

Integration of short-term and long-term thermal energy storage in existing district heating systems

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Abstract:

An important evolution which is occurring in district heating systems consists in the progressive integration of renewable energy sources as set by the targets imposed by the energy efficiency directive. The analysis presented in this work considers the use of groundwater heat pump as the renewable energy source, which is managed using variable settings of the supply temperature, in order to combine the performance of the heat pump with the requirements of the thermal demand. In addition, a latent heat storage unit and a thermochemical storage unit are used in order to exploit the operating conditions characterized with large return temperatures or excess heat production in order to increase the performance in less favorable operating conditions. The analysis is conducted considering a detailed model of an existing district heating network as well as a model of a heat pump, both calibrated on available measurements.

Keywords:

District heating transition, heat pump integration, long-term thermal storage, short-term thermal storage.

1. Introduction

The decarbonization of the heating sector represents a key challenge for the energy transition, as thermal energy demand accounts for a significant share of total final energy consumption. In this context, district heating systems (DHS) are increasingly recognized as an effective solution to enable the integration of renewable energy sources (RES) and waste heat (WH), thus contributing to the reduction of greenhouse gas emissions [1].

In recent years, the evolution of DHS has been driven by the progressive replacement of conventional fossil-fuel-based generation with low-carbon and renewable technologies [2]. This transition is boosted by the European Energy Efficiency directive 2023/1791 (Article 26) [3], which sets progressive targets for the integration of RES and WH:

- From 2028, at least 50% of the heat supply should be provided by RES or WH, or alternatively, at least 80% by high-efficiency combined heat and power (HECHP); finally, a combination of 50% RES, WH, and HECHP, with a minimum 5% share of RES and WH is possible.
- These requirements become more stringent in the following years: from 2035, systems must achieve at least 50% RES or WH, or meet higher thresholds for combined RES+WH+HECHP configurations; from 2040, at least 75% RES or WH is required, or alternatively higher shares of combined sources; from 2045, the minimum RES or WH share remains at 75%; and by 2050, heat supply is expected to be fully based on RES and/or WH.

In this context, the installation of heat pumps (HPs) represents a promising option for the integration of RES and WH, as they allow the exploitation of low-temperature heat sources such as groundwater, ambient air, or industrial waste heat [4], [5]. However, their integration into existing networks is not straightforward, as their performance strongly depends on operating temperatures, which are often dependent on the thermal demand and on the design conditions of existing systems [6], [7].

A further challenge associated with the integration of RES and heat pumps is the mismatch between heat production and demand, both in the short and long term [8]. Thermal energy storage (TES) systems can play a key role in addressing this issue by decoupling heat generation from demand and improving the overall system flexibility [9]. In particular, short-term storage solutions can help manage daily fluctuations, while long-

term storage technologies can be used to store excess energy over longer periods and exploit it under less favorable operating conditions. Several studies have investigated the integration of TES in district heating systems, focusing either on short-term storage [10], [11] or on seasonal storage solutions [12], [13].

In this paper, an investigation of the incorporation of both short-term and long-term TES technologies into an existing district heating system is proposed. A groundwater heat pump is considered as the main RES and is operated with variable supply temperature settings in order to match the thermal demand while maximizing efficiency. In addition, a latent heat storage unit and a thermochemical storage system are introduced to store energy in operating conditions characterized by high return temperatures or excess heat production.

The analysis is based on a detailed model of an existing district heating network, coupled with a calibrated heat pump model, both derived from available measurements. The proposed approach aims to evaluate the potential benefits of combining different storage technologies to improve system performance and support the transition toward more flexible and low-carbon DHS.

2. Case study

The analysis presented in this work is based on a real case study, corresponding to a portion of an existing DHS in operation in Italy.

The network topology is shown in Figure 1: 50 user substations (highlighted in light blue) are connected to the network and supplied by a single supply point (red triangle), which is connected to the main district heating network.

The installation of the HP, as well as short-term and long-term thermal energy storage units, is assumed to be centralized and located near the main supply point.

The available dataset covers the 2018 heating season (January to April and October to December) and includes measurements at the substations of mass flow rate, supply temperature, and return temperature, with a time resolution of 1 hour. The cumulative heat load of the substations is reported in Figure 2: the peak demand exceeds 6.5 MW, while the mean value is below 2 MW.

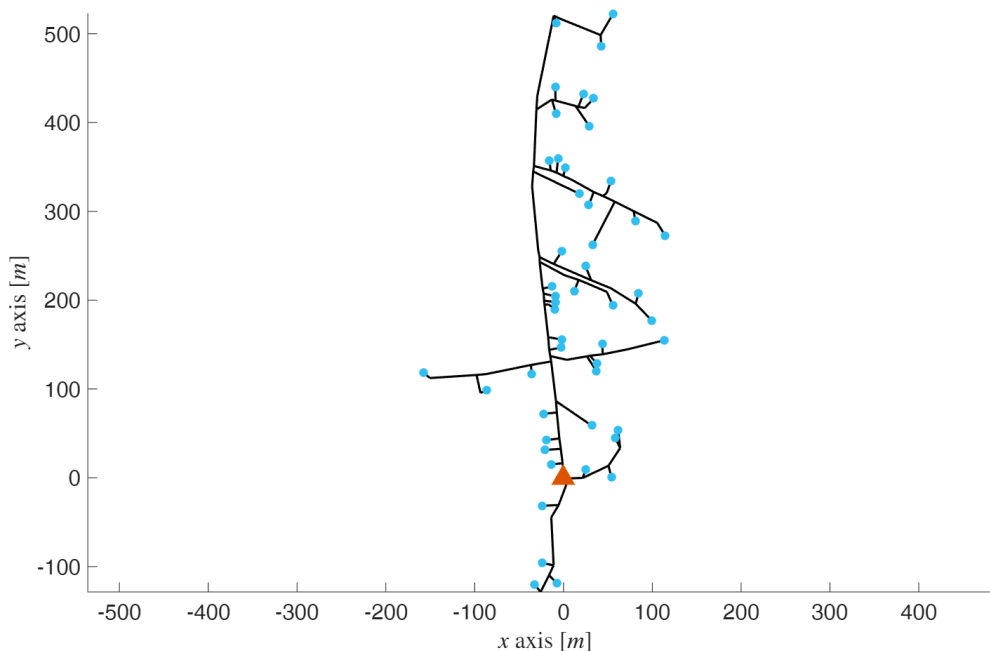


Figure 1. Topology of the district heating network.

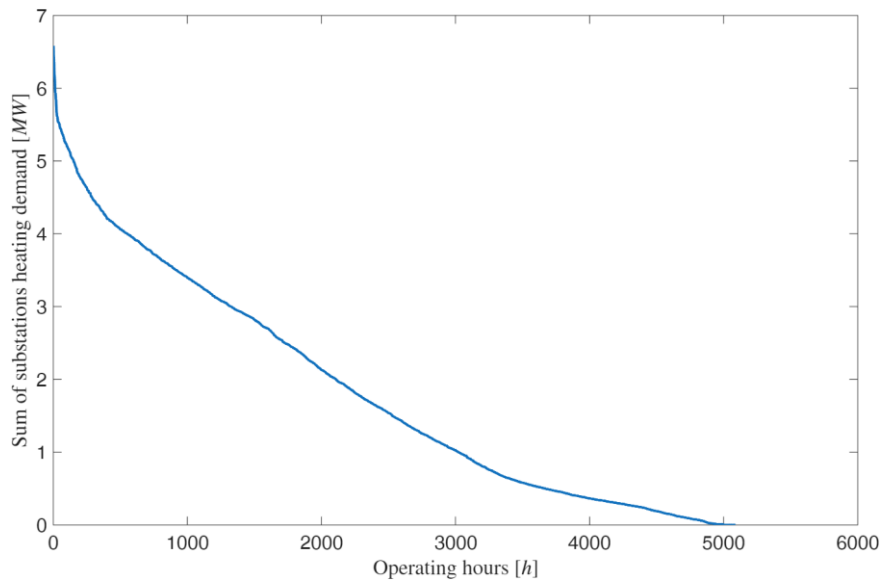


Figure 2. Cumulative heat load of the DHS substations.

All substations are equipped with a single heat exchanger and are used exclusively for space heating. The current supply temperature is approximately 120 °C, while the design specifications indicate an expected temperature difference between supply and return of about 50 °C in deep winter, while larger values are registered in mild seasons. Figures 3 and 4 show the supply and return temperatures of the distribution network.

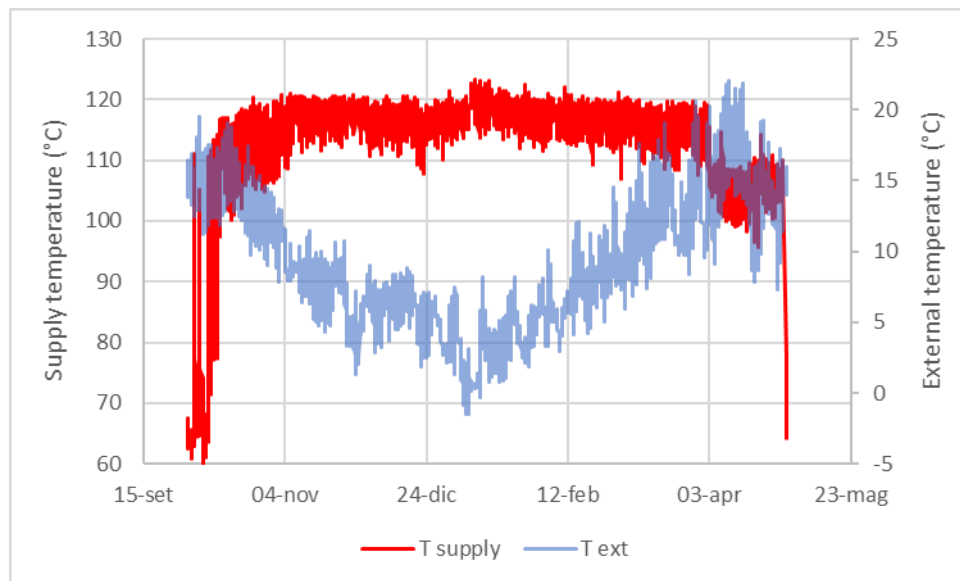


Figure 3. Supply temperature at the distribution network and external temperature during the heating season.

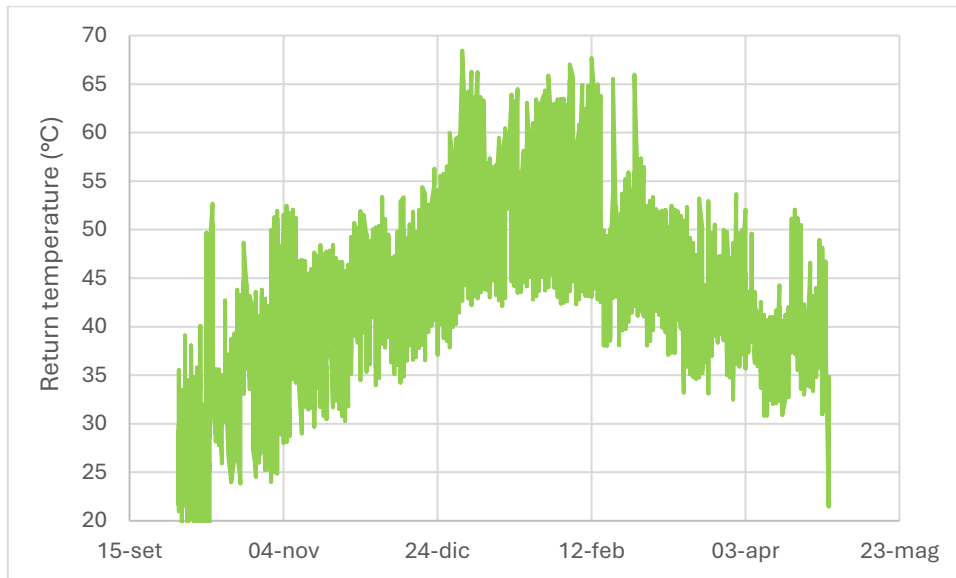


Figure 4. Return temperature of the distribution network along the heating season.

3. Methodology

3.1 Temperature management of the distribution network

Despite the water produced by the different thermal plants connected with the transport network is almost constant during the heating season, the supply temperature to the distribution network varies because of the different impact of the thermal losses (which are almost constant); this is due to the variability of the circulating mass flow rate as the function of the total load. Figure 5 shows, for the considered distribution network, that the circulating mass flow rate depends almost linearly to the thermal demand of the connected buildings. Similar trend is registered for the other distribution networks.

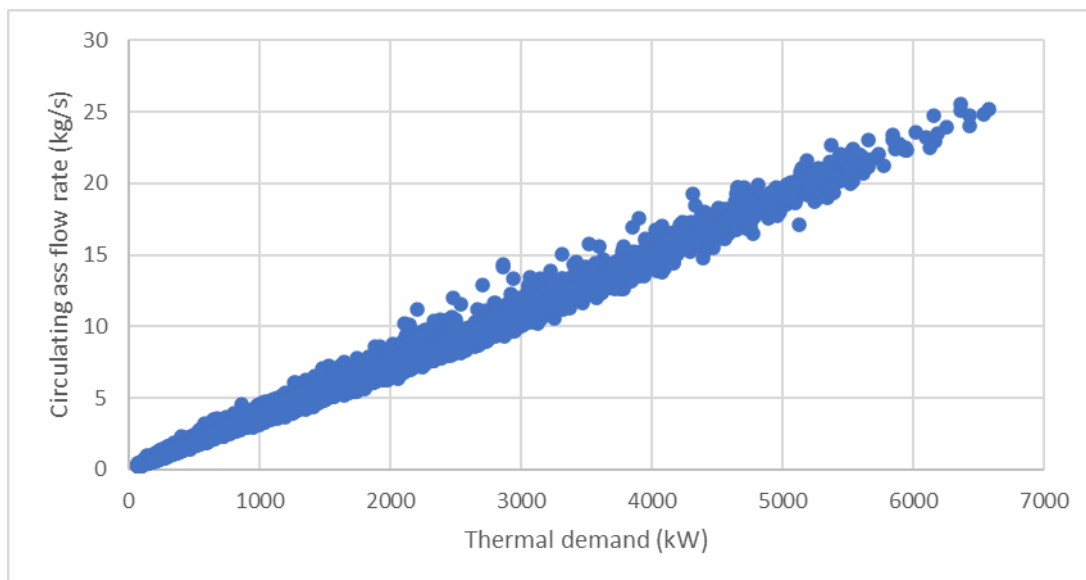


Figure 5. Mass flow rate circulating in the distribution network as the function of the thermal demand.

This piece of information can be handled in order to determine a first boundary condition, which is the minimum supply temperature, which is requested to comply with the requirements of the different heating systems installed in the connected buildings. This is elaborated in order to define a plausible control strategy which can be applied to minimize the supply temperature at the distribution network as the function of the external temperature. To do that, the daily average temperatures are calculated; the graph shown in Figure 6, which relates the supply temperatures to the external temperature, allows one setting the control strategy which can be applied to fix the water temperature at the distribution network.

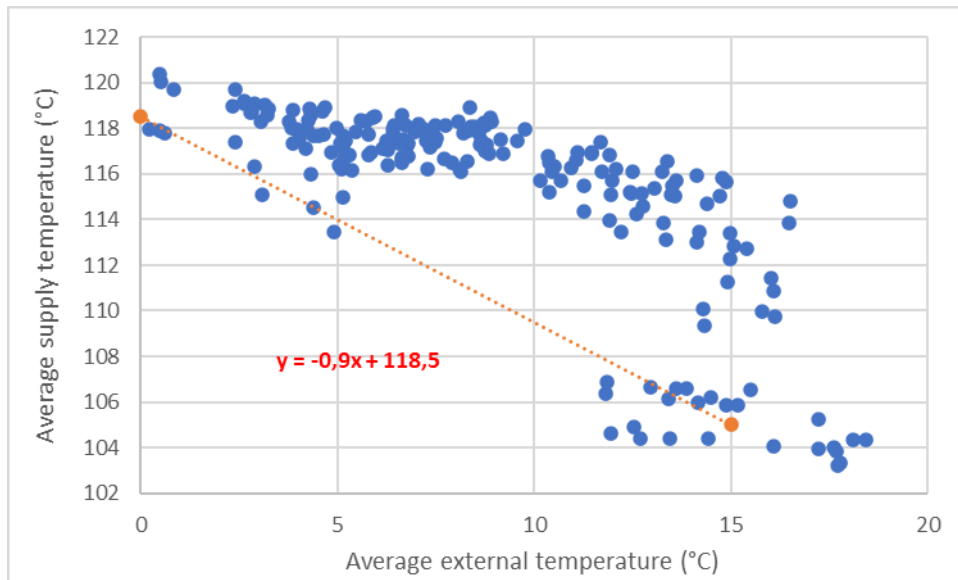


Figure 6. Average supply temperature at the distribution network as the function of the average external temperature.

3.2 Heat pump integration

The integration of a groundwater heat pump with the Turin network is performed using the configuration shown in Figure 7. The heat pump operates in parallel with respect to the thermal plants; this means that the water on the return network is re-pressurized and heated up to the supply temperature. The latter is limited to a maximum value of about 90°C and, in all cases, about 30°C larger than the return temperature. This value is always lower than the water temperature available from the transport network. The idea is that the temperature requested by the end-users is obtained by mixing hot water produced by the heat pump with water extracted from the transport network.

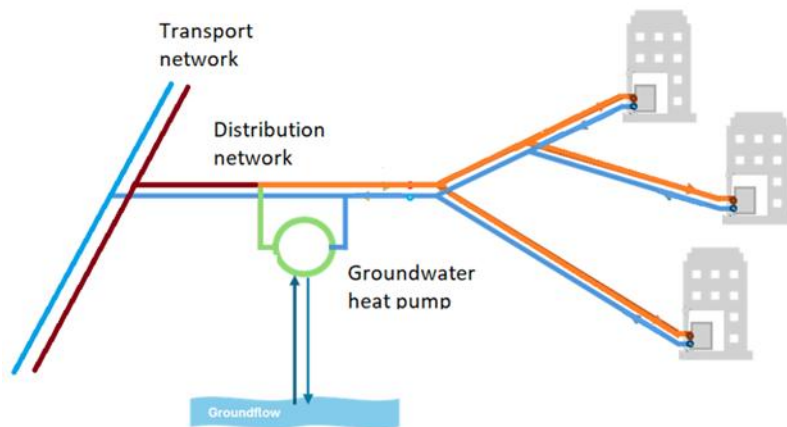


Figure 7. Schematic of the integration of the heat pump in the distribution network.

The procedure to determine the operating mode has the goal of maximizing the contribution of the heat pump and guaranteeing a suitable supply temperature at the end-users. The procedure consists of the following steps:

- 1) Tentative mass flow rates at the heat pump (GHP) and extracted from the transport network (GT) are set, starting from the minimum.
- 2) The mass flow rate elaborated by the heat pump is progressively increased until a value which allows one to obtain an inlet temperature at the substations (T_{in}) larger than the minimum value acceptable in the specific thermal demand of the buildings in the distribution network. This temperature is shown in the graph in Figure 8, which shows the registered inlet temperatures as the function of the total thermal demand of the distribution network. A trend line is considered to fit the minimum temperatures.

In this step, the heat losses in the distribution network are re-calculated considering the circulating mass flow rate and the water temperature resulting by mixing the stream coming from the heat pump and that from the transport network.

3) In the case an acceptable value of the inlet temperature is not reached, the step 2) is repeated with an increased value of the mass flow rate extracted from the transport network.

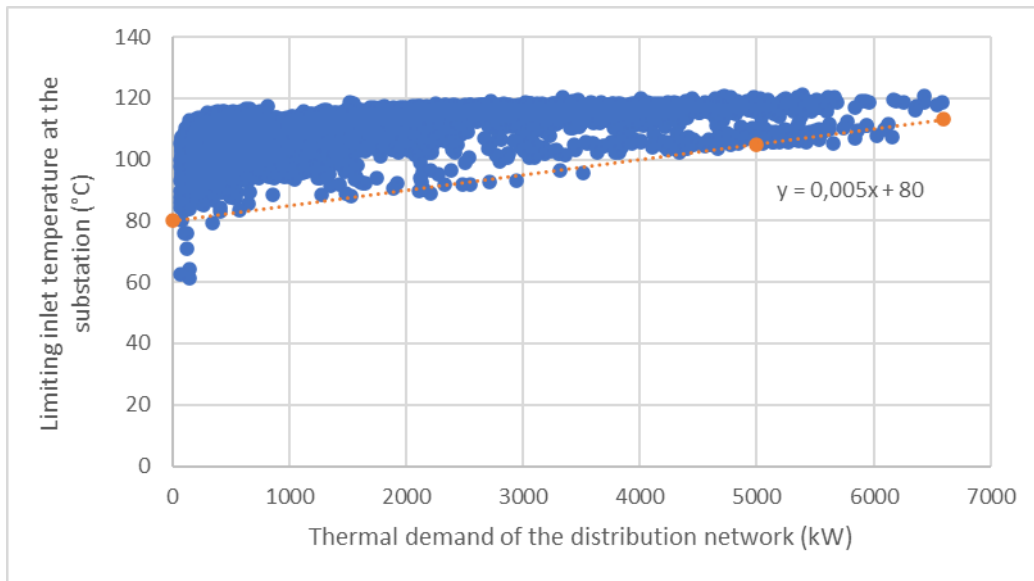


Figure 8. Minimum temperature at the substations as the function of the total thermal demand of the distribution network.

The integration of a 500 kW heat pump is considered; its size is about 7.5% of the maximum load of the distribution network. Figure 9 shows the contribution of the heat pump to the total thermal load along the heating season. The total energy contribution, on annual basis, is about 21.8%, namely 2 GWh out of 9.4 GWh. An important result of this configuration is related with the reduction of the supply temperature, which is, on average 8 °C; this implies a reduction of the heat losses of about 15% with respect to the conventional operation.

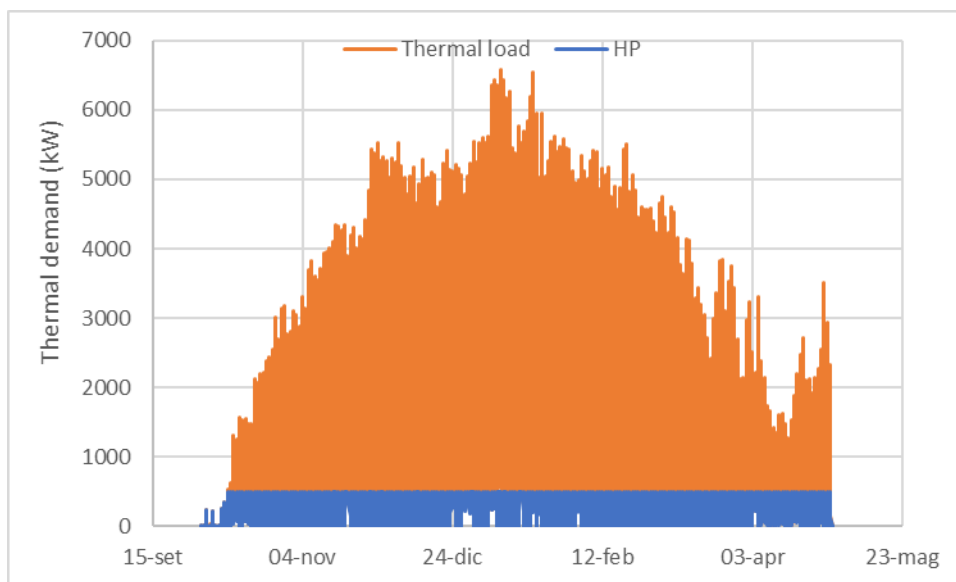


Figure 9. Contribution of the heat pump to the thermal demand of the distribution network.

4. Integration of thermal storage units

The analysis of the operating conditions of the distribution network shows two anomalous behaviours that limit the potential impact of the selected heat pump, which are described hereafter.

Due to the conservative assumption on the minimum supply temperature presented in figure 8, the operating conditions characterized with small thermal load are associated with very large temperature drop between the supply and return networks. The increase in the water temperature which is expected to be performed by the

heat pump in the different operating conditions is shown in figure 10. If the thermal demand is smaller than the heat pump capacity, the contribution of the heat pump must be limited in order to comply with the limitations in the temperature rise that can be achieved by the heat pump (about 30 °C). In these cases, an adsorption thermal storage unit can be applied in order to increase the contribution of the heat pump. In particular, the storage can be charged by the heat pump when the demand of the district heating network is small, i.e. in late summer or in the first part of the heating season. In the case a storage volume of about 500 m³ is available it is possible to store enough heat to increase the heat pump coverage of about 0,08 GWh and thus neutralize this first limitation.

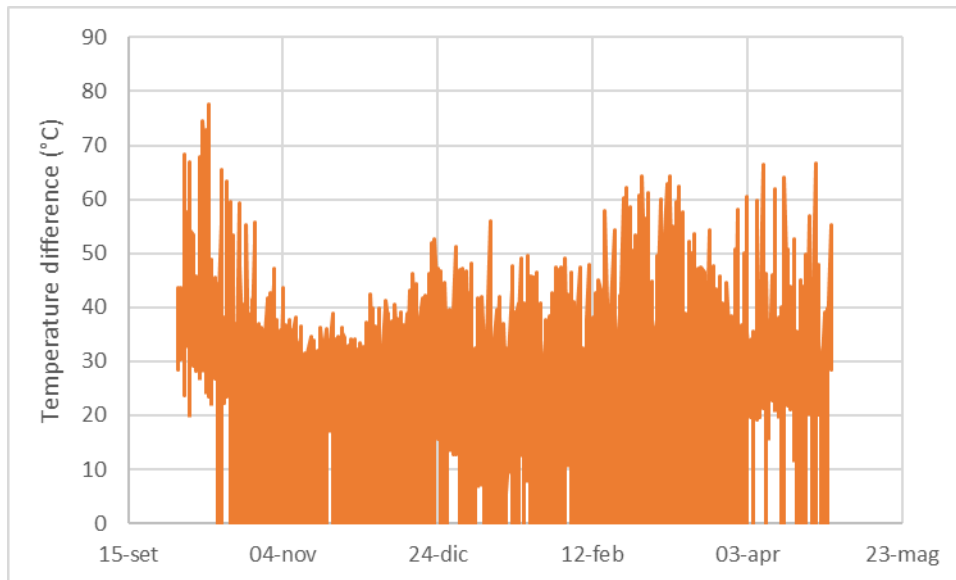


Figure 10. Water temperature difference requested to the heat pump in the different operating conditions.

The second issue is related with the specific management of the thermal substation, which are basically switched off at night. This causes large peak demands of the buildings when the heating systems are switched on in the morning. Consequently, the temperature drop between supply and return becomes very large and the heat pump is not able to reach the requested supply temperature. This behavior is shown in figure 11, where a zoom of the return temperatures in 9 days of the period between the end of January and beginning of February is shown. The figure shows that larger temperatures are registered at night before the heating systems are switched on, then smaller temperatures occur. In the case a short term thermal storage, such as a sensible heat storage or a PCM storage is installed, it is possible to take advantage of these larger temperatures to reduce the temperature rise that is requested in the morning, therefore the heat pump further increases its contribution to the energy balance of the network. The installation of a thermal storage with a thermal capacity of 500kWh is able to further increase the contribution of the heat pump of about 0,09 GWh along the heating season.

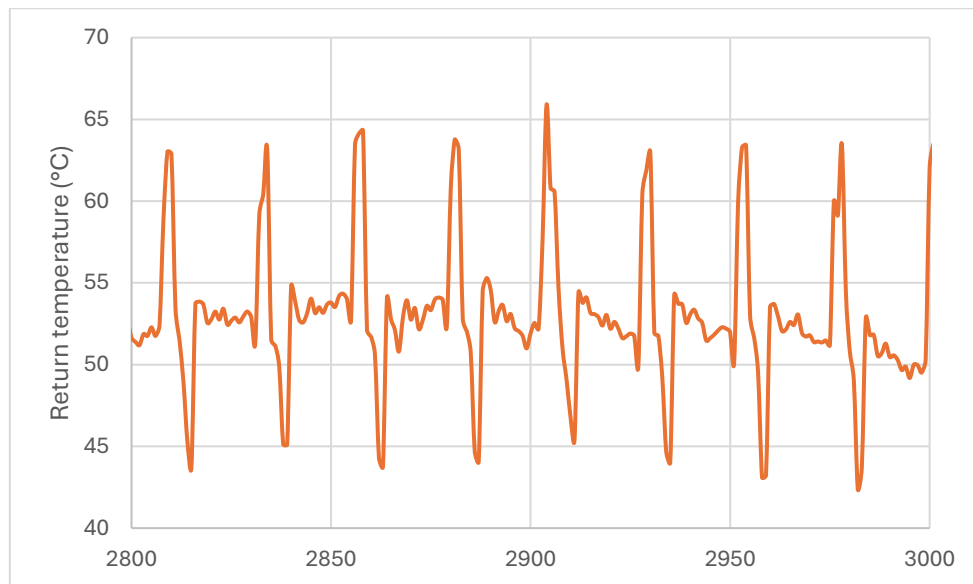


Figure 11. Return temperatures in deep winter.

5. Conclusions

When heat pumps are integrated in district heating networks, supply temperature management constitutes an important point to balance system efficiency with the end-user requirements. In the case of large networks, a possible option is constituted by a centralized infrastructure which is used to adjust the supply temperature to the larger values that are requested in cold days and to cover the peak demand with a distributed generation operated by means of heat pumps. A case study constituted by large district heating network currently operating through superheated water is considered. The analysis is conducted on a distribution network characterized with a maximum heating load of about 6.5 MW, where the integration of a 500 kW heat pump is examined. With this design, the heat pump covers about 21% of the thermal demand during heating season.

Two types of limitations are observed in heat pump operation: 1) when the temperature difference between supply and return is large, the heat pump is not able to cover the full heat load, even if it is smaller than the thermal capacity; 2) the heat pump is not able to operate when the heat load is too large, as the corresponding supply temperature that would be requested is too large even considering the mixing with water produced by the centralized system. The integration of a long-term storage and a short-term storage allows one handling both issues, increasing the thermal energy produced by the heat pump of about 10%.

Acknowledgments

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