13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

CO_2 emission savings of heat-pumps in the residential sector. Case study for multifamily buildings in Geneva

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Abstract

The present paper assesses the CO_2 emissions of air-source and groundwater-source HP systems, with and without complementary PV, for a sample of multifamily buildings (new, retrofitted and non-retrofitted) located in Geneva. HP performance is evaluated by way of numerical simulation in hourly time step, and is cross-cut with the hourly grid CO_2 content of the Swiss electricity mix (taking into account both domestic generation and imports from the neighbor countries). Given the seasonal trend of both the building heat demand and the grid CO_2 content, latter turns out to strongly underestimate the CO_2 content of the HP system electricity. Nonetheless, when compared with a gas boiler, both HP systems induce important annual CO_2 savings (air: 61 - 81% depending on the accounting method; groundwater: 75% - 87%). Finally, while PV can substantially contribute to the summer HP demand, the related annual CO_2 savings remain relatively marginal, also due to seasonality of the grid CO_2 content.

Keywords: heat pump (HP); photovoltaic (PV), multifamily building; CO_2 emissions

1. Introduction

Acronyms

DHW	domestic hot water
HP	heat pump
MFB	multifamily building
PV	photovoltaic
SH	space heating

Symbols

COP	coefficient of performance (kWh_{th}/kWh_{el})
Cbld	CO_2 content of building heat demand, area related (kg/m^2)
Cel	CO_2 content of HP system electricity (kg/kWh_{el})
Cgrid	CO_2 content of electrical grid (kg/kWh_{el})
Cth	CO_2 content of building heat demand (kg/kWh_{th})
Esys	system electricity (kWh_{el}/m^2)
Qdem	building heat demand (kWh_{th}/m^2)
Qdhw	DHW demand (kWh_{th}/m^2)
Qsh	SH demand (kWh_{th}/m^2)
SPF	seasonal performance factor (kWh_{th}/kWh_{el})

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1.1. General issue

An increasing number of authors are evaluating the environmental impact of massive heat-pump (HP) introduction, but only few consider the temporal dynamic of the carbon content of electricity-generation. As a notable exception, [1] shows that introducing direct heat pump heating along with combined cycle gas plants could generate significant reductions of greenhouse gas emissions, when compared with classic fossil-fuel heating and electric resistance heating. Similarly, [2] analyze the temporal load curves of heat pump water heaters and air-source heat pumps in the context of temporal grid-level emissions data. However, while the previous two studies do consider the carbon content of electricity at hourly scale, latter is based on the production accounting principle, which doesn't take into account the impact of electricity imports and exports on the carbon content of the electricity mix. In a country like Switzerland, which relies on a high share of electricity exchanges with the neighboring countries, such an approach is not satisfactory.

1.2. Local context

While the space-heating (SH) and domestic hot water (DHW) production for the building sector of the Canton of Geneva rely 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 HPs, at building level as well as integrated in district heating networks [3].

Even though multifamily buildings (MFB) only constitute 27% of the Geneva building stock, they represent almost half of the heated floor area of the canton, namely 19.3 out of 40.9 million m2 [4]. About half of these MFB, which were built between 1946 and 1980, are nowadays in need of retrofit and possess a strong energy saving potential. In parallel to reducing of the heat demand of the building stock, in particular by way of retrofit, reducing of the CO_2 emissions can also be achieved by replacing fossil fuels by renewable energies, in particular via heat pump (HP) systems. However, in addition to HP performance issues, the CO_2 content of the electricity needed to run such HP systems, as well as the complementarity with local PV production remain a fundamental issue.

1.3. Objective

In this context, [5] performed a numerical simulation study which compares the potentials and constraints of different heat sources exploited by HP systems, with and without complementary PV, implemented in various types of multifamily buildings located in Geneva. As a complement, a recent study evaluates the hourly CO_2 content of the Swiss electricity consumption mix [6], taking into account both domestic production and imports to Switzerland from the neighbor countries.

Objective of the present paper is to cross-cut these 2 studies, for assessing the CO_2 emissions of air-source and groundwater-source HP systems, with and without complementary PV, for a sample of multifamily buildings (new, retrofitted and non-retrofitted), located in Geneva.

1.4. Method and results

The methodological part of the paper is organized as follows: i) Presentation of the building sample and related heat load profiles, which are rescaled to 2017, the reference meteorological year for which hourly CO_2 content of electricity is available; ii) Characterization of the considered heat sources (air and groundwater), HP system layout and simulation algorithm, as well as complementary PV system; iii) Characterization of the hourly CO_2 content of the Swiss electricity consumption mix, which is given for two distinct accounting approaches (lower and upper grid CO_2 content).

The results are discussed as follows: i) HP performance, in terms of daily *COP* and annual *SPF*, for the distinct heat demands; ii) CO_2 emissions of the stand-alone HP systems (without PV) and comparison with the CO_2 emissions of a gas boiler; iii) effect of PV production on the daily and annual consumption/production of electricity, as well as related CO_2 savings.

2. Building sample and heat load

2.1. Building sample

The present study is based on the same multi-family building (MF) sample which was used in [5]: i) 2 new buildings with identical low SH demand, but differentiated DHW demand; ii) 3 retrofitted buildings, of which one with low SH and the other ones with intermediate SH demand but differentiated SH distribution temperature; iii) 1 non retrofitted building. The main characteristics of the building sample (with SH demand corresponding to standard weather data) are summarized in Table 1. Note that 4 of the buildings correspond to real case studies situated in Geneva (*New, RetBest, RetRef, NoRet*), while the 2 other are combinations thereof, in terms of DHW demand (*NewLow*) or of SH distribution temperature (*RetAvg*).

Table 1 Building sample.

Building	**Qsh**	**Qdhw**	**Qdem**	**Tsh.0**
	kWh/m²	**kWh/m²**	**kWh/m²**	**°C**
New	20.8	47.7	68.5	30
New Low	20.8	28.3	49.1	30
Ret Best	37.8	34.6	72.4	40
Ret Avg	69.3	28.3	97.6	40
Ret Ref	69.3	28.3	97.6	50
No Ret	110.0	28.3	138.3	50

Qdhw, Qsh, Qdem: DHW, SH and total annual heat demand (with climatic correction to standard weather).
Tsh.0: SH distribution temperature, at 0° outdoor temperature.

Comparison with a benchmark on the SH demand of the MF building stock of Geneva [4] shows that, except for *NoRet*, all our buildings are in the 1st decile, meaning that they are representative of the best cases in their respective construction periods. *NoRet* is in the 3rd quartile, close to the 4th quartile, meaning that it is representative of a lower than average building envelope.

Similarly, comparison with a benchmark on the DHW demand of the MFB stock of Geneva [7] yields following results: *New* is in the 4th quartile, amongst the highest values; *RetBest* is slightly above the median; all other cases (which by definition have the same DHW demand) are in the 2nd quartile, closer to the 1st quartile than to the median.

2.2. Heat load profiles

For the sake of the present study, the above building demands are rescaled to 2017, the reference meteorological year for which hourly CO_2 content of electricity is available (see further down). To do so we consider that: i) DHW demand is independent of the meteorological year and is therefore the same as for standard weather data; ii) SH demand is multiplied by 1.03, the ratio between 2017 and standard weather degree days.

In agreement with [5], the hourly demand profile is then defined as follows: i) For DHW, the hourly profile is given by the monitored data of a typical multifamily building [8]. It is adjusted by a multiplication factor, so that the integral of the load corresponds to the annual DHW demand of the building under consideration; ii) For SH, the hourly load is given by a linear function of the outdoor temperature, defined by a set point above which SH is off and a nominal heat load at 0°C outdoor temperature (which is adjusted so that the integral of the load corresponds to the annual SH demand of the building under consideration); iii) For SH distribution temperature, it is given by a linear function of the outdoor temperature. The DHW distribution temperature is considered constant, at 55°C. The limits of this methodology, in particular in terms of load curve, was discussed in details in [9]. For the particular case of a HP system on a low-energy building, it was shown that simulation results with the modelled heat demand are very similar to simulation results with the monitored heat demand, at least at aggregated system level.

The resulting heat load profiles of the building sample are presented in Figure 1, in daily values. We observe the relatively constant DHW demand at outdoor temperatures above 18°C, below which the distinct SH demands of the building sample are visible (with linear patterns corresponding to the above construction).

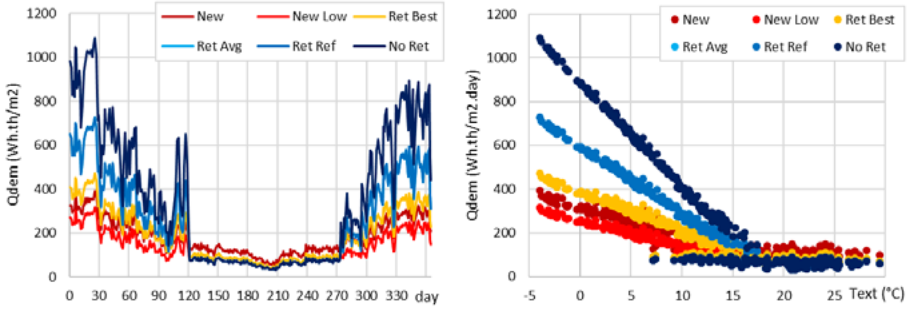

Fig. 1. Heat load of the building sample, profile and relation to outdoor temperature (2017, daily values).

3. HP systems and electrical load

3.1. Heat sources

The above described building sample was previously used for assessing of HP performance for a variety of heat sources [5]: i) ambient air; ii) geothermal boreholes; iii) water from lake of Geneva, pumped from a depth of 35 m; iv) Rhône river, corresponding to the top layer of the lake; v) shallow groundwater; vi) unglazed solar thermal collectors, used as HP heat absorbers in case of insufficient solar irradiation for direct solar production.

As expected, the simulated HP seasonal performance factors (*SPF*) turned out to be strongly related with the heat source temperature: groundwater yielded the highest *SPF* values (4.3 - 4.8, depending on the building heat demand) followed by river (3.9 - 4.5) and lake (3.8 - 4.3). The geothermal borehole performed slightly lower (3.6 - 4.0), while solar and air were at the bottom, with very similar values (solar: 2.9 - 3.5; air: 3.0 - 3.4).

In the present study, we will focus on the two extreme cases: i) air, which is characterized by a strong seasonal and daily variability (hourly values ranging from -5°C to 34°C); ii) groundwater, with a constant temperature of 13°C.

3.2. HP system

The considered system layout (Fig. 2) is similar for the air source HP and the groundwater source HP. Sizing of the components (HP, storage) depends on the maximal hourly heat load of the building under consideration.

Operation of the system obeys following scheme of priorities: i) maintaining the DHW tank above 50°C; ii) covering of the SH demand by way of: a) storage discharge; b) activation of the HP, with surplus production used to charge the heat storage; c) direct electric heating, which is activated only in case of simultaneous SH and DHW without possible storage discharge.

The components are modelled according to energy balance equations, which are integrated in the TRNSYS. simulation software package, taking into account the above defined priority rules [9]. The HP is modelled by an input/output table based on the working temperatures (evaporator input, condenser output), as given by manufacturer data (which, for the air-source HP, includes electricity for de-icing). Each of the storage tanks is modelled by way of a one-node model (disregarding stratification effects, which should be negligible, given the relatively small heat storage capacities), taking into account heat losses to the technical room. Direct electric heating covers the instantaneous difference between demand and production. Auxiliary electricity for circulation pumps is not taken into account. Simulation results were previously validated with monitored values of a solar heat pump system, at component and system level [9]. So as to properly take into account the dynamic of the HP-system, simulation is performed in 6 min time step, with output values stored in hourly time step.

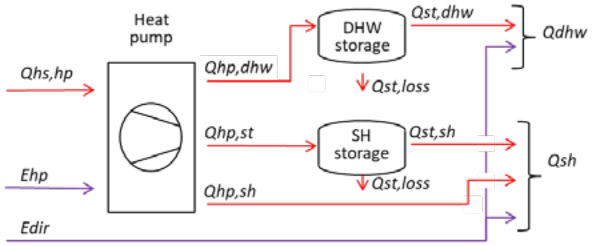

Fig. 2. HP system layout and associated energy flows.

3.3. Reference scenario with gas boiler

As a "business as usual" alternative to the above described HP systems, and for the sake of comparison in terms of CO_2 emission savings, we also consider heat production by way of a centralized gas boiler. In this case the heat production (including storage loses) is considered to match the hourly output of the groundwater HP (plus occasional direct electric heating).

4. PV production

As a complement to the HP system, we study the benefits of adding photovoltaic panels on the available building roof area. In order to do so, we consider following two cases [5]: i) an available roof area of 0.2 m^2 per m^2 heated floor area, corresponding to a "low-rise" multifamily building in Geneva (4 floors, under hypothesis of an 80% ratio between the available roof area, in m^2, and the floor specific heated area, in m^2 per floor); ii) an available roof area of 0.1 m^2 per m^2 heated floor area, which corresponds to a "high-rise" building in Geneva (8 floors).

PV production is based on a 12 % efficiency applied directly to the hourly global horizontal solar irradiation, corresponding to an annual electricity production of 162 kWh per m^2 of PV (2017).

5. CO_2 emissions

5.1. HP systems

In the case of HP systems, induced emissions are calculated on an hourly basis, by way of the 2017 hourly grid CO_2 content of the Swiss electricity consumption mix evaluated by [6]. Latter study takes into account both domestic production and inflows to Switzerland from each of the neighbor countries. To do so, it uses hourly available data concerning the production mix of the various European countries, per type of production, as well as hourly cross-border flows between them. Based on merit-order considerations, it takes into account the impact on the incremental generation mix due to import/export with the neighbor countries.

Finally, the CO_2 content of the resulting electricity mix is calculated by way of the carbon intensity of each production type, as given by the ecoinvent life cycle inventory database [10]. While this method is relatively straightforward for most of the production types (renewables, nuclear, fossils), a specific issue concerns electricity generation from blast furnace gas units in Germany. While latter represent only a small share of the generation capacity of the total market, it plays an important role in compensating for capacity shortages at the European level in the winter period and hence significantly contributes to Swiss imports. In this regard, it should be noted that the CO_2 content of electricity from German blast furnaces is controversial, leading to two distinct accounting approaches: i) on the one hand, such gases can be considered as "waste" from the iron and steel industry, in which case the related CO_2 content is attributed to latter sector and not to electricity generation; ii) on the other hand, in respect to specific economic considerations regarding the decision to flare the gases or to produce electricity, it can also be argued that the corresponding emissions should be attributed to the electricity sector [6].

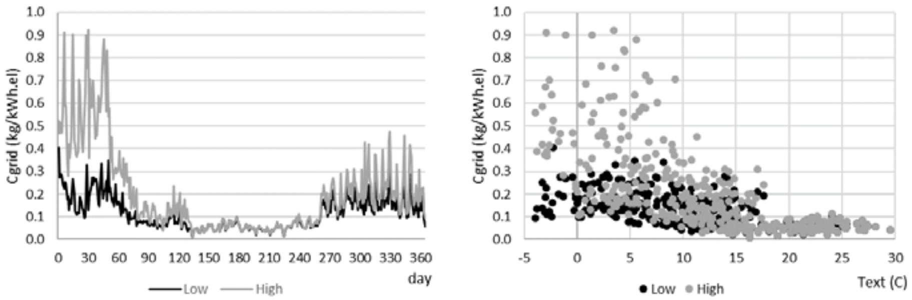

Fig. 3. Grid CO_2 content of the Swiss electricity mix, profile and relation to outdoor temperature (2017, daily values).

Finally, for both of these approaches, the dynamic of the grid CO_2 content (year 2017) is depicted in Figure 3, in daily values. Both approaches reveal a strong seasonal pattern, which results from the seasonality of electricity production and demand in Switzerland and its neighboring countries and the related imports and exports. We further note the fundamental issue of the accounting method for blast furnace gases, with an approximative factor 2 between the resulting annual average (lower grid CO_2: 108 g/kWh$_{el}$, upper grid CO_2: 196 g/kWh$_{el}$).

5.2. PV production and gas boiler

As for the HP systems, avoided emissions related to PV production are calculated on an hourly basis, by way of the above hourly grid CO_2 content. In the case of gas boilers, emissions are directly related to the produced heat, by way of a constant emission factor of 249 g/kWh$_{th}$ given by the Swiss Coordination Conference of Building Services [11].

6. Results and discussion

6.1. Performance and emission indicators

The results will be discussed on the basis of aggregated values of the hourly building heat demand *Qdem* (kWh$_{th}$/m^2), the HP system electricity demand *Esys* (kWh$_{el}$/m^2) and the CO_2 content of grid *Cgrid* (kg/kWh$_{el}$).

Performance of the HP system will be discussed in terms of daily *COP* (kWh$_{th}$/kWh$_{el}$) and annual *SPF*. (kWh$_{th}$/kWh$_{el}$), defined accordingly to their respective daily or annual aggregation level:

$$COP = \frac{\sum Qdem}{\sum Esys} \quad (1)$$

$$SPF = \frac{\sum Qdem}{\sum Esys} \quad (2)$$

Emissions will be discussed in terms of the area related CO_2 content of the heat demand *Cbld* (kg/m^2), the thermal CO_2 content of the heat demand *Cth* (kg/kWh$_{th}$) and the electrical CO_2 content of the HP system electricity *Cel* (kg/kWh$_{el}$). Latter are defined as follows (with daily or annual aggregation level):

$$Cbld = \sum Esys \cdot Cgrid \quad (3)$$

$$Cth = \frac{\sum Esys \cdot Cgrid}{\sum Qdem} \quad (4)$$

$$Cel = \frac{\sum Esys \cdot Cgrid}{\sum Esys} \quad (5)$$

6.2. HP performance

Figure 4 depicts the daily *COP* values of both HP systems. In the case of the air-source HP, when the air temperature is above 10°C the *COP* is mainly in the range of 3 - 4, while it drops for lower temperatures (due to lower resource temperature, as well as related de-icing). In the case of the groundwater-source HP, the *COP* is mainly in the range of 3.5 - 5.5, and is not so sensible to the outdoor temperature.

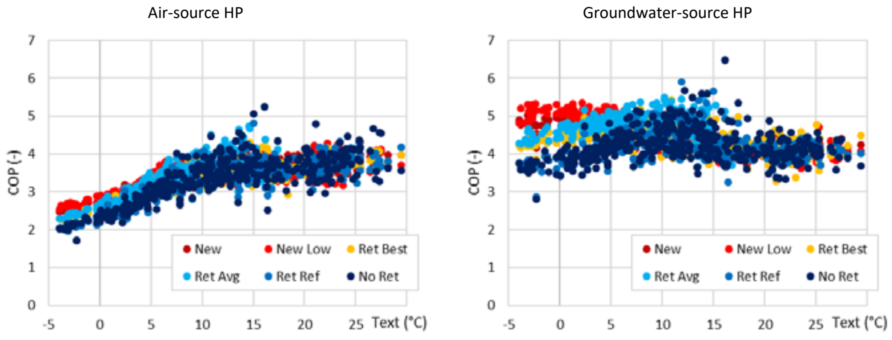

Fig. 4. COP of air and groundwater HP systems (daily values).

The corresponding annual *SPF* values are given in Table 2, with an average of 3.06 for the air-source HP and 4.42 for the groundwater-source HP (not including ancillary electricity for circulation pumps).

Table 2 Annual heat demand and SPF (2017).

Heat demand and SPF		New	New Low	Ret Best	Ret Avg	Ret Ref	No Ret	Average
Qdem	kWh.th/m2	67.12	47.72	69.51	92.23	92.23	129.82	
SPF air	kWh.th/kWh.el	3.24	3.26	3.10	3.11	2.83	2.80	3.06
SPF gw	kWh.th/kWh.el	4.51	4.68	4.46	4.65	4.10	4.12	4.42

air: air-source HP; gw: groundwater-source HP

6.3. CO_2 emissions, without PV

Figure 5 shows the daily values of the system electricity consumption (top) and the area related heat CO_2 content for the lower grid CO_2 content (bottom). While there is a strong correlation between electricity consumption and outdoor temperature, similar to the heat demand (Fig. 1), a much larger dispersion appears for the area related CO_2 content, as induced by the dispersion of the grid CO_2 content (Fig. 3).

The corresponding annual CO_2 emissions are summarized in Table 3, both for the lower and upper grid CO_2 content, as well as for the alternative gas boiler.

While the area related CO_2 content (*Cbld*) obviously depends on the building under consideration, the heat related CO_2 content (*Cth*) turns out relatively constant. In the case of the gas boiler it amounts to 256 g/kWh_{th} (i.e. 3% more than the content of the heat at boiler outlet, see section 5.2, due to storage losses). In comparison, and when considering the lower grid CO_2 mix of electricity, it amounts to an average of 49 g/kWh_{th} for the air-source HP (81% savings as compared to the gas boiler), respectively 33 g/kWh_{th} for the groundwater-source HP (87% savings). When considering the upper grid CO_2 content, it amounts to twice higher values (air: 100 g/kWh_{th} – 61% savings; groundwater: 64 g/kWh_{th} – 75% savings).

Finally, given the seasonal trend of both the heat demand (Fig. 1) and the CO_2 content of the grid (Fig. 3), latter turns out to strongly underestimate the CO_2 content of the HP system electricity (*Cel*). Such is the case both for the lower grid content (grid: 108 g/kWh_{el}; air-source HP: 150 g/kWh_{el}; groundwater-source HP: 144 g/kWh_{el}), as for the upper grid content (grid: 196 g/kWh_{el}; air-source HP: 303 g/kWh_{el}; groundwater-source HP: 282 g/kWh_{el}). While these results confirm the necessity to assess HP emissions by way of hourly values of the grid CO_2 content, the annual derived CO_2 content of the HP system electricity could in principle be used for other annual *SPF* values than the ones considered in this study.

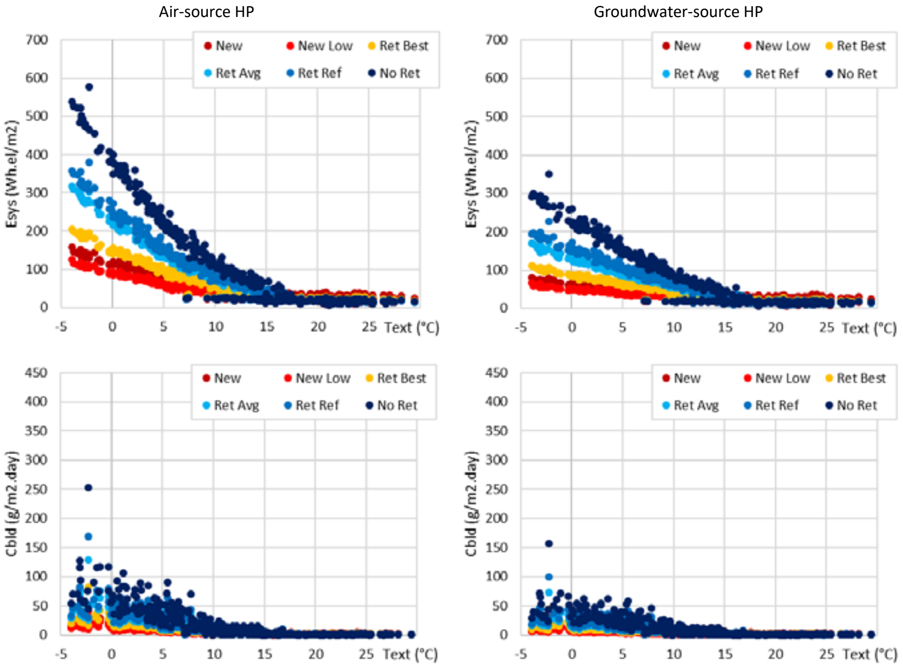

Fig. 5. HP without PV: electricity consumption (top) and area related CO_2 content of the heat demand, for the lower grid CO_2 content (bottom), as a function of outdoor temperature (daily values).

Table 3 Gas boiler and HP (without PV): annual CO2 emissions, for lower and upper grid CO2 content.

Gas boiler			**New**	**New Low**	**Ret Best**	**Ret Avg**	**Ret Ref**	**No Ret**	**Average**
Cbld		kg/m2	17.17	12.25	17.83	23.61	23.72	33.34	
Cth		kg/kWh.th	0.256	0.257	0.256	0.256	0.257	0.257	0.256
HP – lower grid CO_2			New	New Low	Ret Best	Ret Avg	Ret Ref	No Ret	Average
Cbld	air	kg/m2	2.79	2.03	3.28	4.63	5.19	7.54	
	gw	kg/m2	1.90	1.36	2.19	2.98	3.47	5.00	
Cth	air	kg/kWh.th	0.042	0.043	0.047	0.050	0.056	0.058	0.049
	gw	kg/kWh.th	0.028	0.028	0.031	0.032	0.038	0.039	0.033
Cel	air	kg/kWh.el	0.135	0.139	0.146	0.156	0.159	0.163	0.150
	gw	kg/kWh.el	0.128	0.133	0.140	0.150	0.154	0.159	0.144
HP – upper grid CO_2			New	New Low	Ret Best	Ret Avg	Ret Ref	No Ret	Average
Cbld	air	kg/m2	5.42	4.09	6.55	9.54	10.58	15.62	
	gw	kg/m2	3.55	2.58	4.26	5.98	6.89	10.07	
Cth	air	kg/kWh.th	0.081	0.086	0.094	0.103	0.115	0.120	0.100
	gw	kg/kWh.th	0.053	0.054	0.061	0.065	0.075	0.078	0.064
Cel	air	kg/kWh.el	0.262	0.280	0.292	0.321	0.325	0.337	0.303
	gw	kg/kWh.el	0.239	0.253	0.273	0.302	0.307	0.319	0.282

air: air-source HP; gw: groundwater-source HP

6.4. Complementary PV

In this section we analyze the performance of combined HP and PV systems. For a PV system of 0.2 m^2 per m^2 heated area (low-rise building, see section 4), Figure 6 depicts the HP-PV system electricity balance (top) and the area related CO_2 emissions of the heat demand, calculated with the lower grid CO_2 content (bottom).

When considering the HP-PV electricity balance (HP consumption – PV production), and when comparing to the case without PV (Fig. 5), we observe the seasonal mismatch between both technologies: for temperatures below 5°C, consumption is very similar to the case without PV; for temperatures above 10°C, PV production reaches much more important values than HP consumption, resulting in PV injection to the grid.

When considering the area related CO_2 emissions, the situation is quite different. As a matter of fact, while PV injection to the grid results in negative CO_2 emissions (savings), the related values remain relatively small, since such happens when the grid CO_2 content is already low (Fig. 3).

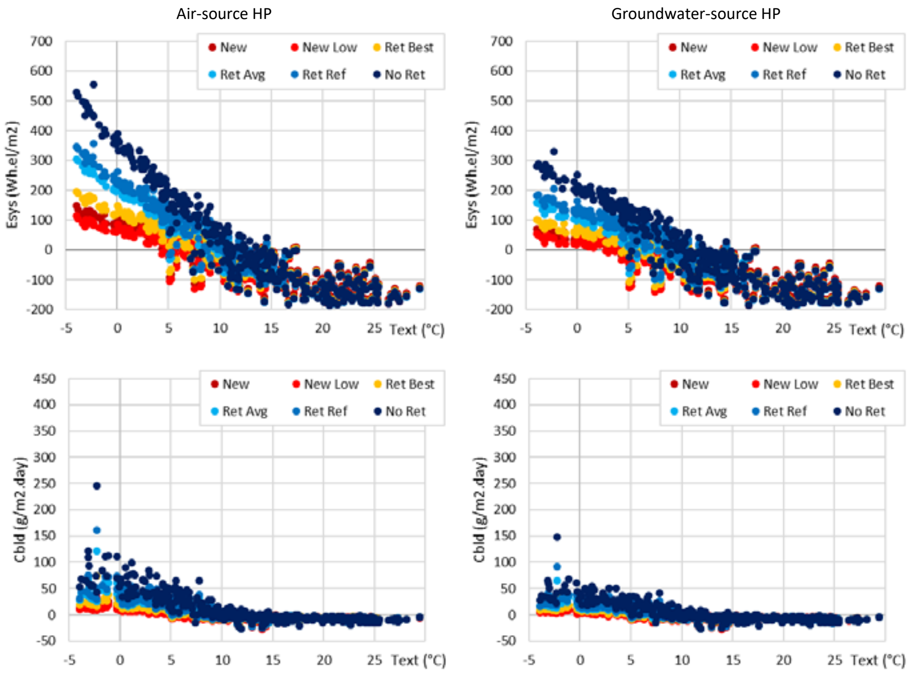

Fig. 6. HP with PV (0.2 m^2 per m^2 heated area): HP-PV electricity balance (top) and area related CO_2 content of the heat demand, for the lower grid CO_2 content (bottom), as a function of outdoor temperature (daily values).

Finally, figure 7 summarizes the annual area related CO_2 content of the 3 production systems (gas boiler, air-source HP, groundwater-source HP) in conjunction or not with PV (0.1 and 0.2 m^2 per m^2 heated area), both for the lower and upper grid CO_2 content of the Swiss electricity consumption mix.

In all cases, the area related CO_2 content is strongly corelated to the building heat demand, with a linear relation between the two. As already pointed out, the CO_2 content of the HP system in all cases smaller than the one of the gas boiler. Finally, while PV can contribute substantially to the summer HP demand, the related annual CO_2 savings remain relatively marginal. Only in the case of buildings with a low heat demand (< 90 kWh/m^2), and in particular for low-rise buildings (0.2 m^2 PV per m^2 heated area), does the annual CO_2 content of the combined HP-PV system lead to CO_2-positive buildings (however not taking into account electricity other than for the HP).

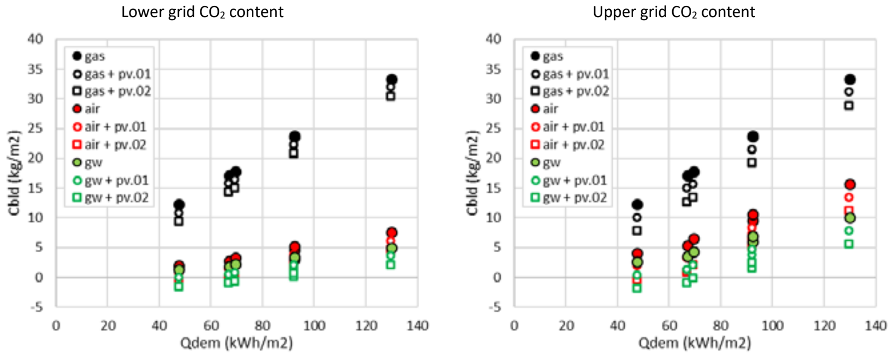

Fig. 7. Gas boiler and HP (with and without PV): Annual area related CO_2 emissions as a function of the building heat demand (for lower and upper grid CO_2 content).

7. Conclusions

The present paper assesses the CO_2 emissions of air-source and groundwater-source HP systems, with and without complementary PV, for a sample of multifamily buildings (new, retrofitted and non-retrofitted) located in Geneva. HP performance is evaluated by way of numerical simulation in hourly time step, and is cross-cut with the hourly CO_2 content of the Swiss electricity mix (taking into account both domestic generation and imports from the neighbor countries).

Latter assessment is done by way of two distinct accounting approaches: i) lower grid CO_2 content, which considers electricity from German blast furnaces CO_2 free (the related CO_2 content being attributed to the iron and steel industry); ii) upper grid CO_2 content, for which the corresponding emissions are attributed to the electricity sector.

The main results are as follows:

- The annual SPF has an average of 3.06 for the air-source HP and 4.42 for the groundwater-source HP (not including ancillary electricity for circulation pumps).
- In both cases, the daily electricity consumption bears a strong relation to the outdoor temperature, with patterns depending on the annual heat demand. A much larger dispersion appears in the case of the CO_2 content of the produced heat, as induced by the dispersion of the grid CO_2 content.
- When comparing with the emissions of a gas boiler, the considered HP systems induce very important annual CO_2 savings, at least for the lower grid CO_2 content of electricity (air-source HP: 81% savings; groundwater-source HP: 87% savings). These savings are somewhat reduced when considering the upper grid CO_2 content of electricity (air: 61%; groundwater: 75%).
- Given the seasonal trend of both the heat demand and the CO_2 content of the grid, latter turns out to strongly underestimate the CO_2 content of the HP system electricity. Such is the case both for lower grid content (grid: 108 g/kWh_{el}; air-source HP: 150 g/kWh_{el}; groundwater-source HP: 144 g/kWh_{el}), as for the upper grid content (grid: 196 g/kWh_{el}; air-source HP: 303 g/kWh_{el}; groundwater-source HP: 282 g/kWh_{el}).
- While PV can substantially contribute to the summer HP demand, the related annual CO_2 savings remain relatively marginal. As a matter of fact, for temperatures below 5°C consumption is very similar to the one without PV; for temperatures above 10°C PV production reaches much more important values than HP consumption, resulting in PV injection to the grid, but related CO_2 savings remain relatively small since such happens when the grid CO_2 content is already low.

Finally, it should be stressed that preceding results are based on numerical simulation, which assumes optimized conditions of HP integration and control, and disregards ancillary electricity of the circulation pumps.

Acknowledgements

This research was co-funded by CTI within the SCCER FEEB&D and SCCER CREST projects.

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