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In-situ monitoring of a groundwater heat pump for a low-temperature district heating network: energy performance, issues and challenges

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Abstract

With the development of district heating networks and the need for decarbonization, heat pumps in district heating are expected to play a major role in the upcoming years. To facilitate the implementation of such systems by sharing lessons learned, this study presents monitoring results of a large-scale heat pump supplying a low-temperature district heating network (LTDH) in Switzerland. Detailed monitoring over a whole year of operation reveals an annual heat production of 8 GWh, of which 85% is covered by the heat pump with an annual SPF of 3.69 (pumping and auxiliaries excluded). However, about 25% of the heat for space heating is produced with very low energy performance. Analyzing the influence of temperatures and flow rates on the heat pump energy performance brings to light potential optimizations of the system and improvements for future LTDH. In particular, the results raise crucial questions related to heat pump sizing and domestic hot water production methods with LTDH, as well as reaffirm the importance of optimizing substations return temperatures when the main heat generator is a heat pump.

Keywords: heat pump ; district heating and cooling ; in-situ monitoring ; faults in substations

1. Introduction

1.1. Context

In 2015, around 45% of the total European energy consumption was due to the heat supply of buildings for space heating and domestic hot water, and was based at 66% on fossil fuels [1]. This sector hence represents a huge potential for the reduction of greenhouse gas emissions.

District heating networks (DH) have long been recognized as a means to decarbonize the heat supply in dense urban areas, as it allows the use of waste heat, which would otherwise be rejected in the environment, and facilitates the integration of renewable energies.

However, renewable energy sources such as geothermal heat, solar heat, surface or underground water are often available at low temperature, unfit for direct use. Thus, their integration into buildings heat supply often requires a temperature lift with a heat pump (HP), either centralized or decentralized.

Therefore, with the development of DH and the need for decarbonization, HP are expected to play a major role in the upcoming years. Heat Roadmap Europe 2050 (HRE2050) prospective scenario [2] shows that DH could cost-effectively cover 50% of the total heat demand by 2050, compared to 12% currently, with 25% of the heat supplied by large-scale HP (520 TWh/year with a COP of 3 and a total capacity of 40 GW_{th}).

Large-scale HP are already in use across Europe for the supply of DH networks. A study made in 2017 [3] identifies 149 units (≥ 1 MW) across 11 European countries, installed between 1981 and 2016, for a total capacity of 1.6 GW_{th} (25 times lower than the HRE2050 scenario). This study also shows that many large-scale HP were commissioned in the last decade in several countries such as Finland, France, Denmark and Italy.

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Despite their use on many systems since the 1980s, there are still barriers to the implementation of HP in DH networks [4], such as the lack of knowledge compared to other technologies (like biomass or gas boilers) and investment cost. Therefore, documentation on existing projects could increase confidence of stakeholders, increase energy efficiency as well as reduce operation and maintenance costs of such systems. IEA HPT Annex 47 [5] produced a short description of 44 case studies of HP in DH networks to show examples of implementation. However, detailed information on the challenges/issues encountered are not always provided.

1.2. Objectives

The present study consists in analyzing the energy performance, in actual conditions of use, of a large-scale HP supplying a low temperature district heating network (LTDH). The aim is to determine whether the HP achieves the expected performance and to identify possible areas for improvement. This provides insight not only on this specific system, but also for the optimization of other existing or future HP in LTDH systems.

Based on detailed monitoring data over an entire year of operation, we first compute daily and annual energy balances of the HP to get an overview of its energy performance. Then, we proceed to an hourly analysis to examine the influence of various parameters on the HP performance, such as temperature levels and flow rates. Finally, based on the results of this study, we make recommendations regarding the use of large-scale HP in LTDH.

2. Case study

2.1. Description

The case study is an eco-district located in the canton of Geneva, Switzerland. It hosts around 1’350 dwellings and various activities, totalizing 170’000 m² of conditioned floor area. A local low temperature district heating network (LTDH) distributes heat to the buildings for space heating (SH) and domestic hot water (DHW). Because all connected buildings meet high energy performance standards, the LTDH supplies heat at a low temperature level (50°C). At fixed time, twice a day, the temperature of the network is raised from 50°C to 65°C to heat up DHW tanks within the buildings over a 2-hour period. Compared to a network operating at a constant supply temperature of 65°C, these DHW batches lower DH heat losses and increase the energy performance of the heat production.

As shown in Fig. 1, the LTDH is mainly supplied by a 5 MW_{th} heat pump (HP), whose heat source is shallow groundwater. Before reaching the HP, this cold water at approximately 12°C supplies a district cooling network, recovering waste heat from the nearby industries, thereby increasing the resource temperature for the HP and improving its efficiency. As a result, the HP source temperature ranges between 12°C (during the winter) and 16°C (during the summer). The HP delivers heat directly to the LTDH and the surplus is stored in two buffer tanks of 20 m³ each (i.e. a total volume of 40 m³) to add inertia to the system.

In addition to the HP, the LTDH is also connected to Geneva’s high-temperature district heating network (HTDH), as complementary or back-up source. The objective is to cover at least 80% of the annual heat demand with the centralized HP, and reach a HP seasonal performance factor close to the nominal values presented below, pumping and auxiliaries excluded.

The HP has two variable-speed compressors, operating in parallel for SH mode or in series for DHW mode (to reach higher outlet temperatures). It admits condenser inlet temperature ranging from 20°C to 45°C, though it only stops when the temperature reaches 50°C to prevent damage. According to the manufacturer [6], the nominal coefficient of performance (COP) of the HP for each operation mode is as follows:

- DHW: COP of 3.62, for inlet/outlet condenser temperatures of 45°C/65°C
- SH : COP of 4.60, for inlet/outlet condenser temperatures of 35°C/50°C

It should be noted that these values are given for an evaporator inlet temperature of 12.5°C, i.e. the temperature of the water at the pumping site. The increase in temperature of this resource due to the heat supplied by the district cooling customers allows in principle to reach slightly higher COP.

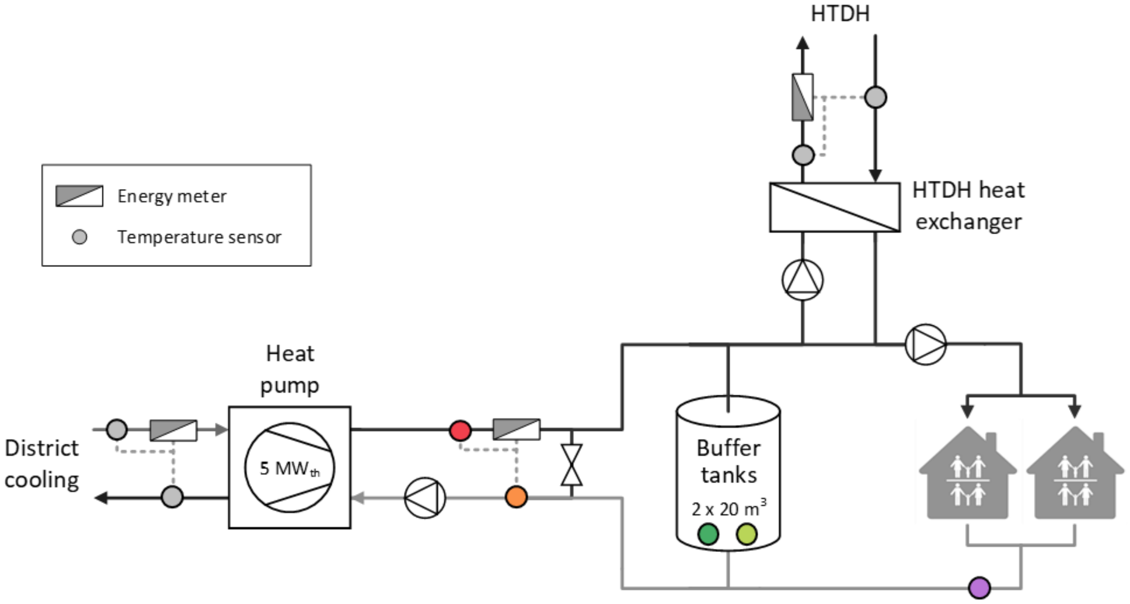

Fig. 1. Schematic of the district heating system. Colored circles indicate the location of the temperature sensors used in Fig. 5.

2.2. Monitoring

To evaluate the actual energy performance of the HP, we analyze monitoring data for a whole year, from June 2019 to June 2020. This time interval corresponds to the first year of operation of the HP and has the advantage of including all possible types of operation, namely:

- A summer period (from June to August 2019) where the HP operates only 4 hours per day (two 2-hour batches) for the preparation of DHW at 55°C-65°C.
- Mid-season periods (from September to October 2019 and from March to May 2020) during which the HP operates not only in DHW mode during the batches (at 55°C-65°C), but also in SH mode intermittently (at 50°C).
- A winter period (from November to March 2020) during which the HP operates almost continuously to maintain the LTDH at 50°C for SH of buildings, and at 55°C-65°C for DHW batches 4 hours per day.

Except for a few breakdowns in February and March 2020, partially due to high condenser inlet temperatures exceeding the HP limits of operation, the HP runs during most of the period. It stops voluntarily at the end of the heating season (mid-May) to test the behavior of the LTDH when the HTDH covers the entire heat demand during the summer.

Data is collected from the system with a 10-min time step and aggregated on an hourly, daily and annual basis. As indicated in Fig. 1, it includes, but is not limited to: i) energy meters, with their corresponding flow meters and temperature sensors, on the evaporator and condenser of the HP, as well as on the HTDH supply; ii) electricity meters on the HP compressors; iii) temperature sensors in the buffer tanks, in particular at the bottom of each tank, as well as on the DH return.

Since the high temperature DHW batches occur at fixed time each day, it is possible to dissociate the heat produced in DHW mode from SH mode (i.e. outside the batches) based on the timestamp. The DHW batches start at 5:00 and end at 7:10 each morning and evening.

The energy performance of the HP is evaluated on an hourly (COP) and annual basis (SPF) as the ratio of the heat produced at the condenser to the electricity consumption of the HP compressors (i.e. pumping and auxiliaries excluded).

To check the validity and consistency of the data, we calculate the hourly and daily energy balances between the load side (condenser) and the source side (evaporator and electricity) of the HP. Following the observation of the data, the limit is set at ± 10% error on the HP balance. Results exceeding the limit are excluded from the analysis. Similarly, outlier COP values are excluded (COP > 7 and COP < 1).

3. Results and discussion

3.1. Energy balance

Fig. 2a shows the daily and annual energy balance between energy source (HP evaporator, electricity and HTDH) and heat production per operation mode (SH / DHW).

The total heat production varies from 7 MWh/day in summer to nearly 50 MWh/day in winter. The heat production in DHW mode, i.e. during the high temperature batches (55°C-65°C), has a seasonal effect: it goes from 7 MWh/day in summer to about 12 MWh/day in winter. It is important to note that this corresponds to the heat production during this period of the day, and not the buildings DHW demand, because the HP stops at the end of each DHW batch and lets the DH temperature come back down to SH level before turning back on. Therefore, part of the heat produced during the DHW batches is used after the batch for SH. This control logic is visible on typical days presented later in Fig. 5.

The total heat production amounts to about 7.98 GWh, with a HP coverage of 85%, thus meeting the target of 80% despite the HP breakdowns (February-March). The HP produces 6.78 GWh of heat with an electricity consumption of 1.84 GWh, leading to an annual SPF of 3.69. Over an entire year of monitoring, the ratio of heat produced during the DHW batches, i.e. between 55°C and 65°C, to the total heat produced is close to 52%. Outside the heating season, from June to early October 2019, the SPF value of 3.25 is lower than the annual SPF (Fig. 2b). It corresponds to the operation of the HP in DHW mode only. During the heating season, from October 2019 to June 2020, the SPF is higher (3.77), indicating that the COP of the HP in SH mode is higher than in DHW mode, as specified by the HP manufacturer. In this regard, the highest daily SPF match the days with the highest share of SH.

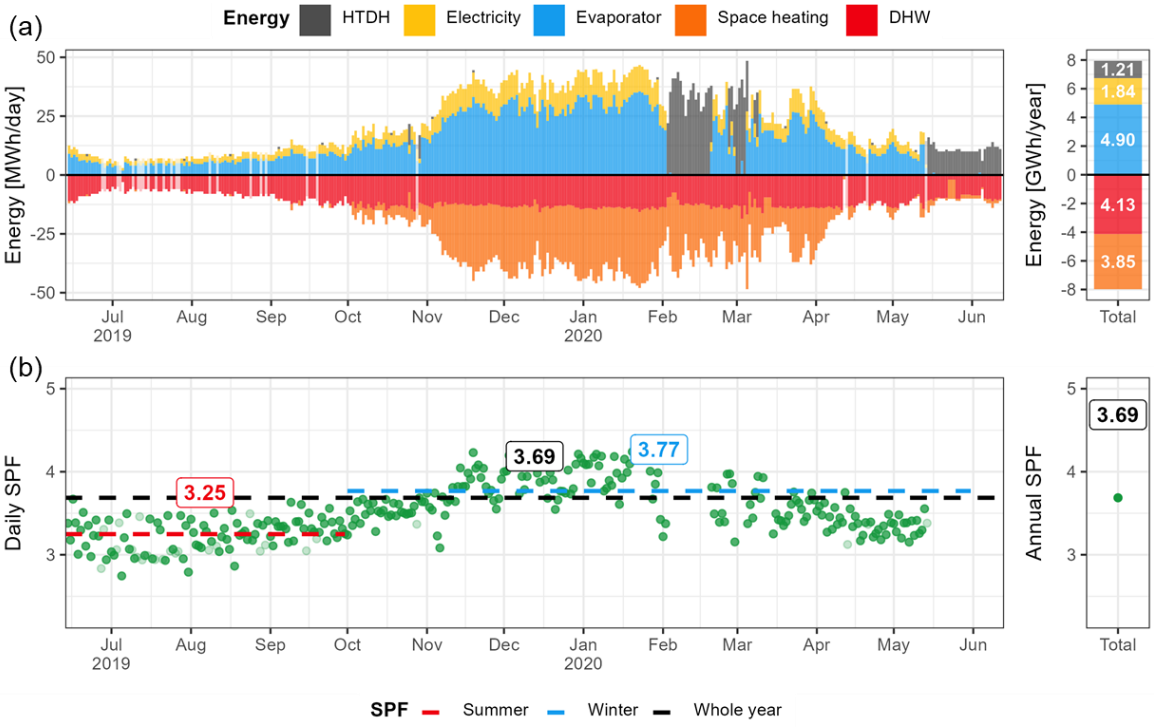

Fig. 2. Energy balance of the system and SPF of the heat pump on a daily and annual basis.

3.2. Measured and expected energy performance

Comparing hourly values of the measured COP with the expected COP provides a more accurate assessment of the HP performance, per operation mode (SH / DHW), than the daily or seasonal SPF presented before. In this regard, Fig. 3 shows, for each operation mode, the distribution of the measured hourly COP in bins of width 0.25, as well as the corresponding cumulative heat output, aggregated from the lowest to the highest COP. Vertical lines represent the measured SPF, as well as the expected COP provided by the manufacturer. These results confirm that the COP in DHW mode is generally lower than in SH mode.

In SH mode, the COP varies greatly, from 2.2 up to 5. A large share of the measured COP (41%) exceeds the expected COP of 4.60 provided by the manufacturer. The corresponding heat production represents nearly half of the heat production of the HP in SH mode. On the other hand, more than a third of the measured COP are below 4, representing about 25% of the heat production. For the whole period, the SPF (4.28) is only 7% below the nominal COP (4.60). Operation with high COP thus largely compensates for operation with very low COP. Hence, while the annual performance in this mode is close to expected, it could exceed expectations thanks to optimization measures.

In DHW mode, the COP is more stable as it varies from 2.8 to 3.5, but never reaches the COP announced by the manufacturer (3.62). While 45% of the measured hourly COP are below 3.25, most of the heat production (74%) is done with a COP between 3.25 and 3.5. Overall, the SPF is equal to 3.32, which is 8% less than the nominal COP (3.62).

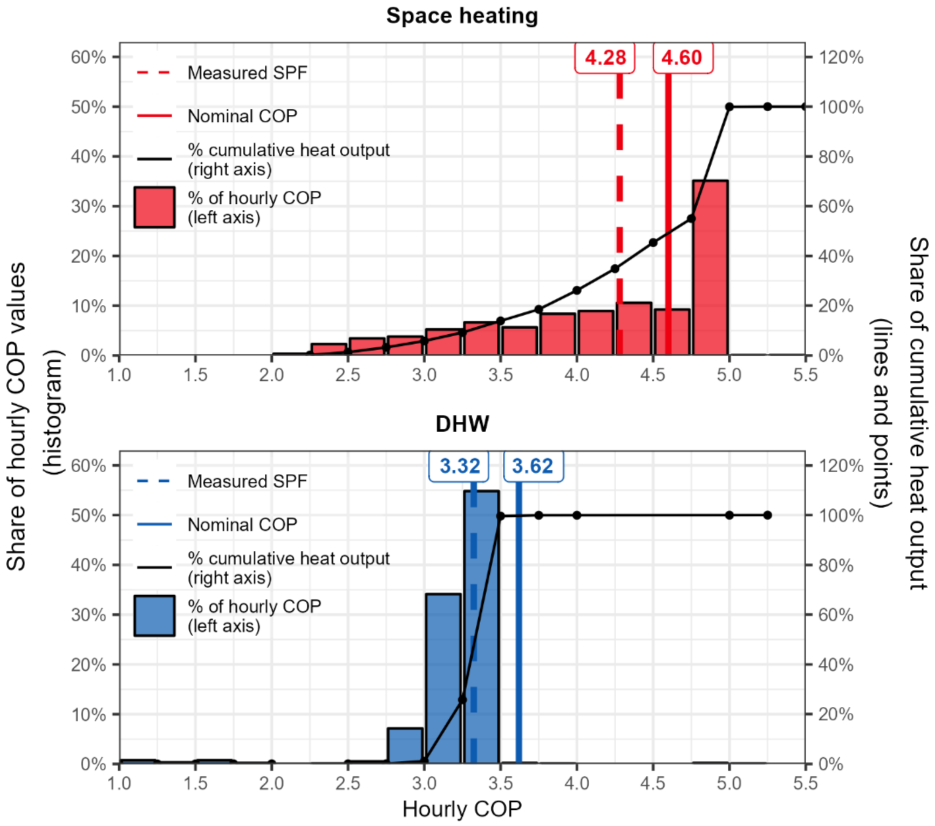

Fig. 3. Distribution of measured hourly COP per bins of width 0.25 (histogram), cumulative heat production aggregated from the lowest COP to the highest (black dots) and comparison with the manufacturer's data (vertical lines).

It should be noted that the results presented in Fig. 3 are based on available hourly data. As explained earlier, some data are either missing or inconsistent and have been excluded from the analysis. In the end, the valid hourly data presented correspond to a total heat production of 4.4 GWh, i.e. 64% of the HP heat production during this period.

With an annual electricity consumption of 1.84 GWh (Fig. 2), the HP is one of the main electricity consumer of the district since it represents about 30% of the total electricity demand (including heat pump and auxiliaries, as well as buildings' electricity consumption). Thus, even though the measured performance of the HP is close to the expected performance, there is a potential for optimization in both operation modes that could lead to significant electricity savings. To identify causes of low COP, the following sections focus mainly on SH mode. Reasons behind COP higher than the nominal COP in SH mode or lower than nominal COP in DHW mode could not be identified from the available information.

3.3. Factors of influence

To explain the performance gap between theoretical and measured COP and to identify optimization strategies, we first investigate the influence of the inlet and outlet temperatures at the evaporator and condenser.

The only temperature which can explain variations in COP within a given operation mode (SH / DHW) is the condenser inlet temperature, because: i) the evaporator inlet temperature is stable in SH mode, i.e. about 13°C, and varies only slightly in DHW mode (from 13°C to 16°C); ii) the condenser outlet temperature, i.e. the production temperature, is a setpoint for each operation mode (50°C in SH mode, 55°C at the beginning of the DHW batch and 65°C for the rest of the DHW batch). According to the system diagram in Fig. 1, the condenser inlet temperature results from two elements: i) the temperature at the bottom of the buffer tanks of the heating plant and ii) the DH return temperature.

Fig. 4a shows the measured hourly COP as a function of the temperature difference (ΔT) between the condenser inlet and the evaporator inlet, as well as the average temperature at the bottom of the storage tanks (color). As expected, the COP is higher in both operation modes when the ΔT is lower. The COP in SH mode is very sensitive to the ΔT: it varies from 2.2 for a ΔT of 28°C, to about 5 for a ΔT of 18°C. Furthermore, when the ΔT is lower than 23°C, there are significant variations in the COP, ranging from about 4 to 5 for the same ΔT. On the other hand, the COP in DHW mode is relatively unaffected by the ΔT since it varies from 2.8 to 3.5 over a wider range of ΔT, from 20°C to 38°C. In both modes, except for COP greater than 4 in SH mode, there is a clear correlation between the buffer tank temperature and the COP: the lower the temperature at the bottom of the tanks, the higher the COP. Besides, in DHW, the bottom of the tank reaches temperatures up to 50°C, which corresponds to the temperature at which the HP shuts down to prevent damage.

Not presented here, the same analysis with the DH return temperature instead of the buffer tanks temperature shows that, in SH mode, there is no systematic correlation between the DH return temperature and the COP. Whereas in DHW mode, results are similar to those of the buffer tanks temperature. Hence, the temperature at the bottom of the tanks is the main source of increase of the return temperature to the HP in SH mode. In DHW mode, the condenser inlet temperature is influenced both by the DH return temperature and by the temperature at the bottom of the tanks.

However, the variations of the condenser inlet temperature alone do not explain why, in SH mode, the hourly COP varies between 4 and 5 for the same ΔT of about 20°C (Fig. 4a). As shown in Fig. 4b, this is due to variations in condenser flow rate. The highest COP (4.8 to 5) occur for condenser flow rates of 90 m³/h or more, while the lowest (below 4.5) correspond to flow rates below 75 m³/h. Intermediate values are associated with the transition phase between these two flow rates.

Therefore, the COP of the HP is mainly influenced by: i) the condenser flow rate (Fig. 4b) and ii) the condenser inlet temperature, itself mainly influenced by the temperature at the bottom of the buffer tanks (Fig. 4a). The performance of the HP in SH is highest for flow rates above 90 m³/h and low condenser inlet temperatures (< 35°C).

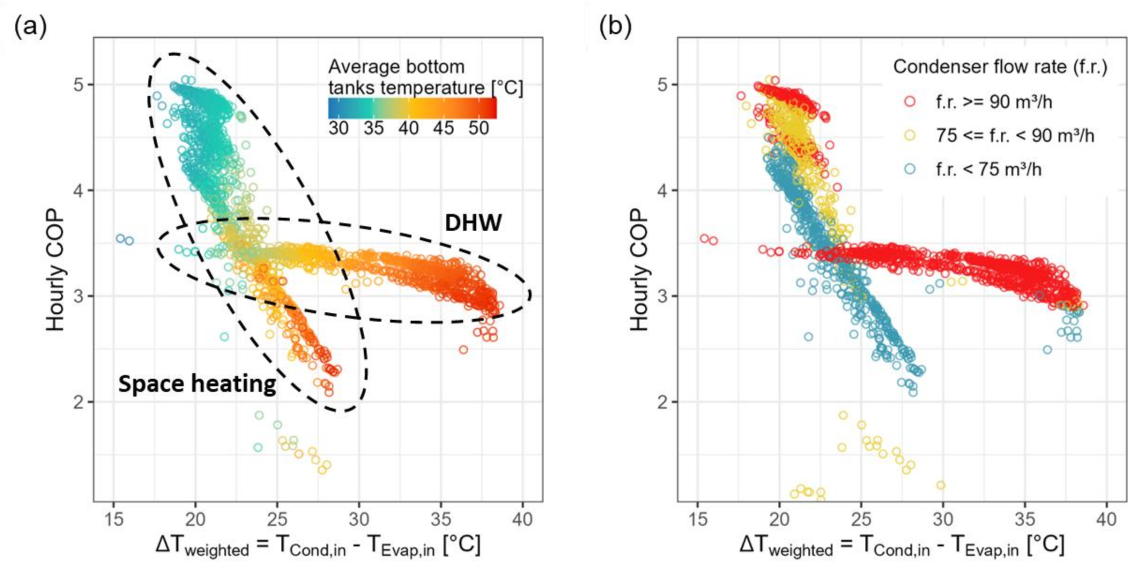

Fig. 4. Influence of the condenser flow rate and the temperature at the bottom of the buffer tanks on the hourly COP of the heat pump.

3.4. Typical Days

To understand more precisely the mechanisms involved in the degradation of the COP in SH, Fig. 5 presents typical days of operation of the HP during the winter. The location of the temperature sensors used to produce this figure is shown in the schematic of Fig. 1, where the colored circles correspond to the color of the lines. During those days (December 6th to December 8th), the HP operates at all times, except for approximately an hour and a half after each DHW batch, where it stops until the LTDH temperature lowers back to SH temperature levels (50°C).

The system dynamics indicates that low COP in SH generally occur before the DHW batches, while they are the highest after, following the temporary shutdown of the HP. During SH cycles *c2* and *c3*, there is a significant degradation of the COP, since it goes from 5 at the beginning of the cycle to about 3 at the end. First, the condenser flow rate decreases from 90 to 70 m³/h. Then, while the condenser flow rate is greater than the DH flow rate, the temperature at the bottom of the buffer tanks increases significantly (up to 50°C), thereby increasing the condenser inlet temperature. In SH cycle *c4*¸ the degradation of the COP is less important than for the two previous cycles (*c2* and *c3*) because the temperature at the bottom of the storage tanks remains low (around 34°C). There is only a reduction of the condenser flow rate in the middle of the cycle (between 1:00 a.m. and 3:00 a.m.). The only SH cycle illustrated here for which the COP of the HP is stable is cycle *c1*, during which the condenser flow rate remains high (equal to about 90 m³/h) and the temperature at the bottom of the tanks stays in the 30-35°C range. It is important to note that, in SH mode, the DH return temperature is stable. This indicates that, at this time of year, the degradation of the COP in SH is not due to high return temperatures from the DH substations. In DHW mode, the DH return temperature often reaches 50°C or more at the end of the batches, which can damage the HP and force it to shut down.

During the mid-season, the COP degradation phenomenon is amplified due to high imbalance between demand and HP production. Furthermore, the increase in condenser inlet temperature is not only due to an increase in buffer tank temperature, but also to high return temperatures of the DH substations.

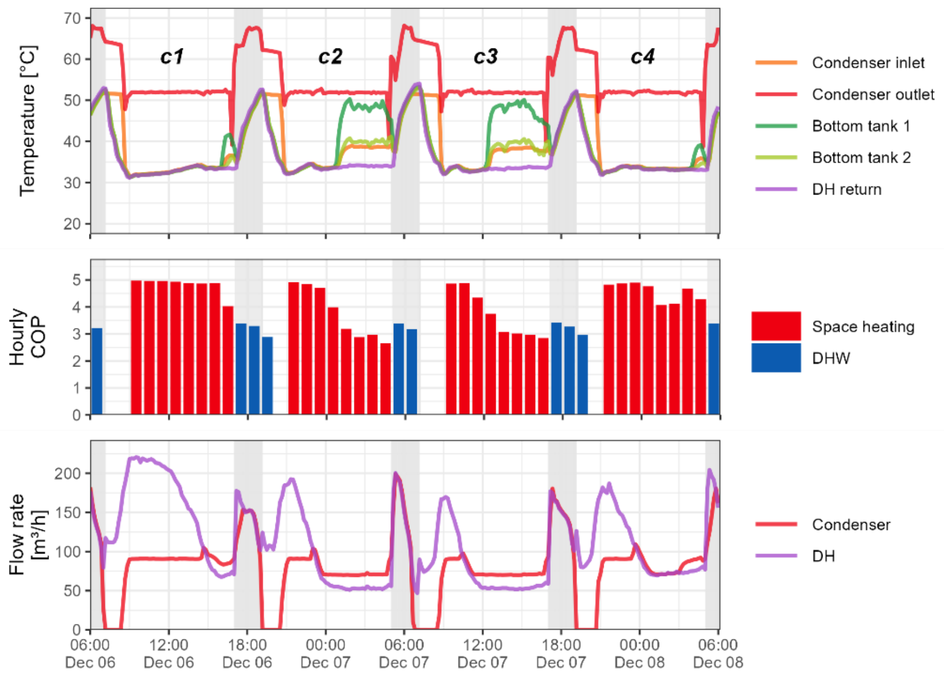

Fig. 5. Typical days of the system for December 6th to December 8th 2019. Gray background indicates the DHW batches. Refer to Fig. 1 for the location of temperature sensors.

In summary, the COP degradation phenomenon observed throughout the year can be caused by two elements:

- The high HP capacity compared to the demand which leads to: i) a reduction of the condenser flow rate to adapt to the demand, and ii) an increase of the buffer tanks temperature caused by storage of excess heat production.

- The substations and buildings control for SH which results in high DH return temperatures, in particular during the mid-season. Possible reasons are: i) a non-optimal control of the building SH circuits, which leads to high return temperature on the secondary side of the substations, thereby causing high return temperatures to the DH; ii) an excessive flow rate on the primary side of the substations, which leads to a low temperature difference between the inlet and outlet on that side, and thus to high return temperatures, regardless of the return temperature of the SH circuit on the secondary side.

3.5. Discussions and recommendations

The use of a HP with such a high capacity when the DH demand is low leads to an unsolvable problem. When the condenser flow rate is higher than the DH flow rate, the bottom of the tanks quickly heats up and increases the condenser inlet temperature. If the DH flow rate is increased, for the same heat demand, then the DH return also heats up. A solution would consist in lowering the production temperature of the HP: either punctually when the demand becomes too low during a SH cycle, or in a more systematic way by applying a heating curve to the DH supply temperature as a function of the outdoor temperature. This would allow to keep a relatively high flow rate at the condenser and to increase the DH flow rate while keeping DH return temperatures low.

It should be noted that the maximum capacity of the HP is 5 MW. However, the maximum heating power measured over this period is only about 2.5 MW in SH mode, while it reaches 4 MW in DHW mode. This difference between the two operation modes seems mainly related to the DHW batch system, gathering the whole daily DHW production in only 4 hours. Therefore, even if these batches avoid supplying the network constantly at 65°C, it raises an interesting point as for the sizing of the HP required for such a strategy, and thus of the necessary investment.

More generally, this analysis leads to the following recommendations, related to this case study in particular, but also to other HP in DH:

Control logic:

- **Adapt the DH supply temperature to the outdoor air temperature** to prevent operating with flow rates below the HP's operating limits, and thus degrading the HP performance. However, special attention should be paid to the network flow rates as such implementation leads to reduced temperature difference between DH supply and return, i.e. to higher DH flow rates. Therefore, to be beneficial, the increase in HP COP must compensate the additional electricity consumption for pumping.
- **Stop the HP sooner and operate on the DH inertia** to avoid reducing the flow rate and/or overheating the buffer tanks. The disadvantage of this solution is that heat pumps need time between each cycle to preserve their lifespan. It is thus challenging to decide when to switch it off, knowing it cannot turn back on immediately. Furthermore, if the HP stops shortly before a DHW batch, then the network temperature will decrease below 50°C. It will therefore take longer to reach the 65°C setpoint at the beginning of the DHW batch. As a result, it may prevent the DHW tanks within the buildings from being fully charged and thus cause comfort issues.
- **Optimize DH substations** to prevent high return temperatures, as pointed out in [7, 8], as high return temperatures reduce the HP energy performance and force it to shut down when it exceeds the operating limits. Such optimization might not only increase the HP performance, but also the overall efficiency of the district, if the faults identified also affect the energy performance of the buildings. For example, as shown in previous work [9], some buildings seem to have a high cut-off temperature of their SH system (> 15°C) despite their highly insulated thermal envelope. This suggests that some buildings are over-heated. Optimizing the control of the heat distribution system for these buildings would thus avoid having very low SH demand when the outdoor temperature is relatively high.

Sizing and system concept:

- **Use several smaller HP instead of one high capacity HP,** to better adapt to the DH demand and prevent overproduction compared to the demand, especially if the storage volume is low. This could however make the system control strategy more complex than with a single HP, because it is then necessary to manage several HPs.
- **Install bigger volumes for thermal storage compared to the minimum capacity of the HP,** to allow the HP to operate longer without overheating the storage and degrading the COP. Needless to say, there are economical and spatial constraints to such solution.

- **Use another strategy for DHW preparation**, as the DHW batch system leads to high return temperatures and causes HP breakdowns. It adds complexity to the system, both in terms of control strategy and equipment sizing compared to a substation that has the possibility to charge DHW tanks at any time of day. In addition, there has been complaints from building occupants regarding the lack of DHW, usually happening in the afternoon. Because supplying the DH network at 65°C at all time would mean achieving an annual SPF of 3-3.5 rather than 4-4.5, other, more energy efficient solutions should be explored. For example, installing booster heat pumps [10, 11] or flat substations [12, 13] with instantaneous water heating would allow to operate the network at lower temperatures than 65°C at all times, thanks to the limited risk of legionella bacteria proliferation. Both options would grant constant access to DHW preparation, thus an improved comfort for the occupants.

4. Conclusions

This study concerns the analysis, in actual conditions of use, of the energy performance of a large-scale heat pump supplying a low temperature district heating network. One of the specificities of this concept is that the district heating network is maintained at 50°C, and at fixed time, twice a day, its temperature is raised from 50°C to 65°C to heat up domestic hot water tanks within the buildings (batch).

Monitoring results show that the heat pump reaches an annual SPF of 3.69 (pumping excluded) and covers about 85% of the district heating demand. While the heat pump energy performance is close to the expected values (6-8% lower), the heat pump electricity consumption represents about 30% of the total electricity demand of the district, it is thus a consumption worthwhile to optimize.

The analysis of detailed monitoring data indicates that low energy performance is associated with low condenser flow rate and high return temperatures. This is mainly due to the high capacity of the heat pump compared to the demand and the storage volume, which leads to: i) a reduction of the condenser flow rate to adapt to the demand, and ii) an increase of the buffer tanks temperature of the heating plant, caused by storage of excess heat production. Furthermore, in mid-season, high return temperature from district heating substations in space heating also participate to the reduction of the heat pump performance, likely due to substations malfunctions. In domestic hot water mode, all substations of the district tend to have a high return temperature, partially due to the complexity of the domestic hot water batch strategy (control, equipment sizing, storage stratification etc.).

To prevent unexpectedly low energy performance of large-scale heat pumps in district heating, it is necessary to consider, but is not limited to, the following aspects: i) heat pump(s) and buffer tank sizing, which should allow to cover the highest demand, but also the lowest to avoid overheating the buffer tank; ii) control of the system, such as the use of a heating curve on the supply temperature of the network to operate the heat pump(s) at the lowest temperature possible, as well as to prevent high capacity heat pumps from operating at flow rates below operating limits; iii) substations monitoring and optimization, which allows to reduce the district heating return temperature to the heat pump(s), thereby increasing the energy efficiency and avoiding heat pump(s) shutdowns; iv) domestic hot water production strategies, as the batch system used in this case study has proven to be more challenging than anticipated, adding complexity to control and sizing of the system (heating plant and building substations) to guarantee the operation of the heat pump, the energy efficiency of the system and occupants comfort.

Because heat pump in district heating systems are expected to develop massively in the upcoming years, it would be interesting to explore alternative solutions to this concept, in actual conditions of use, such as the use of decentralized solutions for the domestic hot water production.

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