

Implementation challenges of geothermal Heat Pump with Gas boiler in existing District Heating

Faessler Jérôme¹, Fraga Carolina¹, Holmuller Pierre¹, Pahud Daniel², Quiquerez Loïc¹

¹ Energy System Group, University of Geneva, Institute F.-A. Forel and Institute for Environmental Sciences, Uni Carl-Vogt, bd Carl-Vogt 66, CH-1211 Genève 4

² LESBAT, Laboratoire d'énergétique solaire et de physique du bâtiment, Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud, Case postale 521, Avenue des Sports 20, CH-1401 Yverdon-Les-Bains

Jerome.faessler@unige.ch

Keywords: Borehole heat exchanger field, heat pump, geothermal storage, geothermal energy, waste heat, district heating.

ABSTRACT

This article concerns a long term in situ monitoring of an existing district heating (DH) that is supplied by gas boilers equipped with heat recovery system and a borehole heat exchanger field connected to a heat pump (HP). The original goal of this concept is to be able to stop the gas boilers during summer and use only the HP for DH heat supply.

The monitored annual energy flows of the system show that gas supplies 94% of the DH energy demand, while geothermal energy supplies 1.5% and electricity 4.5%. In fact, HP heat source is mainly waste heat from the gas boiler (82%) and only 18% from geothermal energy.

In reality, the gas boilers are not stopped in summer because several issues associated with heat demand (domestic hot water - DHW) were underestimated: i) DHW demand is not a base load, in fact it has three characteristic loads peak ii) Legionella bacteria management and its associated high temperatures cannot be underestimated; iii) DH substations architecture is key to achieve temperature levels in the DH that are compatible with the HP operation iv) lower flow rate in DH compared to flow rate in HP condenser leads to decrease in HP production.

Finally, a numerical model allowed to analyse different scenario from the following was observed: firstly, the DH extension significantly increases gas needs, which in turn increases waste heat recovered from gas, which is then used instead of geothermal energy; secondly, resizing of the HP power enables an increase of geothermal energy of +270 MWh/yr, meaning that geothermal energy has the potential to cover 16% of the annual heat demand.

This research, based on long term in situ monitoring, allows acquiring knowledge on energy innovation

when applied in real field conditions: this knowledge is further developed via a feedback process between academics and field workers.

1. INTRODUCTION

Located in Geneva (Switzerland), Laurana-Parc is a 12 multifamily building complex from the 1960s. This building complex, that is equipped with a DH system, was heated with an oil boiler until 2011. Due to conformity to local legislation, the oil boiler had to be replaced and the chosen heat production system was:

- three new gas boilers, with a cumulated thermal power of 9.8 MW, equipped with a two stage heat recovery system;
- dual source heat pump (HP) with a thermal power of 0.34 MW (for $T_{\text{evaporator}} = 14^{\circ}\text{C}$ and $T_{\text{condensor}} = 60^{\circ}\text{C}$).

The HP sources are geothermal (borehole field of 44 heat exchangers of 300m – total of 13,200 linear meters) and gas (waste heat recovered from the vapour condensate of the gas boiler).

With the replacement of the heat production system, the boiler room suffered a major refurbishment and new DH substations (SST) were built in the Laurana-Parc buildings. In 2013, a second sector of the DH was created (called Trois-Chênes) to connect approximately 20 other multifamily buildings of the 1960s. This project was financed and executed by the local utilities “Services Industriels de Genève” (SIG) and is now being managed by them.

This system is an interesting case study due to the coupling of a gas boiler and a borehole heat exchanger field (via a HP) for DH. The original goal of this concept is to be able to stop the gas boilers during summer and use only the HP for DH heat supply (Pahud, 2010). The aim of this study is to analyse the energy efficiency potential:

- of the waste heat recovered from the gas boilers;

- of using a borehole heat exchanger field to phase shift the waste heat from winter to summer (seasonal storage);
- of using a borehole heat exchanger field to extract geothermal energy.

The pertinence of using this type of system in other locations is also studied.

In this regard, this system has been monitored for two years by the Energy Systems Group of the University of Geneva, in cooperation with a steering committee that includes representatives of the contractor, engineer office, heating specialists, building owners, State and municipality (Faessler et al, 2016). The results presented in this paper correspond to a full monitored year from 1 October 2014 until 30 September 2015 (year 14-15).

2. ENERGY ANALYSIS

The system and its different sub-systems are presented in Fig. 1.

Heat production in the two DH is provided by gas boilers supplemented by geothermal energy. Waste heat from gas is recovered at a temperature that is too low to be used directly in the DH, so it is stored into a warm reservoir at a temperature between 20 to 30°C.

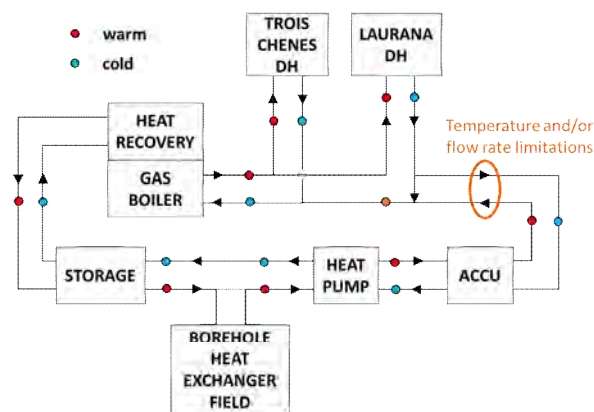


Figure 1: System diagram of Laurana-Parc project

The HP heat sources are the heat stored in the reservoir and heat extracted from the borehole field. As for the HP output heat, it is injected in the return branch of the Laurana DH, which is then mixed with the Trois-Chênes return branch and finally it is heated by the gas boilers until the desired supply temperatures of the DH. Note that the heat in the reservoir can also be used to recharge the borehole field.

Overall, the annual sankey diagram may be represented as follows (Fig 2):

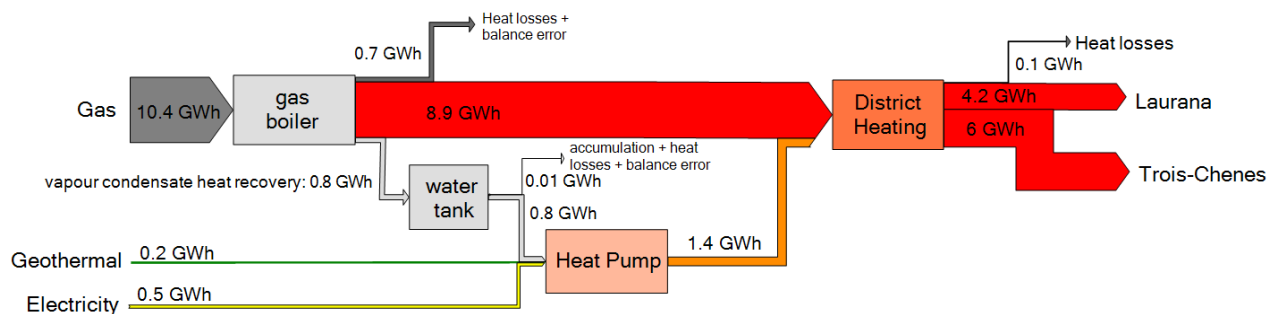


Figure 2: Sankey diagram of the heating system (annual flows, oct. 2014 to sept. 2015)

From Fig.2 we observe that gas supplies 94% of the DH energy needs, geothermal energy supplies 1.5% and electricity 4.5%. The use of gas has an excellent efficiency (93% on higher heating value) due to the connection with the HP (via the warm water storage). Heat losses are very low.

2.1 Heat Demand analysis

The DH network (Laurana and Trois-Chênes sectors combined) has a high linear density (7.3 MWh/m/year) and is responsible for the heat delivered to approximately 100,000 m² of heated surface, with 2,500 inhabitants, for 7 MW of subscribed power. In the Laurana sector, the maximum power of the six

SST (at an outdoor temperature of -10°C) is in average 51 W/m², varying from 42 W/m² to 68 W/m² depending on the SST. These values are standard for non-renovated residential buildings built in the 1960s (Quiquerez et al, 2013). As for the heat demand of this sector, 69% is for space heating (SH) and 31% for domestic hot water (DHW). The specific consumption of DHW (including storage and distribution losses) is 1,650 kWh/hab/yr or 148 MJ/m²/yr, which is in the high range of typical values for buildings in Geneva served by a DH system (Quiquerez et al, 2013).

The heat exchanger temperatures from one SST in the Laurana sector have been studied in detail with supply

and return temperature (Fig. 3), difference temperature (Fig. 4) and flow rate (Fig. 5):

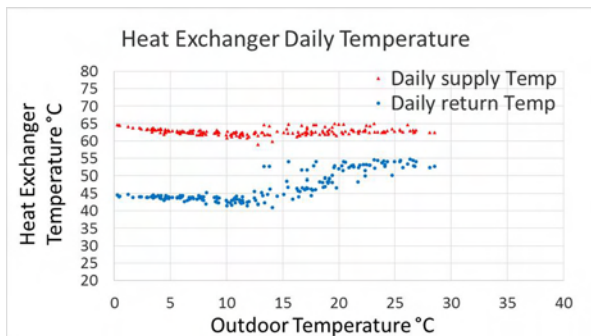


Figure 3: Heat exchanger daily supply and return temperature (°C) as a function of outdoor temperature

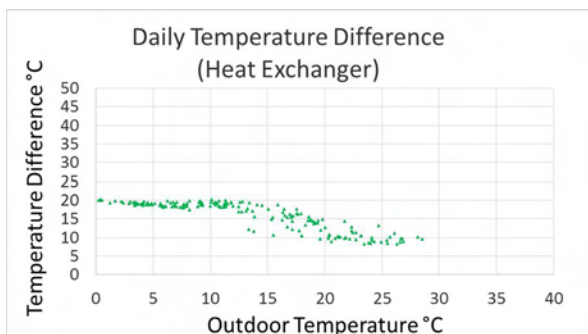


Figure 4: Heat exchanger daily temperature difference (°C) as a function of outdoor temperature

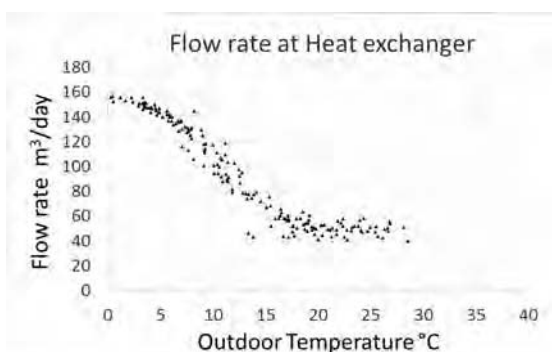


Figure 5: Heat exchanger daily flow rate (m³/day) as a function of outdoor temperature

Daily results in Fig.4 show a decrease in the temperature difference with the increase of outdoor temperature. This means that in summer, DHW demand rises the return temperature of the DH network. This is a consequence of the SST architecture, which was not conceived to allow the lowest possible return temperatures (Frederiksen and Werner, 2013). This increasing in return temperature in summer impacts negatively the HP performance.

2.2 Heat Pump Performance

For the monitored year, the measured HP seasonal performance factor (SPF) is 3.0 (see eq. 1):

$$\text{SPF} = \text{HP heat energy output} / \text{Electricity} [1]$$

Even though it is a modest value when considering the HP high temperature heat sources, this performance is explained by the high temperature heat production (HP works with an average ΔT of 45°C). These results are comparable to what has been found in other studies in Geneva (Mermoud et al, 2014a; Mermoud et al, 2014b).

According to project values, the HP is supposed to run at nominal power for 91% of the time. In reality it works 90% of the time but at partial power only (Fig.6):

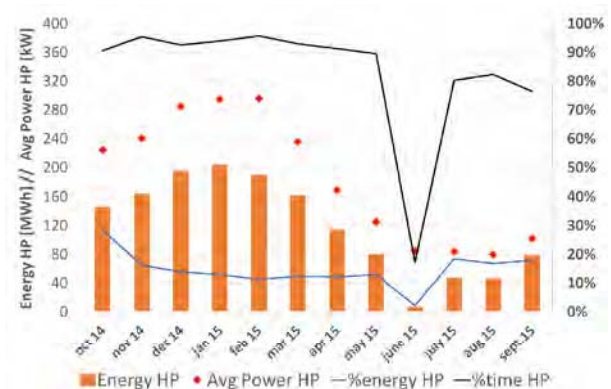


Figure 6: Monthly performance of Heat Pump

Note that during the month of June, a breakdown of HP has occurred. As for the HP heat sources, waste heat from the gas boiler is responsible for 82 % of the heat delivered to the HP whereas geothermal energy is only responsible for 18% (Fig. 7). This happens because there are high amounts of gas used by the boiler, and since it would be wasted if not used, this source has priority over the geothermal energy:

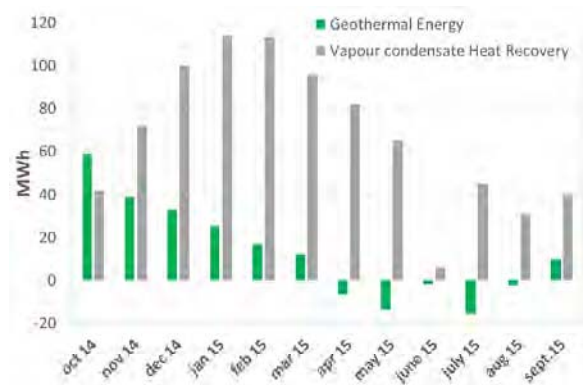


Figure 7: Monthly heat delivered to HP from both sources (in MWh)

The HP covers 30 to 60 % of the DH heat demand (Laurana sector only). 30% coverage occurs in winter, when the HP operates at full load 90% of the time.

The 60% occurs in summer when the HP operates at partial load only (Fig. 8):

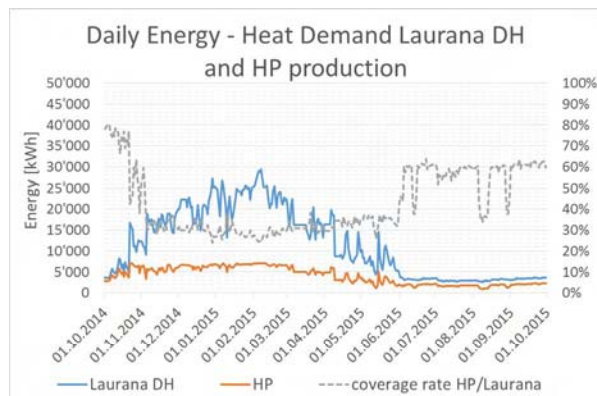


Figure 8: Laurana sector heat demand and HP production (daily energy in kWh) and coverage rate HP/Laurana

In fact, higher coverage was expected in summer because the HP alone (338 kW) should be able to cover the Laurana sector heat demand (hourly average of 130 kW). The 60% limited coverage is explained by three main reasons:

1. Legionella bacteria is controlled by raising the DH temperature to 74°C, every day from 4 to 6 am. This implies a complete stop of the HP for 2 hours a day;
2. In summer, the minimum supply temperature of the Laurana sector is 64°C, which is not compatible with the temperature supplied by the HP (maximum 62°C);
3. In summer, Laurana sector flow rate is inferior to the flow rate in the HP condenser. Since the HP condenser flow rate must be constant, Laurana flow (low temperature) has to be mixed with condenser output flow (higher temperature) to achieve the condenser nominal flow rate. This implies higher input temperatures in the HP condenser, lower temperature differential and therefore, lower power supplied by the HP.

In order to increase the HP heat injection in the DH, different improvements are possible and will be discussed in chapter 3 - numerical model.

2.3 Economic Results

The investment in the Laurana-Parc renovation/extension project has been substantial. SIG, the selected contractor for this project, has invested over 9 Million CHF (1 CHF \approx 0.92 Euro) for heat production replacement, renovation of boiler room and existing DH, and development of new DH sector (Fig. 9). This leads to an overall investment of about 860 Euro/kW installed.

**Total Investissement by contractor
(9'200 kCHF)**

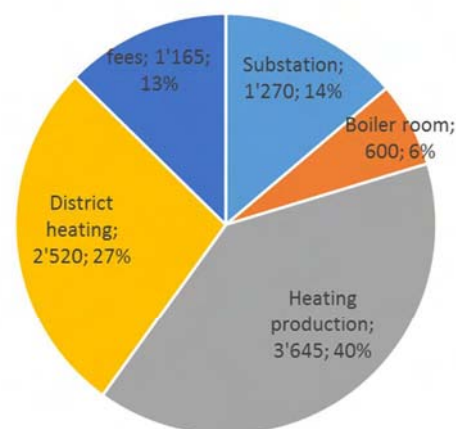


Figure 9: Investment by contractor in kCHF (1 CHF \approx 0.92 Euro)

The heat price practiced at Laurana-Parc is compared for two periods: i) before 2011 (oil boiler); ii) after 2012 (replacement of boiler and renovation). Note that before 2011 there was no fixed cost in the price (no amortization of the oil boilers), therefore a theoretical fixed cost of 3 CHF cents/kWh for the years 2005 to 2011 was added in order to compare the two periods (Fig. 10):

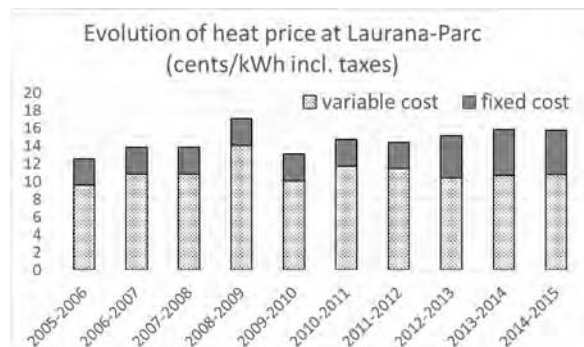


Figure 10: Evolution of heat price (CHF cents/kWh incl. taxes)

Before 2011, the heat price was about 10 to 11 CHF cent/kWh (\approx 17 CHF/m²), due in particular to the absence of a fixed cost. After replacement/renovation and contracting, a fixed cost is integrated in the price. Therefore, since 2012, the heat price is around 15 to 16 CHF cent/kWh (\approx 22 CHF/m²). This increase (+35%) has been borne entirely by the consumers, which presents certain difficulties in terms of acceptability. Nevertheless, through the detailed analysis of one of the owners (4 buildings), we are able to show that the heat prices remain five times lower than the rent costs. Furthermore, the detailed analysis was made for particular low rents compared to the Geneva average.

3. NUMERICAL MODEL

Numerical simulations are carried out, using software PileSim (Pahud, 2007), in order to complement the technical and financial analyses presented above. The main goal of this numerical analysis is to pin point improvement possibilities for the existing system as well as for similar future projects.

3.1 Scenario description

In total, 6 scenarios were defined and modelled. In all scenarios, the HP is connected to Laurana DH sector only (heat demand of 4,250 MWh), has a constant SPF of 3 (no degradation over time) and with water as fluid in borehole field. The first scenario is a calibration based on the existing project conditions and monitored data for the year 14-15 (BASE).

In the other five scenarios, the parameters that vary are: i) the amount of waste heat available (waste heat from all DH sectors – FULL; or waste heat from Laurana sector only - LAURANA); ii) the restrictions in the injection of HP heat in the Laurana DH sector, as explained in section 2.1 (temperature and/or flow restrictions – LIMITED; or no restrictions).

In all five scenarios, HP power sizing is selected to enable the maximum extraction of geothermal energy as defined in the Swiss standard (SIA, 2010).

The six scenarios are briefly described below and summarized in Table 1:

- BASE - calibration scenario with monitored data from year 14-15; Waste heat from gas used in all DH sectors (Laurana and Trois-Chênes). Restricted temperature and/or flow rate (see section 2.1).

- FULL/LIMITED - Waste heat from gas used in all DH sectors. Restricted temperature and/or flow rate. HP power sized for maximum extraction of geothermal energy.
- FULL – Waste heat from gas used in all DH sectors. No restrictions in injection of HP heat. HP power sized for maximum extraction of geothermal energy.
- LAURANA/LIMITED – Waste heat from gas used in Laurana DH sector only. Restricted temperature and/or flow rate. HP power sized for maximum extraction of geothermal energy.
- LAURANA – Waste heat from gas used in Laurana DH sector only. No restrictions in injection of HP heat. HP power sized for maximum extraction of geothermal energy.
- NO RECOVERY – No waste heat recovery. No restrictions in injection of HP heat. HP power sized for maximum extraction of geothermal energy.

3.2 Scenario results

For all the 6 scenarios, Fig. 11 to 16 show the hourly HP injected heat (in green) as well as the Laurana DH sector load curve (in red).

Note that only Laurana DH sector load curve is represented because the HP is only connected to this sector.

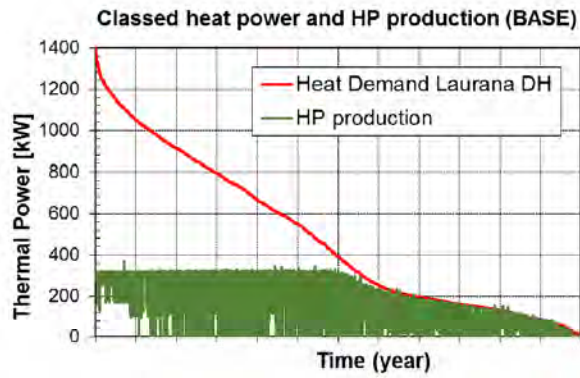


Figure 11: Laurana load curve and HP production for BASE scenario

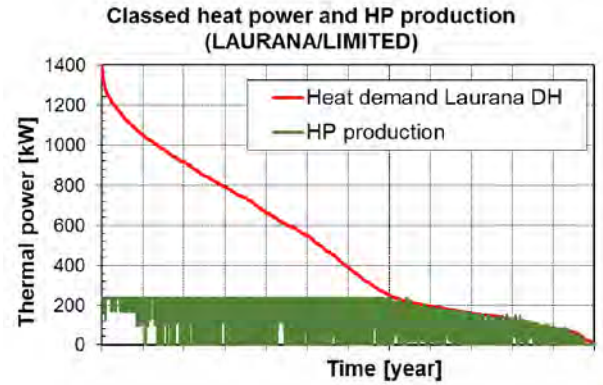


Figure 14: Laurana load curve and HP production for LAURANA/LIMITED scenario

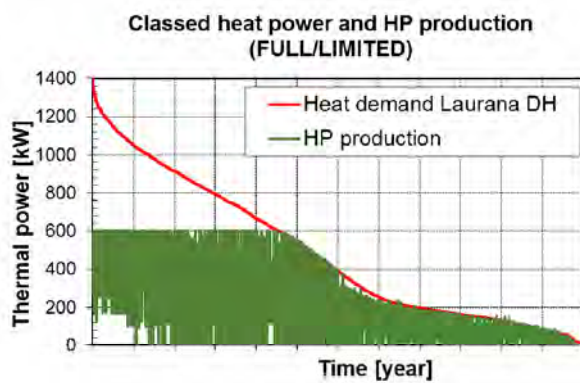


Figure 12: Laurana load curve and HP production for FULL/LIMITED scenario

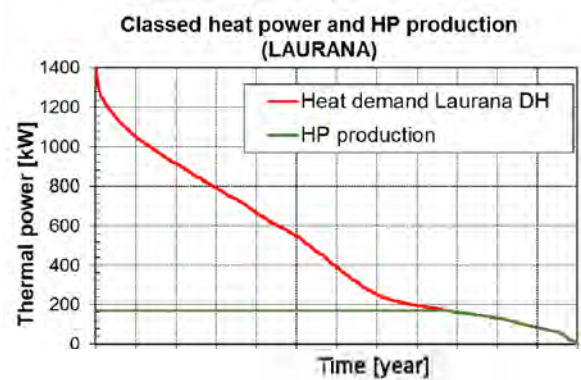


Figure 15: Laurana load curve and HP production for LAURANA scenario

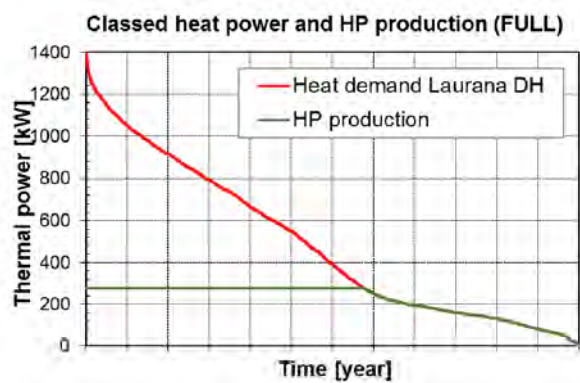


Figure 13: Laurana load curve and HP production for FULL scenario

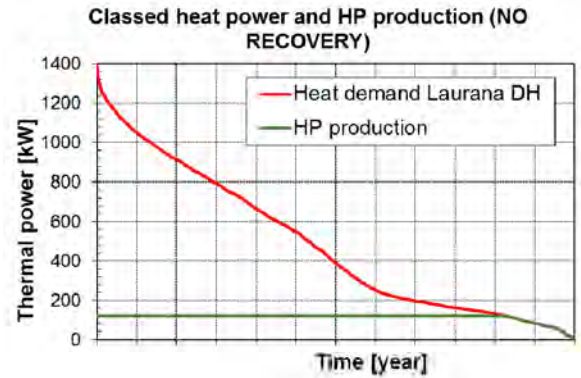


Figure 16: Laurana load curve and HP production for NO RECOVERY scenario

Restricted temperature and/or flow rate scenarios have an intermittent HP power (green) due to the legionella HP brakes and braked caused by the limited temperature/flow rate. All other scenarios have a full power HP for most of the year.

In table 1, the following system performance indicators are depicted for the monitored year and all six scenarios:

- A. Yearly HP coverage of the Laurana DH sector demand (HP heat production / Laurana heat demand) [%];
- B. Yearly geothermal coverage of the Laurana DH sector demand (geothermal HP heat production / Laurana heat demand) [%];
- C. HP power sizing (maximal energy production) [kW];
- D. Borehole heat exchanger field specific power [W/m]
- E. Yearly overall HP heat production (geothermal + recovery gas + electricity) [MWh/yr];
- F. Yearly geothermal heat extraction [MWh/yr];
- G. Yearly waste heat recovered from gas [MWh/yr];
- H. Yearly overall electricity consumption [MWh/yr];
- I. Borehole heat exchanger field specific energy [kWh/m/yr];
- J. Yearly CO₂ emissions [tons/yr].

Table 1: System performance indicators for the monitored year and all six scenarios

Indicator		Unit	<i>Year 14-15</i>	BASE	FULL/ LIMITED	FULL	LAURANA / LIMITED	LAUR- ANA	NO RECO- VERY
A	Yearly HP coverage	%	33	35	43	46	31	31	23
B	Yearly geothermal coverage (incl. elec)	%	5	6	16	20	22	22	23
C	HP power	kW	338	320	603	279	236	168	120
D	<i>P specific</i> borehole	W/m	16	16	22	14	10	8	6
E	Overall HP energy	MWh/yr	1,435	1,480	1,842	1,937	1,302	1,327	991
F	<i>Of which geothermal</i>	MWh/yr	155	139	412	547	603	622	661
G	<i>Of which gas rec.</i>	MWh/yr	806	848	816	744	265	263	0
H	<i>Of which electricity</i>	MWh/yr	473	493	614	646	434	442	330
I	<i>E specific</i> borehole	kWh/m/yr	13	13	34	42	46	47	50
J	CO ₂ emissions	tons	856	827	756	717	741	741	841

3.3 Scenario discussion

When comparing the FULL / LIMITED scenario to the BASE scenario we observe that by doubling the HP power, the HP production rises by a quarter (+362 MWh) and the geothermal energy coverage increases from 6 to 16%.

If the FULL / LIMITED scenario had no restrictions in the injection of HP heat, it is FULL scenario. So HP production would further increase of another 100 MWh and geothermal energy of 135 MWh. This increase makes the FULL scenario the best in terms of HP coverage (46%) and CO₂ emissions (717 tons/yr).

The scenario with waste heat recovered from gas used in Laurana DH sector only (LAURANA / LIMITED) has a similar HP production and coverage as the BASE scenario. However, the HP heat sources contribution is completely inversed. In fact, geothermal heat increases of 464 MWh and waste heat decreases of 583 MWh, making this scenario better than the BASE in terms of environmental performance. Furthermore, from this scenario we can evaluate the impact that the second DH sector (Trois-Chênes) has in the system performance. In fact, the creation of this sector leads to an increase of the gas consumption (and likewise waste heat recovered from gas) that severely diminishes the geothermal energy contribution to the system (waste heat as priority over geothermal because otherwise it would be wasted). Therefore, from a purely energy and environmental point of view, the creation of the Trois-Chênes sector was not necessary.

If the LAURANA / LIMITED scenario had no restrictions in the injection of HP heat, this is the LAURANA scenario. The major difference in the system would be the HP power (168 kW instead of 236). Otherwise, system performance values remain quite similar to LAURANA / LIMITED.

As for the NO RECOVERY scenario (no waste heat recovery), it has the lowest HP coverage (23%) and highest CO₂ emissions (841 tons/yr). Actually, when compared to LAURANA, this scenario has an increase of 100 tons/yr of CO₂ emissions (+14%). This scenario demonstrates the benefits of having efficient gas via HP, not only for LAURANA but also for all other scenarios.

In conclusion, two major improvements are pinpointed: i) lower the supply temperature in the Laurana DH to 62°C; ii) hydraulic connection of the HP to the Trois-Chênes DH sector.

Note that the second pinpointed improvement must be accompanied by a decrease in the return temperature of the Trois-Chênes DH sector and/or a replacement of the HP by another with higher condenser output temperatures (i.e. 75°C).

4. CONCLUSIONS

Laurana-Parc is a pioneer installation that was built with the intention of using a borehole heat exchanger field as a seasonal storage of waste heat recovered from gas (vapour condensate heat recovery), which would allow the shutdown of gas boilers in summer. In this context, the borehole heat exchanger field has two functions: first, storage (to phase shift the heat); second, heat source (geothermal energy extraction).

In theory, the concept is attractive for a HP with two energy sources, which are:

- Waste heat from gas, which increases the overall gas conversion efficiency by 9% (approximately difference between lower heating value and higher heating value);
- Geothermal energy (approximately 600 MWh/yr for 13,200 linear meter of borehole with water as the exchange fluid).

It should be noticed that the concept is only interesting if these two resources are combined, for an increase of renewable energy in the system. If, on the other hand, the goal was to improve the efficiency of gas, then there is no need to have a borehole heat exchanger field, a HP connected to a warm reservoir would suffice.

For this concept to work, the gas boilers need to be shut down in summer. Otherwise the HP will constantly work with heat recovered from gas and the borehole heat exchanger field will be constantly bypassed. Unfortunately, this is what was observed in the case study.

In fact, due to underestimation of several summer heat demand features, it is currently impossible to turn off the gas boilers in summer. Some of the key features that were underestimated are:

- DHW demand is not a base load (even though this simplification is frequently used). In fact, it has three characteristic peak loads (morning, midday and evening);
- Legionella bacteria management cannot be underestimated and its associated high temperatures need to be taken into account when using a HP;
- Return temperatures in DH, and therefore SST architecture, are a key feature when using HP for DH heat production;
- Balancing flow rates between HP and DH may limit the power of the HP during summer;

Moreover, the difference between HP power and DH demand (with Trois-Chênes extension) further decreases the possibility of shutting down the gas boilers in summer.

Truthfully, the restrictions presented above make it impossible to turn off the gas boilers in summer, that in their turn produce more waste heat, which has priority over geothermal energy, and finally leads to a down spiral decrease in the renewable heat fraction of the system.

At the end, the borehole heat exchanger field could be used neither for its seasonal storage function nor for its function as a geothermal energy supplier.

REFERENCES

- Faessler J., Hollmuller P., Mermoud F., Quiquerez L., Réseaux thermiques multi-ressources efficients et renouvelables : retour d'expérience sur la rénovation de la chaufferie de quartier Laurana-Parc à Thônex (GE), *Terre&Environnement (in press)*, Université de Genève (2016), 201p.
- Frederiksen S. and Werner S., District Heating and Cooling, *Studenlitteratur*, Sweden (2013).
- Mermoud F., De Sousa Fraga C., Hollmuller P., Pampaloni E., Lachal B., COP5 : Source froide solaire pour pompe à chaleur avec un COP annuel de 5 généralisable dans le neuf et la rénovation, *Terre&Environnement 126*, Université de Genève (2014a) 145p, <http://archive-ouverte.unige.ch/unige:35401>.
- Mermoud F., Hollmuller P., Pampaloni E., Lachal B., Suivi énergétique du bâtiment tertiaire Polimmo, 5 route des Jeunes à Genève, rénové MINERGIE® et équipé de pompes à chaleur couplées à des sondes géothermiques - Aspects techniques et économiques, *Terre&Environnement 128*, Université de Genève, (2014b) 140p, <http://archive-ouverte.unige.ch/unige:41178>.
- Pahud D., PILESIM2: Simulation Tool for Heating/Cooling Systems with Energy Piles or multiple Borehole Heat Exchangers. *User Manual*, ISAAC – DACD – SUPSI, (2007).
- Pahud D., Dimensionnement et potentiel d'utilisation d'un champ de sondes géothermiques pour le projet Laurana-parc, *expert report*, SUPSI, Trevano (2010).
- Quiquerez L., Cabrera D., Hollmuller P., Lachal B., Températures de distribution de chauffage du parc immobilier genevois, *expert report for SIG*, Université de Genève (2013), 77p, <http://archive-ouverte.unige.ch/unige:27989>
- SIA, Sondes Géothermiques, norme suisse 384/6, SN 546384/6 :2010 fr, Zurich (2010).

Acknowledgements

We are grateful to “Caisse de Prévoyance de l’Etat de Genève”, “CGC Energie”, “Commune de Thônex”, “Conti&Associés Ingénieur SA”, “Office Cantonal de l’Energie”, “ProEnova”, “Services Industriels de Genève” and “Société Privée de Gérance” for their technical support and their participation in the support group.

This work was funded by the “Services Industriels de Genève”.