Hourly CO$_2$ emission assessment of a 5 MW$_{th}$ centralized groundwater HP district heating system in Geneva

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Abstract. In the present paper, we develop an hourly simulation model for determination of the relevant system load curves of a new district of 30 high performance multi-family buildings (163'000 m$^2$ heated floor area) situated in Geneva, which is equipped with a 5 MW$_{th}$ groundwater HP. As a complement, at building level, heat recovery on exhaust air is used for pre-heating of DHW by way of decentralized air-to-water HPs. As a result of our model, the 10.7 GWh annual heat production (65% for SH, 35% for DHW) should require 1.93 GWh HP electricity (85% centralized, 15% decentralized). When crossing the corresponding profile with a recent analysis of the hourly CO$_2$ content of the Swiss electricity mix, the annual carbon content of heat amounts to 47 gCO$_2$/kWh$_{th}$, which is 4 times less than with a centralized gas boiler.

1. Introduction

While the total space-heating (SH) and domestic hot water (DHW) production for the building sector of the Canton of Geneva relies at 93% on fossil sources, the energy policy objective is to reduce this share to 66% by 2035. Given important low temperature resources, in particular in terms of surface and subsurface water, one of the major foreseen contributions for this change consists in massive introduction of centralized heat pumps (HP), in conjunction with the development of district heating (DH) networks [1, 2]. However, in addition to HP performance issues, the CO$_2$ content of the electricity needed to run such HP systems remains a fundamental question [3].

In this context, a new district of 30 high performance multi-family buildings is currently being constructed. It is being equipped with a 5 MW$_{th}$ groundwater HP, by far the largest such system in the Canton of Geneva. As a complement, at building level, heat recovery on exhaust air is used for pre-heating of DHW by way of decentralized air-to-water HPs.

Basing on latter case study, focus and added value of this paper are twofold: i) determination of the hourly heat demand profile of an urban district, by combining basic information on the building stock with actual statistics and unitary load curves, thus taking into account performance gap issues due to actual condition of use; ii) evaluation of the corresponding hourly electricity consumption of centralized and decentralized HPs, and determination of the related hourly CO$_2$ emissions, based on the recent assessment of the actual hourly carbon content of the Swiss electricity mix. As a complement, we also provide an estimation of the fraction of electricity that can be covered by local PV production.

2. Case study

By the end of 2019, the district Les Vergers located in Meyrin (Geneva) will host 30 high performance multi-family buildings (1'350 dwellings and some activities of the service sector). It is the first example
in Switzerland of an entire neighborhood receiving the Minergie A label [4]. It represents 162’700 m² heated surface, whose SH and DHW production are supplied by a low temperature district heating (DH) network, connected to a 5 MWth centralized heat pump. The HP evaporator is connected to a groundwater source with a nominal volumetric flow of 600 m³/h, which deserves as a district cooling (DC) network for the nearby industrial zone Zimeysa. The resulting evaporator inlet temperature is expected to range between 13°C (winter) and 16°C (summer). The HP is designed to work with 2 batches per day at 65°C for charging of the DHW tanks located in each building, while operating the rest of the time with a maximal SH supply temperature of 50°C. Although the centralized HP is designed to cover the entire DH heat demand of les Vergers, backup is provided by the nearby high temperature DH network CADSIG, which also serves as a transitory production plant during the construction phase.

As a complement to the centralized HP, buildings are equipped with heat recovery on exhaust air by way of decentralized HPs, which are expected to cover 50% of the total DHW demand.

![Diagram of heat production schematic and associated temperature levels](image)

Figure 1: Heat production schematic and associated temperature levels.

To increase the share of renewable energy and to obtain the Minergie A label, all roofs and two building facades are equipped with solar PV panels. The total PV surface is estimated at 13’500 m² leading to a total nominal power of 1.7 MWc and an expected annual production of 2.24 GWh.

3. Heat demand and production

3.1. Heat demand

The methodology for determination of the heat demand is as follows. Heated floor area and actual annual delivered heat demand are found, by building alley, within the Geneva SITG database [5]. Since the Vergers neighborhood is still under construction, this data is currently available on 34% of the 68 alleys, with following average values (used for extrapolation on the missing alleys): i) the resulting heated floor area is 88% of the gross floor area (number of floors by ground surface); ii) the actual climate corrected annual heat demand for SH and DHW production (at DH heat exchanger) amounts to 54.3 kWh/m².

Note that latter value does not include DHW preheating by the decentralized HPs on heat recovery. Latter is assumed to cover 50% of the total DHW production, which is estimated at 25 kWh/m² for pure multifamily buildings, respectively 15 kWh/m² for mixt purpose buildings (with an average of 22.8 kWh/m² on the entire neighborhood).

Decomposition of preceding annual values in hourly profiles is based on monitored SH and DHW unitary load curves on an existing DH in Geneva [6]. While the SH load curve is applied “as is”, the DHW load curve is further processed for including the specificity of the Vergers system: i) in the case of the centralized DHW production, the daily unitary load curve values are evenly distributed over 2
production batches (5-7 AM; 5-7 PM); ii) in the case of the decentralized DHW production, the daily unitary load curve values are evenly distributed over 24 h.

| District heat demand       | GWh  | kWh/m² | %  |
|----------------------------|------|--------|----|
| SH                        | Qh   | 6.97   | 42.8| 65%|
| DHW                       | Qww  | 3.72   | 22.9| 35%|
| DHW, district heating      | Qww dh | 1.86  | 11.4| 17%|
| DHW, heat recovery         | Qww rec | 1.86  | 11.4| 17%|
| Total                     | Qhww | 10.69  | 65.7| 100%|

| HP electricity demand      | GWh  | kWh/m² | %  |
|----------------------------|------|--------|----|
| HP district heating        | Ehp dh | 1.64  | 10.1| 85%|
| HPs heat recovery          | Ehp rec | 0.29  | 1.8 | 15%|
| total                     | Ehp  | 1.93   | 11.9| 100%|

Table 1: Estimated heat demand (top) and associated HP electricity (bottom) of Les Vergers district.

As a result (Tab. 1) the total annual heat demand is estimated at 10.69 GWh (6.97 GWh for SH and 3.72 GWh for DHW, latter covered at 50% by the decentralized HPs on heat recovery). The corresponding dynamic is presented in Fig. 2, in terms of hourly dynamic over a winter week (left) and daily dynamic over the entire year (right). Note that, by construction based on actual data from the existing building stock, the specific SH demand of 42.8 kWh/m² is 1.6 times the normalized Minergie value, taking into account the performance gap due to actual condition of use [7].

![Heat demand, winter week (left, hourly values) and entire year (right, daily values).](image)

Figure 2: Heat demand, winter week (left, hourly values) and entire year (right, daily values).

3.2. Temperature levels

The centralized HP temperature levels (Fig. 1), which have a direct impact on the performance, are based on nominal values listed in the project documentation: HP inlet temperature from the groundwater / DC cooling network is assumed to have a constant temperature of 15°C; HP outlet temperature is set at 65°C during DHW batches, while for SH production it varies linearly as a function of outdoor temperature (set points: 50°C at -5°C outdoor; 40°C at 8°C outdoor).

In the case of the decentralized HPs on exhaust air, following hypothesis are made: during the heating season, exhaust air is at 23°C (as commonly observed in multifamily buildings); coherent with the 50% DHW covering, the preheating tank is maintained at 35°C, which induces a HP production at 40°C; taking into account 80% efficiencies on the heat exchangers down and upstream of the HP, latter’s inlet and outlet temperatures are respectively 21.8 and 36.3°C.
3.3. Heat production and electricity consumption

The methodology for determination of the heat production and associated electricity consumption is as follows. At the level of the centralized HP, the hourly COP is determined by the product of: i) the maximum theoretical COP, or Carnot efficiency, function of the groundwater / DC temperature (HP input) and the DH supply temperature (HP output); ii) a constant technical HP efficiency of 55%, according to nominal HP values. Along with the hourly heat supply profile, latter COP allows to compute the hourly electrical load of the HP, as well as its counterpart in terms of heat supply from the groundwater / DC network. Note that eventual heat losses in the DH network and consumption of ancillary pumps are not considered here.

The same basic procedure is adopted for decentralized HPs on heat recovery, with a technical HP efficiency set at 40% relatively to HP input and output temperatures. Taking into account the 5 K differential and 80% efficiency of the down and upstream heat exchangers, the overall technical efficiency of this system (relatively to the Carnot efficiency calculated with exhaust air at 23° and DHW preheating at 35°) only amounts to 25%.

![Figure 3: HP electricity, winter week (left, hourly values) and entire year (right, daily values).](image)

The resulting electricity loads is presented in Fig. 3, in terms of hourly dynamic over a winter week and daily dynamic over the entire year. Finally (Tab. 1), the annual simulated HP electricity consumption (electricity for circulation pumps not included) amounts to a total of 1.93 GWh (SPF: 5.6), of which 1.64 GWh for the centralized HP (SPF: 5.4) and 0.29 GWh for the decentralized HPs (SPF: 6.4).

4. CO₂ emissions

4.1. CO₂ content of the Swiss electricity mix

Assessment of the CO₂ content of the Swiss electricity mix is usually based on production certification, guaranteeing that the equivalent of the purchase/supply of electricity has been produced by a specific type of technology. As such, the Swiss electricity supply mix (including domestic production and imports) is currently estimated at 138.5 gCO₂/kWh[8]. However, these certificates concern annual volumes and do not guarantee the match between production and consumption.

To overcome this problem, the University of Geneva has developed a new accounting method to estimate CO₂ emissions from Swiss electricity demand with an hourly granularity [9]. The method is based on hourly information related to the electricity production of European and Swiss electricity production, classed by technology. Unlike existing approaches, the method is based on the incremental impact of imports on the generation mix of the corresponding exporting country. Furthermore, it differentiates net imports from transit flows (i.e. not consumed by the importing country in question).

In 2017, the resulting average annual emissions amount to 129 or 197 gCO₂/kWhel. The difference between these two values depends on the carbon content attributed to electricity from German plants using waste gases from blast furnaces of the iron and steel industries. Fig. 4 shows the corresponding hourly and daily dynamic over the entire year (for the 197 gCO₂/kWhel case).
Figure 4: Hourly carbon intensity of electricity in grey and daily average in black, for the year 2017.

4.2. CO₂ content of Les Vergers heat demand

The CO₂ content of Les Vergers heat demand is obtained by the product of the above derived HP electricity and the CO₂ emissions factor, in hourly values. Interestingly, and despite the high winter peaks of both latter profiles, the annually integrated carbon content of heat finally only amounts to 47 gCO₂/kWhₘ (Tab. 2), as compared to the 36 gCO₂/kWhₘ obtained by mere multiplication of the annual total HP electricity and average CO₂ emissions factor.

Finally, these results are compared with an alternative scenario where the DH is supplied by a natural gas boiler (with a 90% efficiency and a carbon content of 203 gCO₂/kWhₘ related to the lower calorific power), while the decentralized HPs for DHW preheating on exhaust air are not changed (same heat demand profiles as in Fig. 2). As a result, the carbon content of the delivered heat goes up to 192 gCO₂/kWhₘ, i.e. 4 times more than the current case.

| DH production | Electricity | Gas (*) | CO2 |
|---------------|-------------|---------|-----|
|               | GWhₑₜ       | kWhₑₘ/m²| GWhₘₜ | kWhₘₘ/m² | t   | kg/m² | g/kWhₘₘ |
| Groundwater HP| 1.93        | 11.9    |      | 501     | 3.1  | 47    |
| Gas boiler    | 0.29        | 1.8     | 9.81 | 60.3    | 2050 | 12.6  | 192     |

(*) Gaz: useful energy (heat)

Table 2: Energy and related CO₂ emissions, as per DH production type.

5. Renewable electricity production and auto-consumption potential

At district level, the electric load curve of households and building services, estimated with the ElectroWhat model [10], are summed up to the HP load. Resulting annual values, as well as aggregated hourly match with the estimated hourly PV production, are given in Table 3. As a result, 83.5% of the PV production (1.87 GWh) could be consumed on site, representing 23.4% of the district demand.

| Electricity demand | GWh | % Dem. | Grid balance | GWh | % PV | % Dem. |
|--------------------|-----|--------|--------------|-----|------|--------|
| HPs (dh + rec)     | 1.93| 24.1%  | PV production| 2.24| 100.0%| 28.0%  |
| Households         | 3.16| 39.5%  | Consumed on site| 1.87| 83.5% | 23.3%  |
| Services           | 2.92| 36.5%  | Exported to grid| 0.37| 16.5% | 4.6%   |
| Total              | 8.01| 100.0% | Imported from grid| 6.13| 273.7%| 76.5%  |

Table 3: Yearly balance of electricity demand, PV production and auto-consumption potential.
6. Conclusions
The foreseen transition from fossil to renewable heat production will significantly impact the Swiss electricity demand, rising questions on the associated CO₂ content. The model presented in this article addresses this question at the level of a new district, heated with a centralized geothermal and waste heat recovery heat pump, combined with decentralized heat production.

On the heat demand side, our model is based on actual and projected data concerning annual heat demand (total of 10.7 GWh), which is decomposed in hourly profiles by way of existing monitored SH and DHW unitary load curves, adapted to the specificity of the case study.

On the production side, HP performance is computed on the hypothesis of a constant technical efficiency (ratio of actual and maximum theoretical COP) and taking into account the hourly temperature load profiles. As a result, the annual simulated electricity consumption of the centralized and decentralized HPs (ancillary electricity for circulation pumps not included) is 1.93 GWh (SPF: 5.6).

The associated carbon content is obtained by the product of the HP electricity and Swiss electricity CO₂ emissions factor, in hourly values. The annually integrated carbon content of heat rises up to 47 gCO₂/kWh, i.e. 4 times less than with a centralized gas boiler.

Furthermore, taking into account the district overall hourly electric load (HPs, households and building services), 83.5% of the hourly PV production could be consumed on site, representing 23.4% of the district demand.

Finally, it is worth noticing that the model relies on simplified hypotheses. However, the first measures of real consumptions show that the estimations on the demand side are fairly matched, whereas actual electricity load of the HPs still needs to be analyzed.

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