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In-situ analysis of a centralized wastewater heat pump for a complex of high energy standard buildings

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Abstract

While heat pump systems combined with district heating could reduce the CO₂ emissions of Geneva's heating sector, it is crucial to know and control their performance in real condition of use. This paper concerns detailed monitoring (hourly data, entire year) of a new low energy multifamily buildings complex, with centralized heat pump on wastewater (200 kW) and complementary gas boiler (600 kW). Heat production is covered at 45% by the heat pump (SPF: 3.03), with 55% complement by the gas boiler (85% efficiency). At the level of the buildings, domestic hot water supply (39.5 kWh/m²) accounts for 59% of the demand, against 41% for space heating (27.3 kWh/m²). For space heating, the gap between measured and climate corrected design values can be explained by operation conditions which differ from the norm (indoor temperatures, window openings), but remains quite lower than benchmark values on the recent building stock. Domestic hot water supply is also above the normed value, but coherent with a benchmark on other buildings. Finally, we highlight some issues and recommendations for optimized system integration and control concerning this type of innovative solution.

Keywords: wastewater heat recovery ; district heating ; multi-family buildings ; in-situ monitoring ; performance gap

1. Introduction

Nomenclature

| | |
|-------|---|
| DH | district heating |
| DH1 | district heating network with the 4 studied buildings |
| DH2 | district heating network with the last 3 buildings under construction |
| DHW | domestic hot water |
| HEX | substation heat exchanger |
| HP | heat pump |
| MFB | multifamily building |
| SH | space heating |
| SPF | seasonal performance factor (annual or seasonal value) |
| VHR | ventilation heat recovery by dual flow |
| WW | wastewater |
| WW-HX | wastewater heat exchanger |

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1.1. Context and issues

In Geneva, the heat demand is mainly covered by fossil fuels, with individual gas or heating oil boilers. One of the most realistic and expected option for renewable heat integration in this dense urban area is the development of district heating (DH), along with integration of centralized or individual heat pumps (HP) [1].

The potential and performance of HP systems is however linked to the temperature range of available heat sources such as ground, ground water, lake water or air, and its adequacy to the related heat demand in terms of quantity and temperature level [2]. A further key point for HP integration in heating systems is its eventual combination with other resources, typically fossil boilers, which requires careful system design planning and regulation [3].

Moreover, on the heat demand side, actual values of energy demand usually turn out to be higher than project values, as well for retrofit of old buildings [4], as for new buildings with high energy standards [5]. Concerning new buildings, the heat demand for domestic hot water (DHW) production represents a growing share compared to the space heating (SH), and becomes a key point for HP integration, as it requires relatively high temperatures levels.

In this context, in particular in the case of innovative systems, it is important to understand real conditions of use and operating constraints through system monitoring, which is also an opportunity to highlight optimization issues and possibilities.

1.2. Objectives

This paper concerns a new low energy MFB complex located in Geneva, whose heat is produced by a centralized 200 kW_{th} HP on wastewater (WW) with a complementary 600 kW_{th} gas boiler, and distributed via a local DH network.

Based on detailed hourly monitoring over an entire year of operation, we derive the annual energy balance of the entire system and analyze the annual daily dynamic of heat production and demand. We then display daily heat production temperatures, and highlight their impact on operating constraints, especially for the HP. Finally, we focus on the performance gap of SH and DHW supply, as compared to project values.

2. Case study

2.1. Buildings and system layout

Situated in Geneva, the case study concerns the first 4 buildings of a complex of 7 new MFB, built according to the *Minergie* low energy demand standard. The studied buildings have a total heated area of 17'400 m², of which 16'150 m² for housing and the rest for extracurricular activities for school kids. Note that the 4 buildings have an identical heated surface area (4'350 m²), structure and form (9 storeys), as well as thermal envelope.

The simplified schematic of the heat production and distribution system is depicted in Figure 1. Base load production is supplied by way of a 200 kW_{th} wastewater HP, which is connected to a centralized wastewater tank with immersed heat exchanger system (WW-HX) [6]. On condenser side, the HP delivers its heat to a 20m³ buffer. Complementary peak load is supplied by a 600 kW_{th} gas boiler.

Heat distribution to the buildings is provided by way of 2 local DH networks, one for the 4 buildings of the case study (DH1), the second for the 3 buildings still under construction (DH2). At the level of each building, supply is delivered by way of a heat exchanger (HEX) on a secondary circuit, which supplies a DHW storage tank (in priority) and the SH floor heating circuit (connected to the outlet of the DHW supply).

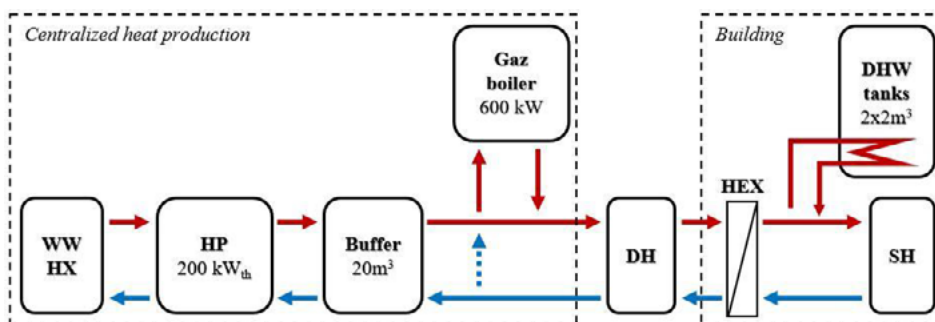


Fig. 1. Simplified schematic of heat production and distribution

2.2. Monitoring

The main data in 20 min time step is collected from the centralized control system, and aggregated in hourly and daily values. In terms of energy flows, it concerns: i) electricity for the HP and related circulation pumps; ii) heat production of HP and gas boiler; iii) in each building, heat supply for DHW (at storage inlet) and for SH. The associated temperatures, as well as the wastewater temperatures (tank inlet and outlet, evaporator in and outlet) are also collected.

As a complement: i) spot monitoring of the mechanical ventilation system (temperatures and air flows) allows to characterize the corresponding heat recovery and loss; ii) weekly reading of the gas consumption is used to determine the boiler efficiency.

3. Results

The results presented in this paper concern the first year of operation (2018) with complete hourly data on centralized heat production and heat demand of the 4 buildings under consideration (DH1).

3.1. Annual heat production and demand

The annual heat production and demand flows are depicted in following Sankey diagram (Figure 2).

The HP production (613 MWh) accounts for 45% of the total production, with a seasonal performance factor (SPF) of 3.03, including ancillary electricity of circulation pumps on evaporator and condenser side. This SPF can be related to an annual energy weighted average temperature of 56°C (at condenser outlet) and 7°C (at evaporator inlet), corresponding to 45% of the Carnot performance factor. The 55% complement by the gas boiler (761 MWh) is produced with an 85% efficiency (on higher heat value).

The produced heat is mainly distributed to the 4 buildings under consideration (DH1), while the remaining part goes for the last 3 buildings, which were already partially heated while under construction (DH2), and for storage and distribution losses.

At the level of the 4 buildings, DHW supply (687 MWh) accounts for 59% of the total, against 41% for SH (474 MWh). As a complement to direct SH, ventilation heat recovery by dual flow (VHR) with a measured 80% efficiency, contributes with 420 MWh to compensation of heat losses through the building envelope.

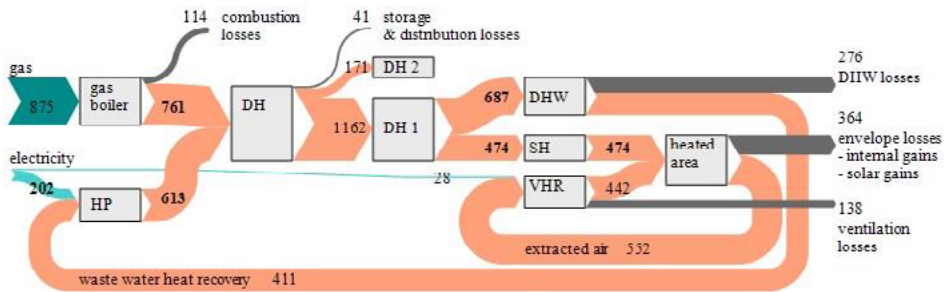


Fig. 2. Sankey diagram, 2018 (unit: MWh; bold font: completely monitored values; normal font: derived values and/or spot monitoring)

3.2. Seasonal dynamic

The seasonal dynamic of heat production and demand is presented in Figure 3. In summer the HP is able to fully furnish the DHW supply, except for a weekly temperature rise of 1 h, for legionella prevention, done by the gas boiler. The HP production slightly drops during winter, and is complemented by a high heat fraction from the gas boiler. Unlike what could be understood at first sight, winter HP production actually doesn't cover the DHW supply, but rather part of the SH supply at lower temperatures, as clarified below.

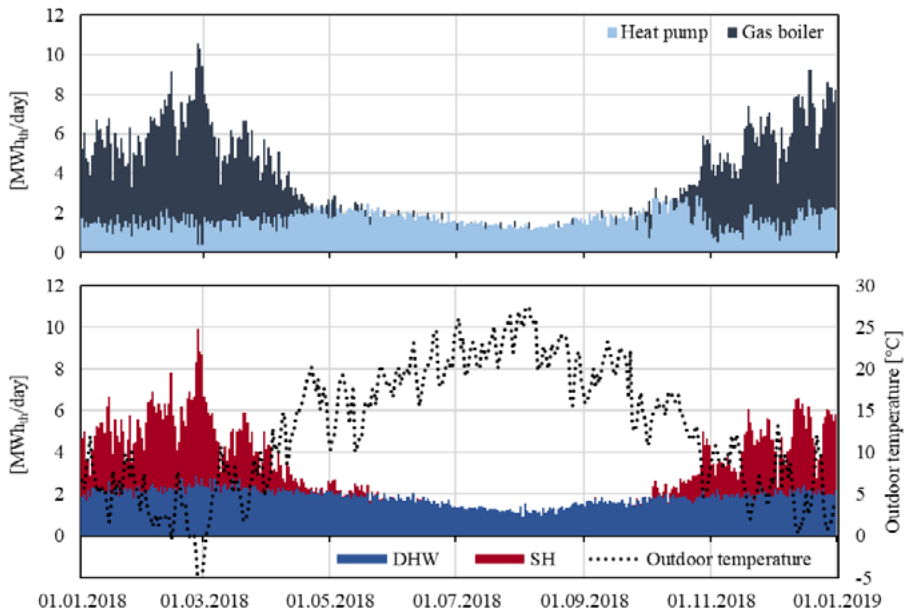


Fig. 3. Heat production (top) and demand (bottom), Jan – Dec 2018 (daily values)

The related dynamic of the daily average heat production temperatures is presented in Figure 4, which highlights differentiated operation modes and set points between summer and winter. During the summer, the HP production is set to its maximum at 63°C, which is sufficient for DHW supply (except during the above-mentioned anti-legionella treatment at 75°C by the gas boiler). During winter, the HP production temperature varies between 45 and 55°C, according to the upper and lower buffer set points, while the gas boiler produces at an average of 65°C (including the 1h anti-legionella treatment).

On the cold source side, we notice a relatively stable temperature at wastewater tank inlet (in the range of 20-25°C), while the evaporator inlet as well as tank outlet are quite lower (5-10°C). This surprising drop is

possibly linked with recurrent fouling of the wastewater heat recovery system, an issue which is still under investigation.

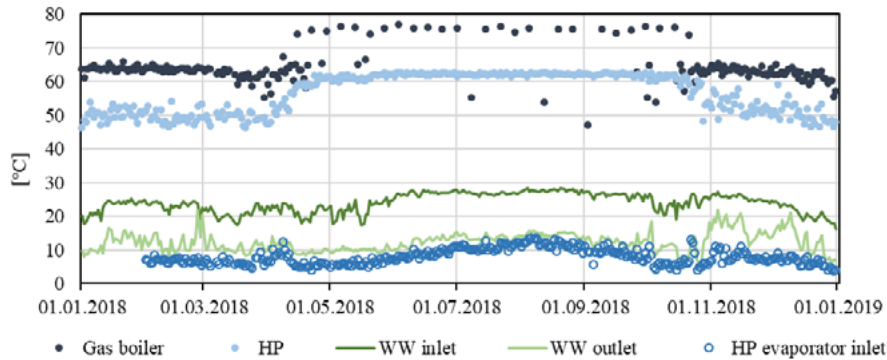


Fig. 4. Heat production temperatures, Jan – Dec 2018 (daily values)

3.3. Heat production issues

The above described differentiated summer/winter operation mode induces a distinct use of the HP and gas boiler, as explained (but not depicted) hereafter. In winter, due to the lower HP production set point, it can no longer cover the DHW supply. Latter is hence produced by the gas boiler, which induces return temperatures higher than those of the HP buffer. As a consequence, to avoid heating of the HP buffer with the gas boiler, the HP and its buffer are isolated from the DH distribution. Once the DHW storage tanks of all the buildings are fully charged, the DH drops to a SH supply temperature of around 35°C, which is again compatible with the HP and buffer temperatures.

Note that the differentiated winter operation mode was planned for SPF optimization reasons, with the objective to take advantage of the lower SH temperatures. However, it does in fact limit the operation duration of the HP to short periods, between DHW supply cycles. As a result, the HP share is lower than expected. In this regard, it could be worth using the same set points and operation mode as in summer, which would probably induce a higher share of HP production. Despite a possible drop in SPF, latter could actually lead to a better system performance in terms of CO₂ emissions, when taken into account the related reduction in gas consumption. This issue is currently being tackled by way of numerical simulation.

3.4. Heat demand issues

Figure 5 shows the disaggregated SH and DHW supply by building. We observe a strong variability, despite identical heated surface areas and thermal envelopes (note: as a unique difference, the ground floor of building no 3 has apartments instead of extracurricular activities). This variability, as well as the discrepancy with the projected and available benchmark values, will be discussed here after.

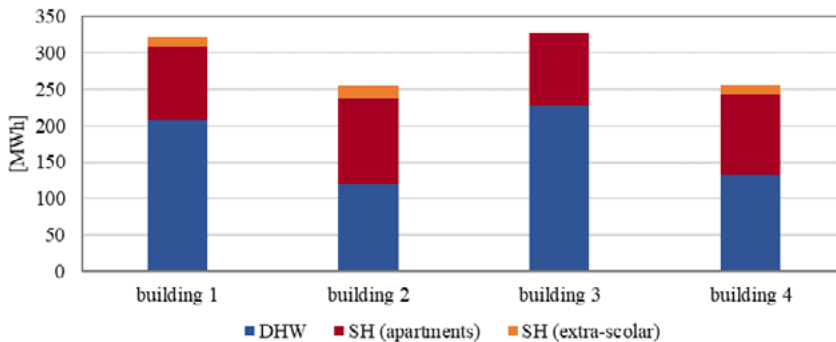


Fig. 5. Disaggregated heat demand by building, 2018

SH supply and performance gap are analyzed by way of a sensitivity analysis carried out with the Lesosai thermal balance calculation tool [7], with following scenarios (Table 1):

1. *Project*, simulated with the project design values, taking into account standard weather data, as well as normed indoor temperature and ventilation rates (without heat recovery).
2. *Real weather*, simulated with the actual weather data of 2018.
3. *Real weather & indoor temperature*, simulated with actual weather data of 2018, as well as actual indoor temperatures (as measured on the exhaust air of the ventilation system of each building).
4. *Measured*, simulated with actual weather and indoor temperatures, as well as adjusted ventilation rates, so as to reproduce the actual monitored SH of 2018.

Note that for the sake of simplicity and coherence, this analysis only concerns SH related to apartments (and not the one for extracurricular activities).

Table 1 Main input parameters for SH performance gap analysis

| Scenario | Meteorological year | Indoor temperature [°C] | Air flow [m ³ /h/m ²] |
|-----------------------------------|---------------------|----------------------------|--|
| Project | Standard | 20.0 | 0.7 |
| Real weather | 2018 | 20.0 | 0.7 |
| Real weather & indoor temperature | 2018 | [22.3 - 22.7] ¹ | 0.7 |
| Measured | 2018 | [22.3 - 22.7] ¹ | [0.9 - 1.3] ² |

¹ Based on extracted air temperature measurements [per building]
² Adjusted air flow to reach the measured heat demand [per building]

The results are depicted in Figure 6 and yield following comments. As 2018 was warmer than the standard weather (2'347 instead of 2'894 heating degree days), the SH demand for the *Real weather* scenario turns out around 20% lower than for *Project*. The demand however rises when taking into account the actual indoor temperature. Finally, reproduction of the actual monitored SH implies to adjust the ventilation rate to 0.9 - 1.3 m³/h.m² (instead of the normed value of 0.7 m³/h.m², without heat recovery). Latter adjustment could be related to window openings. In this regard, of the average adjusted value of 1.1 m³/h.m², 0.2 m³/h.m² actually correspond to mechanical ventilation (i.e. 1.0 m³/h.m² subject to 80% heat recovery efficiency). The remaining 0.9 m³/h.m² is equivalent to 9 constantly open windows of 1x1m per building (as given by a standardized airflow chart). So as to corroborate the plausibility of such window openings, we conducted an infrared photography campaign of the total 768 windows, at a rate of 289 pictures per day over a typical winter week. As a result, we observed an average per building of 3.5 open windows, 8.4 partially open windows and 5.9 open windows behind shutters (i.e. an order of magnitude which could explain the gap between *Measured* and *Real weather & indoor temperature* scenarios).

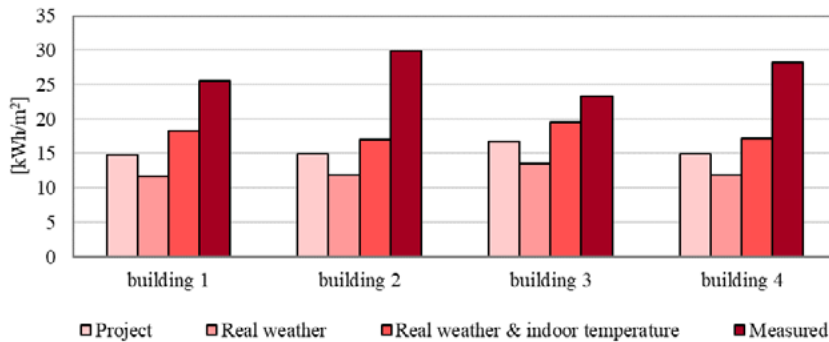


Fig. 6. SH demand, calculated and monitored values

Preceding results lead to following remarks:

- The ratio between *Measured* and *Real weather* (1.7 - 2.5, depending on the building) can in principle be explained by: i) higher indoor temperatures than the ones given by the norm; ii) window openings which over-compensate heat recovery by the mechanical ventilation.
- While this performance gap may seem relatively important, it is in the order of magnitude of other monitored buildings [5]. Furthermore, despite this gap, the actual SH demand (27.3 kWh/m²) is quite lower than the 68 kWh/m² average value of Geneva's MFB stock constructed between 2001 and 2010 [4].

Finally (Figure 7), the measured DHW supply is compared to normed values concerning as well supply to the storage [8], as end use at taps [9]. The measured average (39.5 kWh/m²) is above the normed supply value (32 kWh/m²), but in between the median and 3rd quartile of a benchmark on 61 sub-station of Geneva's main DH network [10]. Also note that the important discrepancy between the 4 buildings, which cannot be explained by distinct number of inhabitants, still is in the dispersion range of latter benchmark.

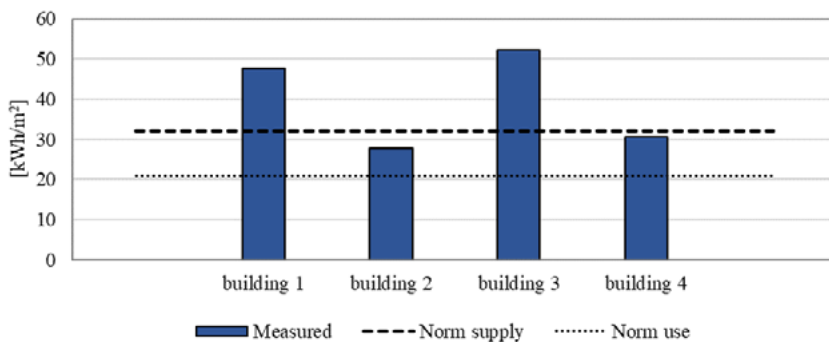


Fig. 7. DHW supply: measured and normed values

4. Conclusions

This paper concerns a new low energy MFB complex in Geneva, whose heat is produced by a centralized HP on wastewater with a complementary gas boiler, and distributed via a local DH network. Detailed hourly monitoring over an entire year of operation yields following main results.

At production level:

- The HP production accounts for 45% of the total production, with a seasonal performance factor of 3.03, including ancillary electricity of circulation pumps on evaporator and condenser side.
- The dynamic and annual energy balance of the system show a lower HP production than expected, especially during winter. This is due to operational constraints linked to distinct temperatures set points between summer and winter, as well as to high return temperature from the gas boiler. Note that this issue is currently being tackled by way of numerical simulation.
- While the wastewater resource temperature is relatively high all year round (20-25°C), the evaporator inlet temperatures is quite lower (5-10°C). Such is possibly linked to recurrent fouling of the wastewater heat recovery system, an issue which is still under investigation.

At demand level:

- At the level of the buildings, DHW supply (39.5 kWh/m²) accounts for 59% of the total, against 41% for SH (27.3 kWh/m²).
- As a complement to direct SH, ventilation heat recovery by dual flow, with a measured 80% efficiency, contributes by 24.1 kWh/m² to compensation of heat losses through the building envelope.
- The ratio between measured and climate corrected design values (1.7 - 2.5) can in principle be explained by: i) higher indoor temperatures than the ones given by the norm; ii) window openings which over-compensate heat recovery by the mechanical ventilation. While this performance gap may seem relatively important, it is in the order of magnitude of other monitored buildings, and the actual SH demand is quite lower than the average for Geneva's multifamily buildings constructed between 2001 and 2010.
- Finally, the measured DHW supply is above the normed supply value, but in between the median and 3rd quartile of a benchmark on 61 sub-station of Geneva's main DH network.

As a conclusion of this case-study, centralized HP systems on wastewater can play a substantial role for the combined SH and DHW heat production of low-energy multifamily buildings. Implementation and operation however need adequate system integration, control and commissioning.

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References

- [1] QUIQUEREZ, Loic (2017). Décarboner le système énergétique à l'aide des réseaux de chaleur: état des lieux et scénarios prospectifs pour le canton de Genève. Université de Genève – Thèse. <https://archive-ouverte.unige.ch/unige:93380>
- [2] DE SOUSA FRAGA, Carolina (2017). Heat pump systems for multifamily buildings: which resource for what demand? Université de Genève – Thèse. <https://archive-ouverte.unige.ch/unige:94939>
- [3] ROGNON, Fabrice, YUSHCHENKO, Alisa and RUETSCHI, Matthias (2017). Retrofitting fossil-based heating systems with air to water heat pumps in multifamily houses. 12th IEA Heat Pump Conference, Rotterdam, the Netherlands. <http://hpc2017.org/wp-content/uploads/2017/05/P.1.5.4-Retrofitting-fossil-based-heating-systems-with-air-to-water-heat-pumps-in-multifamily-houses.pdf>
- [4] KHOURY, Jad (2014). Rénovation énergétique des bâtiments résidentiels collectifs: état des lieux, retours d'expérience et potentiels du parc genevois. Université de Genève – Thèse. <https://archive-ouverte.unige.ch/unige:48085>
- [5] ZGRAGGEN, Jean-Marc (2010). Bâtiments résidentiels locatifs à haute performance énergétique : objectifs et réalités. Université de Genève – Thèse. <https://archive-ouverte.unige.ch/unige:13093>

- [6] FEKA (2019). Energie aus Abwasser. <http://feka.ch/>
- [7] Lesosai (2019). Lesosai: certification and thermal balance calculation for buildings. http://www.lesosai.com/fr/01_spec.html
- [8] OCEN (2012). Directive relative au calcul de l'indice de dépense chaleur. Office cantonal de l'énergie, Genève. <https://www.ge.ch/document/directive-relative-au-calcul-indice-depense-chaleur/telecharger>
- [9] SIA (2009). Norme SIA 380/1: 2009, L'énergie dans le bâtiment.
- [10] QUIQUEREZ, Loic (2017). Analyse comparative des consommations de chaleur pour la production d'eau chaude sanitaire estimées à partir de relevés mensuels: Etude sur un échantillon de bâtiments résidentiels collectifs alimentés par un réseau de chaleur à Genève. <https://archive-ouverte.unige.ch/unige:91218>