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Optimization of SPF or CO₂ emissions? Impact of control strategies on a bivalent waste water heat pump system for high energy standard buildings

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Abstract

While heat pump (HP) systems could be a main solution to achieve the energy transition, their operation in actual condition of use still face specific issues, in particular when integrated in multi-energy systems with fossil complement. Based on detailed monitoring (hourly data, entire year), this paper concerns the monitoring and simulation of the heat production system of a new low energy multifamily buildings complex in Geneva - Switzerland, comprising a centralized HP on waste water (200 kW_{th}) and complementary gas boiler (600 kW_{th}). For SPF optimization reasons and in order to take advantage of the lower space heating temperatures, a seasonally differentiated operation mode was planned for the HP, with a lower temperature production setpoint in winter than in summer (when only domestic hot water is needed). However, this does in fact limit the operation of the HP to short periods, and leads to a lower HP share (45%) than expected. By way of numerical simulation, we show that alternative operation modes could induce a higher share of HP production, up to 70%. Despite a possible drop in SPF (from 3.2 in the current situation to 2.7 when maximizing the heat pump production), we highlight that this could actually lead to a better system performance in terms of CO₂ emissions, when taking into account the related reduction in gas consumption of the complementary gas boiler, as well as the actual hourly electricity mix for the HP.

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1. Introduction

1.1. Context and issues

In the canton of Geneva, CO₂ emissions from the energy system represent about 4.2 t/capita, of which 2.2 are emitted by the building heat supply sector, 1.1 by the transport sector (excluding the airport), and 0.8 by the electricity sector [1]. As a result, the greatest potential for reducing CO₂ emissions lies in the building heat supply sector, which also accounts for nearly half of the final energy consumption delivered to consumers. In 2018, the energy consumption of this sector (climate adjusted) amounted to 5'300 GWh or 10.6 MWh/capita, and was mainly based on fossil fuels.

One of the options to valorize local renewable resources is the use of heat pumps (HP). In 2018, this technology covered 1.7% of the heat demand of the Canton of Geneva [1]. However, a set of recent prospective scenarios [1, 2] shows that the development of HPs, in combination with other production methods such as medium-depth geothermal energy, the development of district heating networks, as well as the reduction of the demand for the building stock, would allow a reduction of CO₂ emissions related to this sector to about 1 t/capita by 2035, respectively 0.2 t/capita by 2050.

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In this respect, it is however crucial to know and control: i) the actual performances of HP systems, in condition of use; ii) the effective thermal demand of high and very high energy performance buildings (in terms of heat load and temperature). These points are particularly crucial with regard to multifamily buildings, which represent 79% of the heated surface of Geneva's residential building stock, against 21% for single family houses [3].

The issue of using HPs for multifamily buildings is addressed in [4], which analyzes the potentials and constraints of various cold sources (air, unglazed solar panels, geothermal boreholes, lake, river, groundwater) for different types of buildings (new and existing). In new constructions, with reduced space heating (SH) demand and distribution temperature, the important share of domestic hot water (DHW) turns out to have a significant impact on the HP performance.

In order to use the warmest possible heat sources, and with the idea that the majority of the heat demand is in winter, geothermal and hydrothermal energy are a priori well placed, since their temperature remains relatively constant during the year, unlike the outside air. However, in many cases, legislation prohibits geothermal boreholes or water collection in subsurface aquifers (protection of drinking water resources). In this respect, waste water of the proper buildings is an interesting resource, both because of its temperature level which is higher than for low enthalpy geothermal resources, and because of its local and temporal availability matching the heat demand of the buildings, especially for the heat supply of DHW.

1.2. Objectives and structure

This paper concerns the monitoring and simulation of the heat production system of a new low energy multifamily buildings complex in Geneva, comprising a centralized HP on waste water (200 kW_{th}) and complementary gas boiler (600 kW_{th}) with heat distribution by a local district heating.

After a brief description of the buildings and heat production system, we present the heat production balance over an entire year of operation, followed by a detailed analysis and characterization of the related subsystems (waste water pit, HP, gas boiler). CO₂ emissions are assessed by taking into account the hourly Swiss electricity mix. Finally, numerical simulation shows that alternative operation modes could induce a higher share of HP production, with a drop in SPF but a better system performance in terms of CO₂ emissions.

2. System description

2.1. Buildings

Constructed between 2014 and 2019, the residential complex under consideration consists of 7 buildings, 4 of which comply with the legal requirement of "high energy performance" (HEP) for new constructions, and 3 comply with a "very high energy performance" (VHEP) requirement, equivalent to the Minergie label [5]. In total, the complex includes 335 apartments totalizing a heated area of 29'192 m², as well as 1'245 m² for extracurricular activities. The buildings are built according to an identical structure and shape (ground floor + 8 floors). Their thermal envelope differs by triple glazing for the VHEP buildings instead of double glazing for the HEP buildings, as well as by a tested airtightness for the VHEP buildings.

2.2. Heat production

The schematic diagram of the heat production is shown in Fig. 1. The waste water from the 7 buildings is collected in a central pit (approx. 37 m³), in which a filtration system retains and removes the solid waste. Heat extraction is realized by submerged heat exchanger, which is connected to the evaporator of the heat pump (HP) by way of a glycol water circuit. The cooled waste water is evacuated by a siphon from the bottom of the pit. The heat production of the HP (200 kW_{th}) is transferred to a buffer storage (2 x 10'000 l). A condensing gas boiler (600 kW_{th}), located downstream of the buffer, allows for complementary heat production. Except for the building that houses the boiler room and whose substation is directly connected to the primary circuit, the heat is transferred to the other six building substations by way of two heating networks (DH1 for the HEP buildings, DH2 for the VHEP buildings), which consist of classical 2-pipe distribution system. Within the substations (not depicted here), the hydraulic configuration allows for production or preheating of the domestic hot water tanks (DHW), with serial connection to the space heating (SH) distribution system.

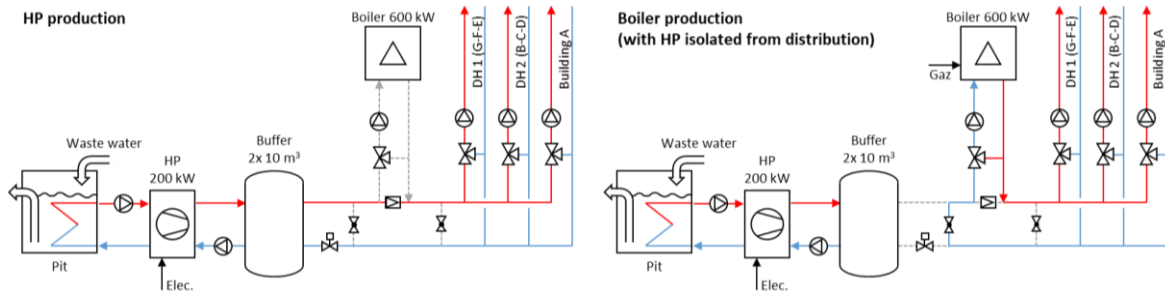


Fig. 1. Heat production scheme and modes.

The heat production system operates according to following alternative modes:

- HP production (Fig 1, left), which is engaged when the heat pump and its buffer can meet the demand (load and temperature).
- Boiler production (with the HP isolated from the distribution system - Fig 1, right), which is activated when the HP and its buffer can no longer meet the demand (in terms of load or temperature). In this case, in order to prevent the boiler from heating up the HP buffer via the return flow of the networks, the HP is isolated from the gas boiler and the DH networks, and operates in a closed loop for recharging of the buffer.

So as to improve the performance of the HP production and to limit the distribution losses, the system control includes temporary temperature rises (batches) several times a day for meeting the demand for domestic hot water (DHW), and differs between summer (DHW only) and winter (DHW + SH):

- In summer, the HP produces at its maximum temperature of 63°C, for covering of the DHW demand. The boiler only ensures the weekly rise in temperature for the treatment of legionella (heat production at 75°C during 2h), in which case the HP operates in closed loop with its buffer, which is maintained between 45 and 60°C (with an HP production at 63°C).
- In winter, the HP produces at 45°C, for covering of the SH demand along with preheating of the DHW tanks. As soon as there is a demand for DHW from any of the substation, the boiler ensures the production at 65°C for loading of all DHW tanks. During these periods, the HP operates in closed loop with its buffer, which is maintained between 40 and 55°C (with an HP production between 45 and 60°C).

2.3. Monitoring

The following data are collected from the centralized control system, in 20 minute time step, and aggregated into hourly and daily values: i) electricity for the HP, including associated circulating pumps (on evaporator and condenser side); ii) heat production by the HP and the gas boiler, as well as associated flow rates and temperatures (including HP buffer temperatures); iii) heat supply for SH and DHW production in each building, as well as associated flow rates and temperatures; iv) waste water temperatures (inlet and outlet of the waste water pit). In parallel, the inlet and outlet temperatures of the HP evaporator are collected by data-loggers placed by us.

3. Heat production balance

Within this study we focus on the year 2018, corresponding to the first full year of operation of the 4 HEP buildings (A, G, E, F - DH1), during which the VHEP buildings were still under construction. During that year, the heat demand (1'162 MWh, or 66.8 kWh/m²) is split between 59% for DHW and 41% for SH. The production (Fig. 2) is covered at 45% by the HP with an annual COP of 3.04 (including auxiliaries on the evaporator and condenser side), the 55% complement being covered by the gas boiler (with an efficiency of 86% on the upper heating value). While the HP provides the entire DHW production during the summer (except for the weekly anti-legionella temperature rise), in winter it essentially provides SH as well as DHW preheating, the boiler providing the DHW production.

The last 3 buildings were completed and connected to the heating network in the following year (2019). During that year, the HP was temporarily taken out of service due to repeated blockages of the waste water pit by unwanted materials from the construction site [6], reason why we do not include 2019 in this article.

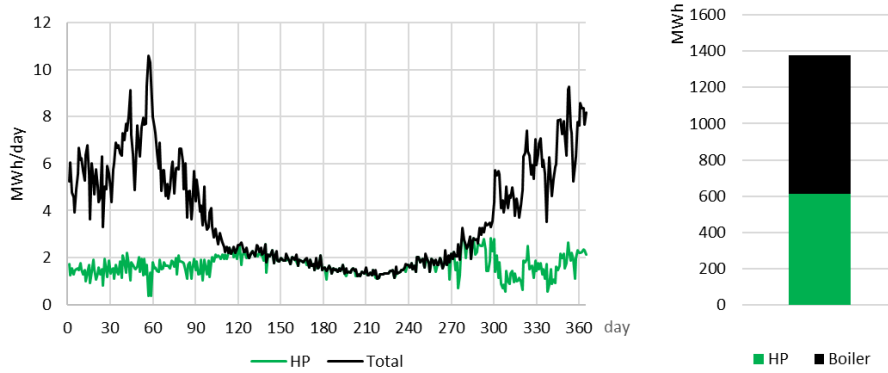


Fig. 2. Heat production dynamic and balance (daily and annual values).

4. Waste water pit

4.1. Temperatures

Operation of the waste water pit and its relationship to the HP is analyzed on the period ranging from February to December 2018, for which all the temperature data is available (in particular at HP evaporator as well as within the pit). In order to avoid intermittent operation, which make the analysis of the measurements more difficult, only the hours during which the HP operated continuously (60 min) are retained (corresponding to 85% of the HP production over the period). Finally, the filtered measurements are aggregated and analyzed in daily values (Fig. 3, left).

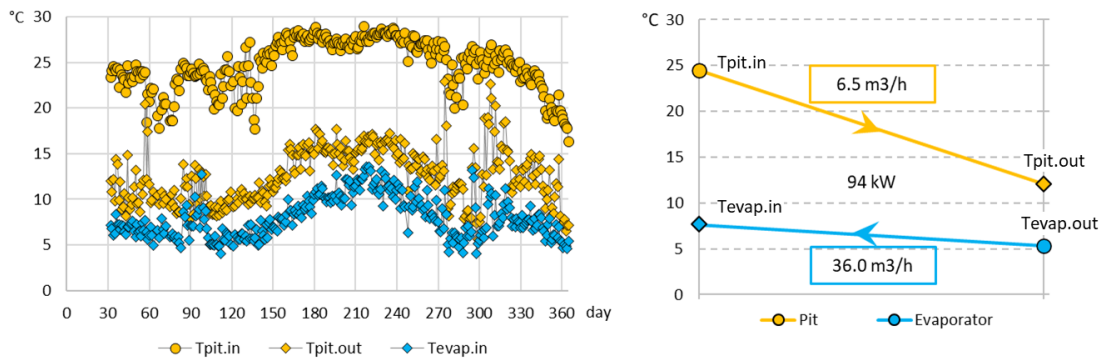


Fig. 3. Left: Temperature of pit (top and bottom) and evaporator inlet, daily values (Feb - Dec 2018); Right: Counterflow heat exchanger model (annual average).

Analysis of this figure leads to following observations:

- The temperature at the top of the pit (waste water inlet) varies between about 28°C in summer and 18°C in winter, with an annual average of 24.5°C. Based on a DHW share of 46% (as measured over a subsequent period, see further down), the latter value is about 7 K lower than the value resulting from the mixture of DHW (at 55°C) and cold water (at 12°C), which could be due to heat losses in the buildings and in the ground, especially in winter.
- In the pit, we observe a relatively important temperature drop (12.4 K in annual average) between the top of the pit (waste water inlet) and the bottom of the pit (waste water discharge, after exchange with the HP evaporator).
- Finally, the temperature at the evaporator inlet (corresponding to the heat exchanger outlet) has an average 7.6°C, i.e. 4.4 K below the bottom of the pit.

4.2. Flowrates

By transferring the daily power extracted from the evaporator (and therefore from the pit) to the temperature loss between the top and bottom of the pit, we can estimate the flow of waste water transiting through the pit

during HP operation. Except for a few peaks, this calculated flow is around 5 to 10 m³/h, with an average of 6.5 m³/h, i.e. 1.6 m³/h per building. For the sake of comparison/validation, hourly monitoring of the DHW consumption yields values between 0.5 and 1 m³/h per building (during day-time), and weekly readings of total water consumption yield an average share of 46% for DHW and 54% for cold water. Assuming that the cold-water consumption follows the same profile as the DHW, the total day-time water consumption would amount to about 1 - 2 m³/h per building, compatible with the value of 1.6 m³/h used here.

By comparison, the nominal flow rate in the evaporator is 36 m³/h (5.5 times higher than the 6.5 m³/h estimated for the waste water of the 4 buildings, in period of HP operation), corresponding to an evaporator inlet / outlet temperature differential of 2.2 K (i.e. 5.5 times lower than that observed between the top and bottom of the pit).

4.3. Characterization of the heat exchange

The average annual operation of the heat exchange between the pit and the HP evaporator can be characterized by way of a counterflow heat exchanger [7], which links the heat exchange efficiency ε to the flowrate ratio V_{ratio} and to the number of transfer units NTU (ratio between the heat exchange factor and the heat flowrate of the pit):

$$\varepsilon = \frac{1 - \exp(-NTU(1 - V_{ratio}))}{1 - V_{ratio} \exp(-NTU(1 - V_{ratio}))} \quad (1)$$

Where:

$$\varepsilon = \frac{T_{pit.in} - T_{pit.out}}{T_{evap.in} - T_{evap.out}} \quad (2)$$

$$V_{ratio} = \frac{V_{pit}}{V_{evap}} \quad (3)$$

$$NTU = \frac{H}{C_{water} \cdot V_{pit}} \quad (4)$$

With the average annual operation conditions described above (Fig. 3, right), the efficiency of the waste water heat exchanger amounts to 65%, which corresponds to a NTU of 1.1, i.e a heat exchange factor H of 8.5 kW/K.

4.4. Alternative scenarios

All other things remaining equal (load absorbed at the evaporator of 94 kW, pit inlet temperature of 24.5°C, heat exchange factor H of 8.5 kW/K), the model in question allows to evaluate the performance of the waste water / HP heat exchange, for various alternative configurations (Fig. 4):

- **4 Bld**: This configuration, which corresponds to the situation observed above, concerns the 4 buildings connected in 2018, with a waste water flow during HP operation of 6.5 m³/h, for a flow in the evaporator of 36 m³/h. It results in the observed evaporator inlet temperature $T_{evap.in}$ of 7.6°C, respectively an evaporator average temperature T_{evap} of 6.5°C (where $T_{evap} = (T_{evap.in} + T_{evap.out})/2$).
- **7 Bld**: This configuration corresponds to a waste water flow rate of 11.3 m³/h (all 7 buildings), for an unchanged evaporator flow rate. It results in an evaporator inlet $T_{evap.in}$ of 10.9°C, i.e. an evaporator average T_{evap} of 9.8°C.
- **7 Bld + Veq**: This configuration is identical to the previous one for waste water, however with a reduced flowrate in the evaporator (11.3 m³/h, equal to the one of the waste water). As a result, the evaporator inlet $T_{evap.in}$ rises to 13.5°C. However, the reduction of the evaporator flowrate results in an increased temperature drop in the evaporator (7.1 K, identical to that of the waste water), i.e. to an average evaporator temperature T_{evap} of 10.0°C, almost identical to the previous case.
- **7 Bld + 2 S**: This configuration corresponds to 7 buildings (without balancing of the evaporator flowrate), but with a doubled heat exchanger surface (i.e a doubled heat exchange factor H). It results in an evaporator inlet $T_{evap.in}$ of 16.2°C, respectively an evaporator average T_{evap} of 15.1°C.

- **7 Bld + Veq + 2 S:** This last configuration combines the balancing of the flow rates and the doubling of the exchange surface, resulting in evaporator inlet $T_{evap.in}$ of 19.0°C, respectively an evaporator average T_{evap} of 15.4°C, again almost identical to the previous case.

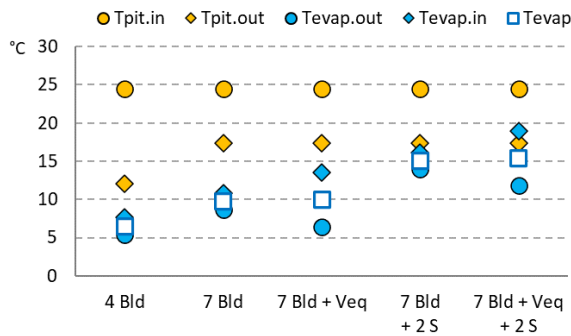


Fig. 4. Temperatures of waste water pit and HP evaporator, for various configurations.

With the connection of the last 3 buildings, the temperature in the evaporator should be around 3.3 K higher than the one observed in 2018. In principle, this performance could be further improved by 5.3 K with doubling of the submerged heat exchanger surface.

5. Heat production units

5.1. Heat pump

The dynamic of the ΔT (condenser outlet – evaporator inlet) and COP of the HP (including auxiliaries) is presented in Fig. 5. HP operation at a high ΔT mainly occurs in the summer, for DHW supply at 63°C. In the winter, the operation at a lower ΔT is mainly related to the production of SH at 45°C.

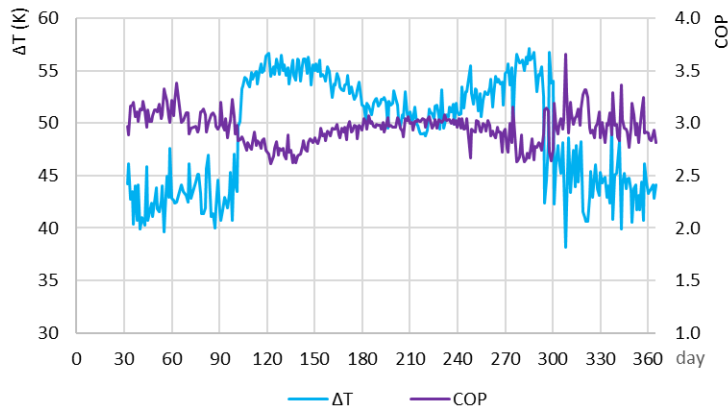


Fig. 5. HP performance (including auxiliaries) and temperature difference between condenser and evaporator (ΔT), daily values (COP filtered when the heat pump operates 60min/hour; ΔT weighted by the energy supplied by the heat pump).

The 2018 SPF is 3.04 including electricity for the auxiliaries (circulation pumps on evaporator and condenser side). This value is related to an energy-weighted temperature average of 7°C at the evaporator and 56°C at the condenser, representative of the average HP operation. The corresponding thermodynamic HP efficiency hence amounts to 45% (ratio between the actual SPF and the Carnot SPF, the latter corresponding to the maximum theoretical performance, for the same operating point).

For comparison, according to the HP data sheet, operation at 14°C / 60°C announces a COP of 3.67 (195 kW thermal supply, 53.2 kW electrical consumption), corresponding to a thermodynamic efficiency of 51%. However, note that latter values do not take into account the electricity of the circulation pumps on the evaporator and condenser side.

5.2. Gas boiler

Based on manual readings of the gas and heat production meters (taken between April 2019 and January 2020), the boiler efficiency is 86%, as calculated on the higher heating value of 11.39 kWh/m³ of natural gas. This efficiency, which may seem low for a condensing boiler, is related to the relatively high operating temperatures of the boiler, mainly due to heat production for DHW, which limits the possibility of heat recovery by flue gas condensation. For the 2018-2019 period, the energy-weighted average temperatures for the boiler supply and return are 61°C and 50°C respectively. For comparison, the manufacturer announces an efficiency of 88% at a temperature regime of 70/50°C, respectively 92% at a regime of 60/40°C.

6. CO₂ balance

6.1. CO₂ content of gas and electricity

While the CO₂ content of gas is well established (228 gCO₂-eq/kWh on higher heating value [8]), the same is not true for electricity, whose origin is subject to debate. In this study, we use the Swiss consumption mix emission factor, calculated on an hourly basis [9]. This calculation takes into account domestic production and inflows into Switzerland from its neighboring countries. To do so, it uses hourly data of the production mix of the different European countries, by type of production, as well as hourly cross-border flows. On the basis of economic considerations with respect to merit order of the various types of production, it takes into account the impact of Swiss imports on the production mix of neighboring countries. Finally, the CO₂ content of the resulting electricity mix is calculated from the carbon intensity of each type of generation. During the winter of 2018, there were occasional peaks of more than 500 gCO₂-eq/kWh_{el}, mainly due to fossil electricity imports from Germany. These peaks are much smaller in daily values, rarely exceeding 300 gCO₂-eq/kWh_{el}. Finally, given a low-carbon electricity in summer, the annual average is 107 gCO₂-eq/kWh_{el}. Note that this value is very close to those observed over the previous two years (105 and 108 gCO₂-eq/kWh_{el}).

6.2. CO₂ content of the heat mix

The CO₂ content of the heat production is calculated in hourly values, based on the above data. It is represented in daily and annual values in Fig. 6. It can be seen that the dynamic of the emissions is strongly correlated to the heat demand, and is essentially linked to the use of the gas boiler, whose emissions largely dominate those of the HP. Thus, although the HP covers 45% of the annual heat production, it represents only 10% of the CO₂ emissions. In total (HP + boiler), the latter amounts to 224 tCO₂-eq (or 163 gCO₂-eq/kWh_{th}).

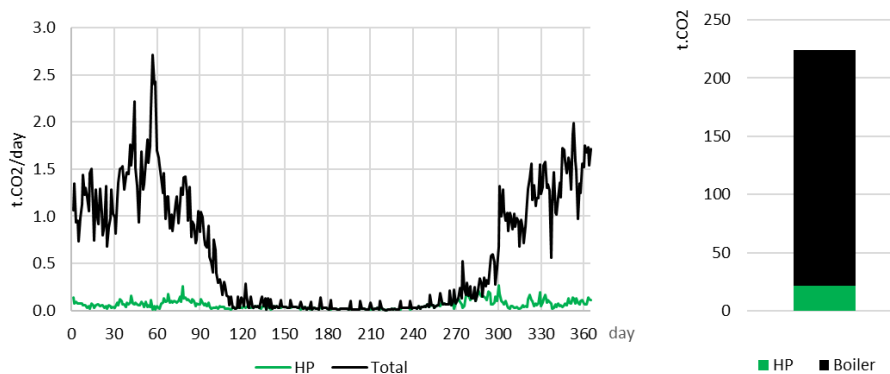


Fig. 6. CO₂ emissions, dynamic and balance (daily and annual values).

In other words, given an efficiency of 86%, the carbon content of the heat production by the boiler is 265 gCO₂-eq/kWh_{th}. Given a relatively constant COP of around 3, the carbon content of the heat production by the heat pump is 7 times lower, namely 35.4 gCO₂-eq/kWh_{th}. As a consequence, up to an electricity carbon content 7 times higher (820 gCO₂-eq/kWh_{el}), the HP heat production would still have a lower carbon content than that of the gas boiler.

7. Evolution and optimization potential

As we have just seen, the CO₂ content of the kWh produced by the heat pump is much lower than the one produced by the boiler, which argues a priori for the most intensive possible use of the HP. However, it turns out that with the current settings, the HP produces less in winter than in summer, despite a higher heat demand (see Fig. 2). In order to evaluate the system optimization potential in relation to the HP operation settings, we conduct an hourly numerical simulation, based on the values measured in 2018. The model also allows to evaluate the evolution of the heat production mix with the connection of the 3 additional buildings (not yet present in 2018).

7.1. Simulation model

The simulation model takes up, in a simplified way, the essential elements of the heat production system, namely: i) the HP and its buffer; ii) the gas boiler; iii) the primary distribution circuit (internal to the boiler room) and the outlet of the district heating / building substations. The algorithm, which is integrated in a spreadsheet, is executed in hourly time step.

The inputs to the model are as follows (in hourly values):

- At source level, the evaporator inlet temperature ($T_{evap.in}$), which is given by a sinusoidal between 5°C at the end of January and 12°C at the end of July, in accordance with what has been observed.
- The instantaneous heat demand, given in terms of load (Q_{dem}) by the demand measured at the substations, and in temperature (T_{dem}) by the temperature measured at the outlet of the boiler room / inlet to the district heating network (note: for simplification purposes, the thermal losses of the district heating network, as well as the phase shifts linked to the transit time to the substations, are not taken into account).

The main characteristics and parameters of the model correspond to the observed values, and are summarized as follows:

- The HP is characterized by a fixed electrical power of 50 kW, and a thermodynamic efficiency of 45%, which allow at each moment to calculate the COP and the heat production Q_{HP} , according to the temperatures at the condenser and evaporator (T_{HP} and $T_{evap.in}$).
- The buffer is represented by a non-stratified one-node model, characterized by a thermal capacity of 20 m³ and a single temperature (T_{buffer}). Depending on the imbalance between production (Q_{HP}) and demand (Q_{dem}), the buffer is used for storing/retrieving of the excess/missing heat. Its operating range is limited by upper and lower temperature setpoints, which determine the on/off switching of the HP (see the control concept below).
- The gas boiler is characterized by an efficiency of 86% on the higher heating value.

The operating modes are as follows (in order of priority), and correspond to the observed operating modes:

- HP + buffer charge: this mode is activated when the HP production is sufficient to meet the demand (in terms of load and temperature), the excess heat being stored in the buffer.
- HP + buffer discharge: this mode is activated when both: i) the HP production allows to meet the demand temperature, but not the load; ii) the buffer temperature is sufficient to meet the demand.
- Buffer discharge alone: this mode is activated when the HP is stopped (buffer setpoint reached) and the buffer temperature is sufficient to meet the demand.
- Boiler on: this mode is activated when neither the HP nor the buffer can meet the demand (temperature and/or load). In this case, the HP and the buffer are isolated from the primary distribution circuit, and operate in a closed loop, for recharging of the buffer.

Finally, in accordance with what is observed at the level of monitoring, the control setpoints are adapted according to the season: i) in summer, the HP produces at its maximum temperature of 63°C, and the buffer is maintained between 45 and 60°C; ii) in winter, the HP produces at a temperature 5 K higher than that of the buffer, which is maintained between 40 and 55°C.

7.2. Validation

Initially the simulation is carried out on the basis of the demand observed in 2018, corresponding to the first 4 constructed buildings, connected to heating network DH1 (buildings A-F-G-E).

As shown in Fig. 7 the simulation reproduces very well the share of the heat production between HP and boiler. In the case of the boiler, the difference observed on the last 2 months of the year is due to the recent connection of an additional substation (building B), which is not accounted in the demand used for the

simulation. The consistency between simulation and measurement is also very satisfactory regarding the electrical consumption of the HP, with a simulated SPF of 3.10, against 3.04 for monitoring.

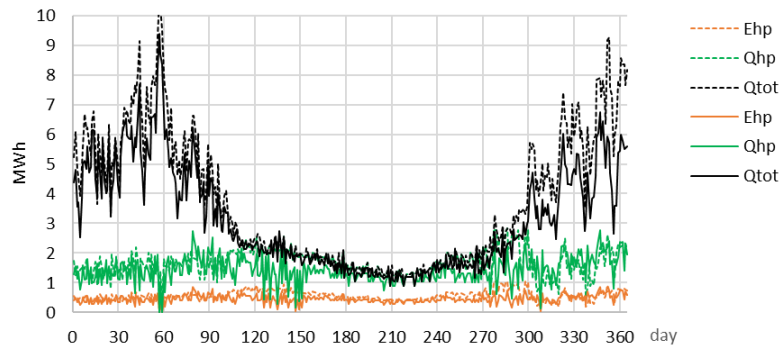


Fig. 7. Heat production (total and HP) and HP electricity, integrated daily values, monitoring (dashed lines) and simulation (solid line).

7.3. Sensitivity analysis

For the sake of comparison with the base case simulated above, we perform a sensitivity analysis for following HP operation scenarios:

- **Reference:** this is the basic scenario described above, in which: i) the HP and the boiler operate in alternating mode (the HP and its buffer being decoupled from the distribution network when they cannot meet the load and temperature of the demand); ii) the HP control setpoints are adapted according to the season (with lower production temperatures in winter than in summer).
- **Alternate:** in this scenario, the HP and the boiler also operate in alternate mode, but the HP control setpoints are maintained all year round at their high values (summer setpoints of the base case).
- **Series:** in this scenario, the heat pump and the boiler operate in series, the heat pump continuing to deliver heat to the network when its temperature is high enough, the additional load being provided by the boiler. In this scenario, the production setpoints of the HP are maintained throughout the year at their high values.
- **Series + 60°C:** this scenario corresponds to the previous scenario, but the network temperature never exceeds 60°C (except for the weekly rise for the anti-legionella treatment).

Fig. 8 represents the network demand and the heat production of the HP, for these various operation modes. Moreover, the various scenarios are simulated on the one hand for the demand of the first 4 buildings (as was the case in 2018), and on the other hand for a demand multiplied by a factor of 1.75, representing in a simplified way the demand of all 7 buildings. The following qualitative observations can be made:

- While in the **Reference** scenario the HP production drops during the winter, it remains at a slightly higher level in the **Alternate** scenario, when the summer setpoints are maintained throughout the year as.
- Winter HP productivity increases significantly in the **Series** scenario, with the HP operating in series with the boiler, and reaches its full potential when the network temperature is maintained below 60°C (**Series + 60°C**): the winter productivity ceiling of 3 MWh/day corresponds to 20 hours of operation at 150 kW, i.e., the available capacity for an evaporator temperature of 5°C and a production at an average of 50°C.
- When taking into account the demand of all 7 buildings, the HP productivity increases slightly (in MWh/day), but covers a proportionally smaller fraction of the demand. We observe in particular that the HP can no longer provide 100% of the summer DHW demand. Indeed, with 7 buildings, the demand linked to DHW batches typically reaches a daily peak of 400 kW, which can no longer be fully met by the HP.

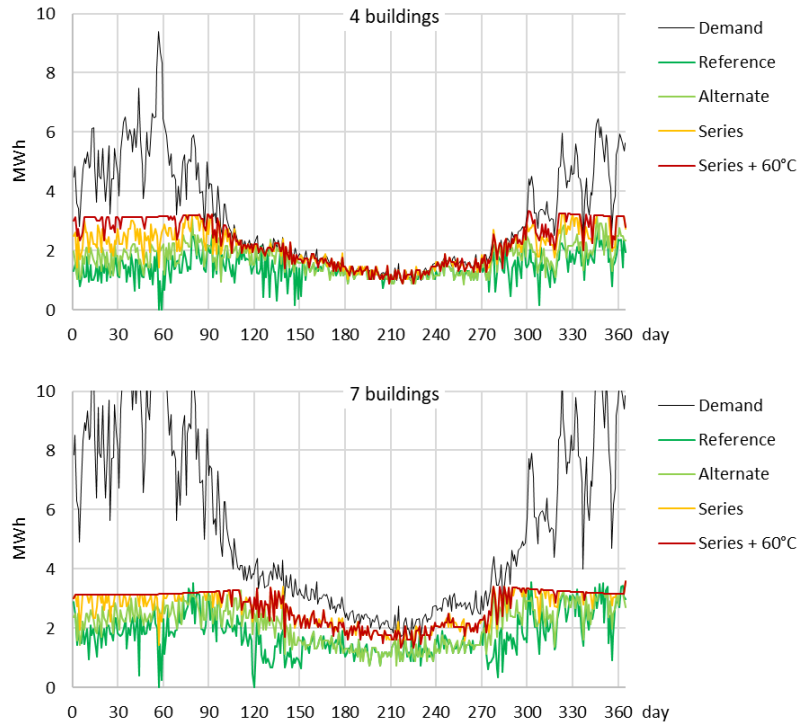


Fig. 8. Demand and HP production for various operating modes (daily values, 4 or 7 buildings).

Fig. 9 represents a set of annual performance indicators (boiler share in the heat mix, CO₂ content of total thermal kWh, SPF of the heat pump), for the various operating modes above, as well as for a 100% boiler scenario. The following conclusions are drawn:

- With 4 buildings to be supplied with heat, the **Reference** scenario allows to reach a coverage rate of 45% via the heat pump, but this rate might drop to about 30% with the connection of the 7 buildings. These rates could in principle increase significantly with the operation of the heat pump in series with the boiler, and a high production temperature maintained throughout the year: thus the **Series** and **Series + 60°C** scenarios both show coverage rates of about 70% (for 4 buildings), respectively 50% (for 7 buildings).
- Given the low CO₂ content of the heat produced by the heat pump, the carbon content of the heat mix falls in a totally correlated way with the fall in the boiler coverage rate, despite a slight fall in the COP of the heat pump (which goes from about 3.2 in the **Reference** scenario to about 2.7 in the other scenarios).
- The linear correlation between the carbon content of the heat mix and the boiler coverage rate is explicitly shown in Figure 9.

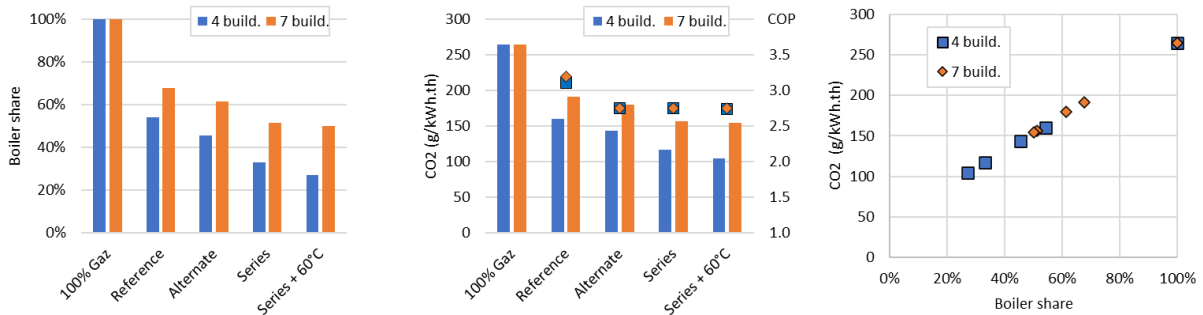


Fig. 9. Performance indicators (boiler share of the heat mix, CO₂ content of the thermal kWh and SPF of the heat pump) for various operating modes (annual values, for 4 or 7 buildings).

Note: in this model, the evaporator inlet temperature is in all cases defined in accordance with the monitored values of the reference case. As has been seen in section 4.4, such is strictly speaking not correct for 7 instead

of 4 connected buildings, in which case we would theoretically expect the evaporator temperature to be about 3.3 K higher. Latter would have a slight positive impact on the annual SPF and on the HP share of the heat production, but would not drastically change the insights gained by this analysis.

8. Conclusions

This paper concerns the monitoring and simulation of the heat production system of a new low energy multifamily buildings complex in Geneva, comprising a centralized HP on waste water (200 kW_{th}) and complementary gas boiler (600 kW_{th}) with heat distribution by a small-scale district heating network. For SPF optimization reasons and in order to take advantage of the lower space heating temperatures, a seasonally differentiated operation mode was planned for the HP, with a lower temperature production setpoint in winter than in summer (when only domestic hot water is needed). However, this does in fact limit the operation duration of the HP to short periods, and leads to a lower HP share than expected.

By way of numerical simulation, we show that alternative operation modes could induce a higher share of HP production, up to 70%. Despite a possible drop in SPF (from 3.2 in the current situation to 2.7 when maximizing the heat pump production), this could actually lead to a better system performance in terms of CO₂ emissions, when taking into account the related reduction in gas consumption, as well as the actual hourly Swiss electricity mix consumed by the HP. At this point, it is however important to emphasize that the current performance of the system is already much better than in the case of 100% fossil fuel production, especially as the heat demand remains low overall.

As a complement, future simulation work could include additional scenarios concerning issues like: i) enhanced flue gas heat recovery by coupling with the HP evaporator, which could also enhance latter's COP; ii) sensitivity analysis concerning HP sizing, in link with possible HP cascading,

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