet is driven from the building return flow instead. In this situation the total capacity required by the building is still being provided partially from the network (by connecting the network forward flow to the condenser inlet), and partially from the HP unit (extracting heat from the demand-side return instead of from the network). Expected COPs will be similar to those considered in mode II: an higher T_DH_F to the condenser inlet moves in the direction of a better COP; depending on the return temperature from the building imputed to the evaporator (i.e. T_HE_R can be higher or lower than the DH supply temperature of Operation Mode II depending on the specific system functioning), the HP COP can be higher or lower than in Operation Mode II.

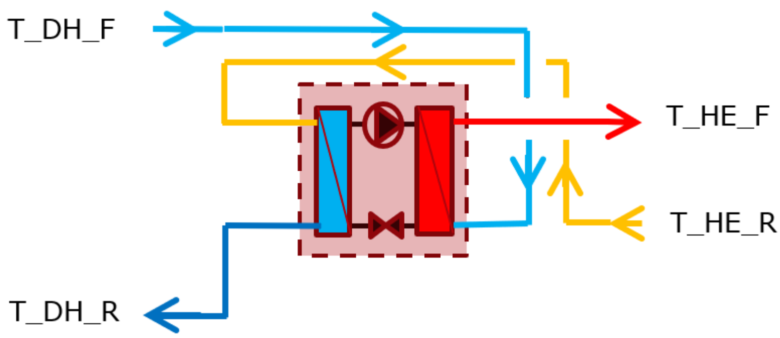

Figure 9. Operating mode III: T_DH_F > T_EVAP_IN_MAX > T_HE_R

Operation modes I to III can be used on alternatively to the others or "mixed" to minimize electricity consumption at specific part load and T_HE_R/ T_DH_F conditions or to minimise the size of the HP at specific DH network supply and building distribution design temperature conditions.

4. Operation Mode IV (T_DH_F > T_HE_F; HP by-pass)

This fourth operation mode considers the situation in which the network forward temperature is higher than the supply temperature required at the demand-side circuit and the building thermal load can be covered without using the HP, hence a by-pass for directly connecting the network to the demand-side circuit is provided.

This operation mode is not frequent in NTDH networks while it would be most frequent in LTDH networks, since this would imply network operation at relatively high temperatures, at least sufficient to covering the space heating loads. In NTDH control strategies allowing for network temperature variations along the year produce end-use substations connected to the network to enter mode IV. Moreover, enabling Operation Mode IV can be seen as relevant in transition scenarios from higher to lower network temperatures were the energy boosting from lower network temperature levels would be targeted and progressively introduced into the operation of a specific grid.

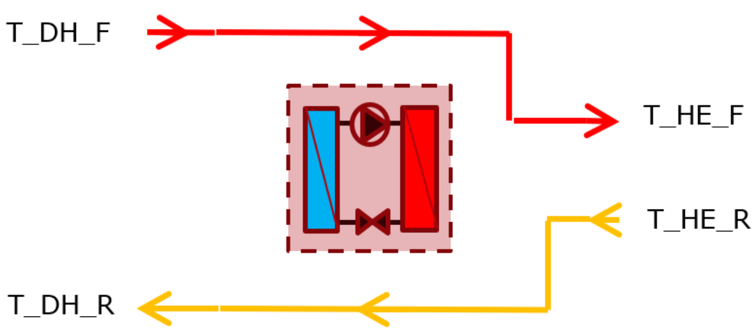

Figure 10. Operating mode IV: T_DH_F > T_HE_F (HP by-pass)

Finally, it should be noted that heating operation is assumed in all of the previous discussions; however, analogous cooling modes would be also enabled if reversible HP units are integrated.

In cooling mode, instead of T_EVAP_IN_MAX, the limiting temperature to select one operating mode or another is the minimum acceptable inlet condenser temperature (T_COND_IN_MIN) (see [4] for more detailed discussion on this). Besides, in this case, the connection of the HP to the network through two diverter 3-way valves installed on the primary loop (as described in Substation C, Figure 2) will play a key enabling role.

4.3 Thermal storage utilisation

Other key components of a DH building substation including HPs are the storage units. This section is dedicated to the definition and sizing of short-term thermal storages for individual packaged substations according to the design guideline encouraged by REWARDHeat and considering the purpose to cover DHW as well as SH/SC demands. In the following preliminary recommendations to integrate possible solutions for warm and cold storages and their location in the P&I diagram are discussed.

At building level, a DHW Thermal Energy Storage (TES) is typically used to store the thermal energy at a suitable temperature, enabling to decouple energy production and utilisation periods while sizing the production equipment (e.g. the HP) at a smaller capacity than the maximum DHW load. Nevertheless, it also causes higher thermal losses and specific costs per stored kWh compared to centralised short-term tank TESs that are found in conventional DHC systems.

In addition, H&C systems based on HPs also requires a buffer tank to compensate the transients of space heating/cooling loads and the on-off cycles of the HP, as to minimise the possible intermittent operation of the system. The buffer tank can be connected to the HP in several ways.

Previous experience from HP-based building H&C systems constitutes the reference base for the proposed integration of local small TES systems in DHC end-use substations approached in REWARDHeat. In particular, Figure 11 shows a reference layout for a stand-alone H&C solution based on a HP as the production unit.

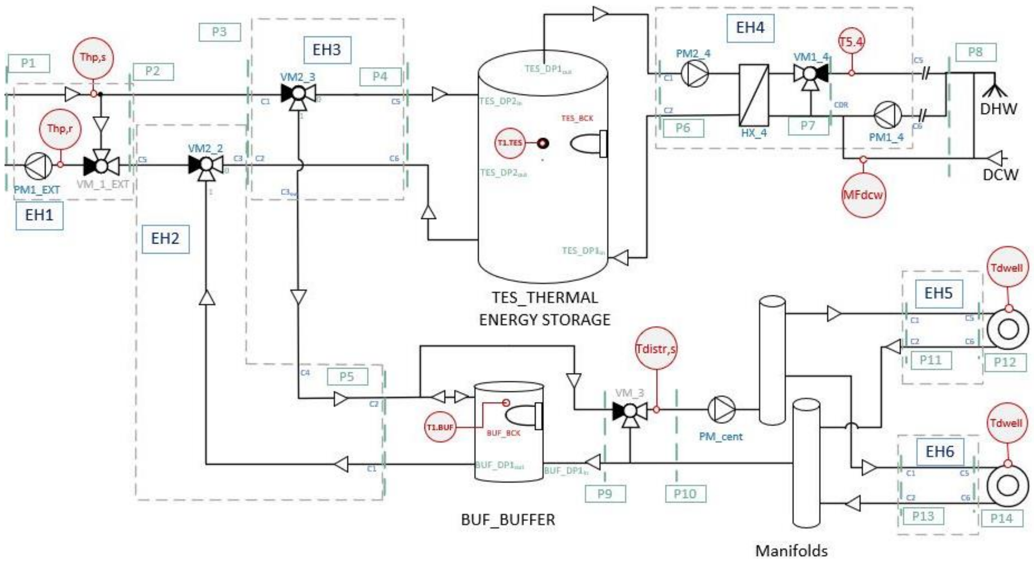

Figure 11. Reference system layout from a stand-alone HP-based H&C system (Source: EURAC). The generation system in Fig. 6 to 9 is connected to the left of the distribution system.

This layout addresses the H&C supply of small multi-family houses (s-MFH), which also represents the most relevant application targeted. In particular, it has been analysed for different building characteristics in terms of energy targets and terminals fulfilling the design goals of flexibility and versatility: the building profiles include medium-/high-energy intensive s-MFH equipped with radiators and split units, as well as low-energy intensive s-MFH equipped with radiant floor systems.

In line with this concept, the inclusion of two storage units with different functional purposes are proposed to support the HP operation in end-use substations:

1. Buffer unit (BUF)

This is a small-size tanks used for SH/SC and designed for two main objectives. First, this is useful to decouple hydraulically the generation side and the distribution side (working as a hydraulic junction). Secondly, it is used to provide thermal inertia for the HP.

The BUF can be simply sized considering around 10 to 15 litres of volume per kW_{th} of HP rated capacity:

$$V_{buf} = 15 \cdot \dot{Q}_{th,HP} \ [litres] \quad \text{Eq.4}$$

A peculiar buffer layout is considered, consisting of a **3-connections tank** (Figure 12), i.e. 1 bidirectional, 1 connected to the source/generation and 1 connected to the load/distribution. The bidirectional connection allows to charge and discharge the buffer.

In traditional storages with 2 double ports (1 for the generation system and 1 for the distribution system), when high flow rates are encountered at distribution while the generator is off, a big uprising flow is generated along the skin of the tank, between the inlet and the outlet connection. Therefore, the mixing phenomenon inside the storage is inhibited and the temperature of the water supplied to the distribution system is very close in temperature to the return flow. By using at least one bidirectional connection, this water stream is forced to pass through the storage, increasing the mixing phenomenon.

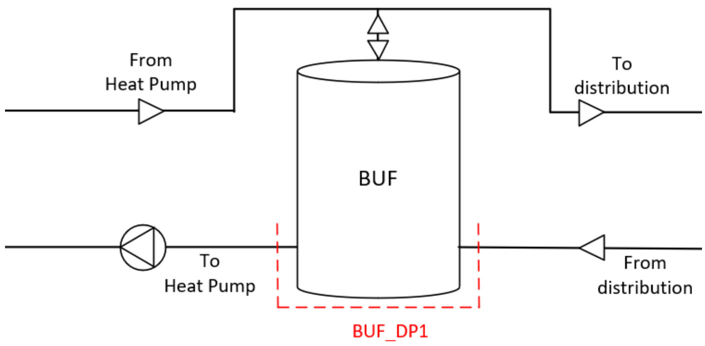

Figure 12: Layout of 3-Connections storage (BUF)

Moreover, such buffer automatically balances the mass flow rates: the amount of fluid entering or leaving the buffer from the bidirectional connection is the difference between the mass flow rates at the generation and distribution sides, hence the quantity of water moving through the tank is minimised.

If the two mass flow rates are the same, there is no water moving through the bidirectional connection. The fluid coming from the generation system bypasses the buffer and moves directly into the distribution system. The mass flow coming from the distribution system enters and leaves the buffer from the bottom to the generation system (Figure 13).

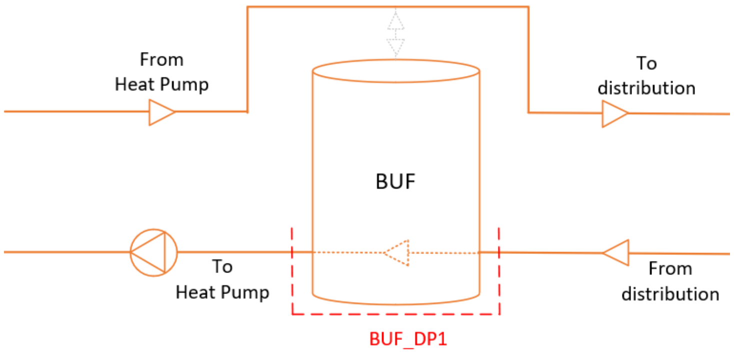

Figure 13: Layout of 3-Connections storage (BUF) at equilibrium

If the mass flow rate at the generation side is higher than the flow rate at the distribution side (e.g. low loads are present in shoulder seasons), the difference between the two flow rates enters the buffer from the bidirectional connection. In this condition the buffer is charged (Figure 14).

On the contrary, if the mass flow rate at the generation side is lower than the flow rate at the distribution side (e.g. the HP works in part load conditions or during HP ramp-up-ramp/down), the difference between the two flow rates exits the buffer from the bidirectional connection. In this condition the buffer is discharged (Figure 15).

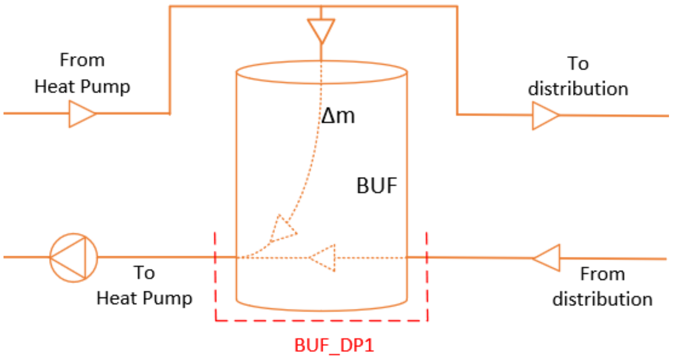

Figure 14: Layout of 3-Connections storage (BUF) during charging phase

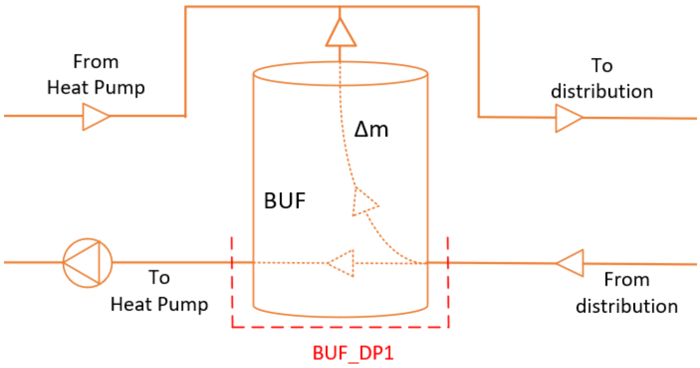

Figure 15: Layout of 3-Connections storage (BUF) during discharging phase

2. DHW thermal energy storage (TES)

Europe misses a unitised normative regulating the design and sizing of a DHW thermal storage tank. Each member states adopt own norms or technical guidelines imposing or suggesting sizing rules to planners for a range of TESs arrangements, i.e. with/without internal coil heat exchanger, "tank-in-tank", etc. All calculation methods are largely discretional: they define the minimum volume of fully mixed hot water the TES needs to always contain in its top section. This however depends on a span of variables; some of them are easily assessed or normed, such as minimum supply temperature to the user and tap water temperature, other are hardly known and are often imposed by the planner based on experience, e.g daily use of hot water and maximum duration of a peak draw-off. As a consequence, a relatively large variability of results can be encountered based on hypothesis adopted during design.

For the sake of clarifying what above, a calculation based on the Italian UNI 9182:2014 [9] is reported here. Firstly, the minimum required volume of fully mixed hot water in the TES is individuated and, secondly, the minimum generator capacity required to allow a timely charge is calculated, as reported in Eq.1 and Eq.2. The dimensioning is made according to user withdrawal related to the different domestic uses:

$$V_{DHW} = \dot{m}_{shower} \cdot t_p \cdot \frac{T_m - T_f}{t_p + t_{pr}} \cdot t_{pr} \cdot (T_c - T_f)\ [litres] \quad \text{Eq.1}$$

$$\dot{Q}_{DHW} = \dot{m}_{shower} \cdot t_p \cdot (T_m - T_f) \cdot \frac{c_{p,w}}{t_p + t_{pr}}\ [W] \quad \text{Eq.2}$$

where:

- $\dot{m}_{shower}$ is the DHW withdrawal in litres per hour
- t_p is the duration of the peak of DHW request in hours
- t_{pr} is the time needed to charge the storage, (to be imposed)
- T_m is the supply temperature to the user
- T_f is the tap water temperature
- T_c is the setpoint temperature of the storage (to be imposed)
- $c_{p,w}$ is the specific heat of water

The nominal DHW withdrawal is computed as follows:

$$\dot{m}_{shower} = \dot{m}_{shower,rated} \cdot N \cdot f_D \cdot f_R \cdot f_L \quad [l/h] \quad \text{Eq. 3}$$

where:

- $\dot{m}_{shower,rated}$ is the rated DHW withdrawal, equal to 540 l/h per dwelling as defined by the norm
- N is the number of dwelling in the building
- f_R is the dwelling factor. It varies according to the number of dwellings as defined by the norm to account for the contemporaneity of the loads
- f_D is the room factor, as defined by the norm to account for the number of inhabitant in a dwelling based on the average number of the rooms per dwelling

- f_L is the living conditions factor as defined by the norm to account for the use of the building.

Example results for the sizing process of a DHW TES for a small multifamily house with 3 5 and 7 storeys, according to the aforementioned methodology are presented in Table 2. The volumes indicated in Table 2 correspond to the minimum volume that should be kept in the working temperature range. The entire volume is bigger, and it depends on the position of the set temperature sensor, normally around 60% of the TES height.

Table 1. Example reference values resulting from the DHW TES sizing calculation method

Building type	Minimum DHW volume [litres]	Number of dwellings [-]	Dwelling factor [-]	Peak power [W]
MFH (3Floors)	355	6	0.56	9027
MFH (5Floors)	496	10	0.47	12627
MFH (7Floors)	650	14	0.44	16549

This stated, it must be noticed that all norms and guidelines define minimum volumes served to satisfy energy demand and user comfort; they never define an optimal size based on the utilisation or system performance expectations. The same applies to the HP BUF tank.

Oversizing the system's TES and BUF might be required, accounting for specific application encountered, system energy performance pursued and eventual services the substation needs to provide to the building and the DH network.

This assessment is under investigation in REWARDHeat at the time of this report preparation; the results of the study will be made publicly available.

5 Conclusions and future work

This document has collected the REWARDHeat vision end-use substations for low- and neutral temperature DH networks. Below, the main design drivers and recommendations are summarized:

Residential and light commercial applications are mainly targeted

A **water source HP** unit constitutes the core component of the substation, providing the required temperature lift/boost between the network and demand thermal levels

Flexibility and modularity: Substations must be adaptable to different network and demand temperature boundary conditions by enabling different operational modes capable of selecting the preferred connection of the booster HP unit (including a complete bypass of it) for maximized COP and guaranteed comfort provision. Depending on the targeted energy demand characteristics (DHW/SH/SC) the substation components can be added/removed thanks to a modular configuration.

This does not only allow to use the substation at DH networks supplying water at different, constant temperature levels; thanks to a **smart hydraulic design**, it also allows to adapt the operation of the substation to a network supply temperature that is continuously varying through the day and the seasons.

A **split-flow layout** for the connection of the HP to the network will enable a reduction on the HP capacity and costs, by sharing the energy load between the network and the HP unit under certain favourable conditions.

A **recirculation loop** on the network side of the HP might be needed to accommodate different grid temperatures to the operational limits of the booster unit. <u>There is need to develop HP units adapted to the operation with high temperatures (i.e. 25 to 40 °C) at the evaporator; this would avoid wasting exergy, produced by reducing supply temperature from the network to the HP evaporator.</u>

Short-term thermal storage systems must be included into the substation, both comprising a dedicated DHW storage and a buffer tank for SH/SC services. 3-connections tank designs with bidirectional ports to control the charging/discharging processes are suggested.

A **reversible HP** is considered to keep the concept open for cooling services. In case of enabling reverse operation, a hydraulic solution based on two diverting 3-way valves at the primary loop of the substation is necessary to avoid thermal mixing in 2-pipe networks.

Hydraulic separation from the network can be optionally integrated by means of a plate HE and is recommended to protect the building facilities against leakage from the DHC network.

Based on the former discussion, room for future work is identified. In particular:

- The design premises related in this report have been integrated into a novel substation prototype developed. The prototype's performance will be thoroughly analysed in the laboratory environment by means of dedicated experimental tests.

- Laboratory testing will feed modelling and simulation activities that will complement the contents of this report and provide suitable design tools and adaptability results based on reliable validated models. Assessment of expected performance of the proposed solution accounting for typical dynamic operational conditions along long periods needs to be studied.
- Control rules for automated operation of the whole substation depending on source/load boundary conditions will be defined, integrated into the system prototype and refined according to laboratory tests feedback and simulation assessment.

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