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Research paper

Decarbonizing residential buildings with heat pumps: Transferability of front-runner experiences from Swiss Cantons

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ABSTRACT

The replacement of fossil-fuelled heating systems with systems using renewable energy sources is a central energy and climate policy concern and one of the prerequisites for reducing CO_2 emissions to a climate-friendly level. The Swiss decarbonization strategy considers the use of electric air-to-water heat pumps (HP) operated with electricity generated from renewable sources or from a power mix with low CO_2 content. However, the installation of HPs, which is essential for decarbonizing heat supply in buildings, is proceeding very slowly, and fossil fuel heating replacement is still the rule rather than the exception. This study investigates how a strong climate protection law (Energy Act of Basel-Stadt) has managed to overcome resistance to the installation of HPs, which is observed in many other Swiss cantons. The research question to be answered is whether the experience made with HP implementation in one location (with Basel-Stadt as forerunner canton) would be similarly viable in another location (Canton of Geneva). The results indicate that although the two cantons have different characteristics in terms of building stock, the potential of buildings where HP installation is considered 'easy' is high in both cases (50% in Basel-Stadt and 40% in Geneva). This is equivalent to 40% (in both cities) of the energy used for thermal use that is currently produced by fossil energy and that could be instead generated with HPs. Although there are many factors to take into account in order to design effective policies that are truly effective for the extensive installation of HP, it is worth remembering that there are many cases where it is already possible to easily install a HP today, and these should be the starting point.

1. Introduction

1.1. Background

Existing buildings account for approximately 40% of the energy consumption in the European Union (EU) placing them among the most significant CO_2 emission sources in Europe (Odyssee Project, 2018). The decarbonization of the built environment is highlighted as a priority to achieve the EU's long-term energy and climate goals (EU Parliament, 2018). The replacement of fossil-fuelled heating systems with systems using renewable energy sources is a central energy and climate policy concern and one of the prerequisites for reducing CO_2 emissions to a climate-friendly level (Fajardy and Reiner, 2021). In Switzerland, the Federal Council has been developing the Swiss Energy Strategy 2050 (ES-2050) since 2011 (Bundesamt für Energie BFE, 2021). The ES-2050 is based on three strategic objectives: increasing energy efficiency, increasing the use of renewable energy, and withdrawal from nuclear energy (Prognos, 2012). The strategy for the retrofitting of buildings falls into the first two areas and recent studies suggest that more attention in energy retrofitting should be paid to mitigating emissions from heat supply (Cozza et al., 2020a; Streicher et al., 2020).

As a result of the ES-2050, alternative heat generation technologies are becoming increasingly important. Electric air-to-water heat pumps (HP) are expected to play an important role in heat supply (Steinke et al., 2018). The decarbonization strategy considers the use of HP operated with electricity generated from renewable sources or from a power mix with low CO_2 content (Freyre et al., 2021). HP have proven themselves especially in single-family houses and in new buildings with high thermal performance. For a long time, however, HP were considered impractical for the replacement of heating systems in existing residential buildings, because they pose greater challenges in terms of system size, noise protection, and visibility

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(Varga et al., 2018). Still today HP face obstacles in urban areas, they are considered to be noisy, aesthetically unsatisfactory, not very energy-efficient, and the systems installed outside often trigger complaints (Steinke et al., 2018). The installation of heat pumps, which is essential for decarbonizing heat supply in buildings, is proceeding very slowly, and fossil fuel heating replacement is still the rule rather than the exception (econcept AG, 2020). For example, about two thirds of the properties in Basel-Stadt currently have a fossil heating system. In the city of Zurich, this applies to 80% of the dwellings, and for Geneva the percentage is even higher (more than 85%) (FSO, 2017). In the last ten years, for the entire Swiss residential building stock, the existing heating systems were replaced with heat pumps in only 20% of the energy retrofits performed (Cozza et al., 2020b). This heavily undermines the energy targets of the confederation and of many cantons. It is therefore very important not only to increase the rate of energy retrofitting but also to ensure that the heating systems installed release practically no CO_2 emissions. And to this end, the legal framework conditions set by the federal government (Bundesamt für Energie BFE, 2021) and the cantons (Office federal de l'énergie, 2018) are central to the choice of energy source for heating system replacement. They are the strongest levers for influencing the choice of heating system. The cities and municipalities must act within these legal boundaries (econcept AG, 2020).

The canton of Basel-Stadt (*German* for*:* Basel city, BS) is a good example in this respect, as it has been pursuing a progressive energy and environmental policy for many years (Müller et al., 2014). The vision of a "greener" society is anchored as a leitmotif in the government's current legislative plan (Basel-Stadt, 2019). The decarbonization of heat generation in buildings is the core part of the canton's Energy Act of 2017 – revised in 2020 – on the basis of the cantonal model regulations for energy (Conferenza Cantonale dei Direttori dell'Energia CDE, 2014). By means of legal requirements, a sustainable energy supply is to be ensured by 2050 and the share of fossil fuels is to be reduced to one tonne of CO_2 per person and year (Ott et al., 2014). The use of fossil fuels for heat supply is to be reduced with various measures. These are strictly regulated in the ordinance to the Energy Act that came into force in autumn 2017 (Kanton Basel-Stadt, 2020). One important aspect is the replacement of existing heating systems using fossil fuels. The revised Energy Act of Basel-Stadt specifies: "*When replacing the heating system in existing buildings, a switch to renewable energy must be made if this is technically possible and if there are no additional costs compared to oil or gas heating*". The higher investment costs associated with this switch are compensated with subsidies from Basel-Stadt's energy promotion fund (Steinke et al., 2018). In locations where it is not possible to switch to district heating and given the restrictions for biomass boilers for reasons of air pollution, heat pumps typically represent the main option in this context, with air source heat pumps mostly being preferred over ground source heat pumps (Forster and Varga, 2018). While before implementation of the new Energy Act the overwhelming majority of all oil and gas-fired boilers were again replaced by fossil fuel-fired boilers, a turnaround in favour of renewable heating technologies has been achieved since then (Amt für Umwelt und Energie Kanton Basel-Stadt, 2021; Sprecher et al., 2014). This is particularly clear from the evolution of the shares of installed power by type of heating system (Fig. 1). The figure also shows the drastic decrease of installed heating systems in total, indicating that many owners postponed the replacement of their heating system following the entry into force of the Energy Act and that heating system replacement has not yet reached a steady state (these observations were confirmed by Mathys (2021)). This makes Basel-Stadt an excellent case study for other Swiss cantons and for countries with similar climate and urban morphology, raising the question whether the experience is replicable in other locations.

The success of policies depends on many factors (chosen regulatory design and its effective implementation, permit procedures, level of incentives, susceptibility of population, willingness of owners, and readiness of installers), with the physics of the building stock and other local conditions being among the decisive factors for the decarbonization of cities. Conditions differ across locations, e.g.: thermal performance of buildings differ across regions and countries, urban density differs, and so does the availability of waste heat and presence of district heating infrastructure. These factors should therefore be considered when aiming to transfer the experience made in one place to another place.

1.2. Aim and scope

While the canton of Basel-Stadt is leading the transition to heat pumps in Switzerland, a major transition is still pending in most other Swiss cantons including Geneva as well as in most other European countries. In Switzerland, HP are quite common in new well-insulated single-family and multi-family houses while they are only sporadically installed in existing residential buildings (albeit more frequently in single-family houses than in multi-family houses; (Amt für Umwelt und Energie Kanton Basel-Stadt, 2021)). There has been a perception that technical challenges make heating replacement with HP difficult (Varga et al., 2018). In the case of renovation of multi-family buildings, there is a general fear that HP will no longer function properly in winter (Freyre et al., 2021). The canton of Geneva, for example, has tried to counteract this mentality with subsidies, but so far without success (Geneve-ReC, 2017). For some years now, the canton has been running an information and training programme for experts on heat pumps together with the local utility SIG (Geneve - ReC, 2019). However, according to experts, the programme has not led to an increase in applications for subsidies, only to a greater diversity of applicants (private homeowners, institutional owners etc.) (Freyre, 2019). In this work, we aim to study the implications of the experience of the canton Basel-Stadt for applying a similar approach to Geneva. This analysis is not only relevant for the transfer of successful approaches from Basel-Stadt to Geneva but also to other Swiss cantons, and given their similar building stock and climate, also for other countries in Northern Europe.

We aim to answer the question whether the experience made with HP implementation in one location (with Basel-Stadt as forerunner canton) would be similarly viable in another location (and if not, to which extent it would be viable). Specifically, we aim to assess the extent of exemptions to HP implementation that can be expected for perceived technical barriers in another location (e.g., Geneva) when applying the strategy implemented in a forerunner location (e.g., Basel-Stadt). Since, as mentioned above, successful policy implementation depends on many soft factors we focus here on hard factors describing the building stock in cities.

We examine the following questions:

- What is the current status of Geneva, in comparison with Basel-Stadt, with regard to switching to HP for heating purpose?
- Which are building stock characteristics (indicators) that should be considered to assess the easiness of implementing HPs?
- How can the indicators be used to establish the likely resulting share of the building stock for which a relatively easy installation of HP can be expected?

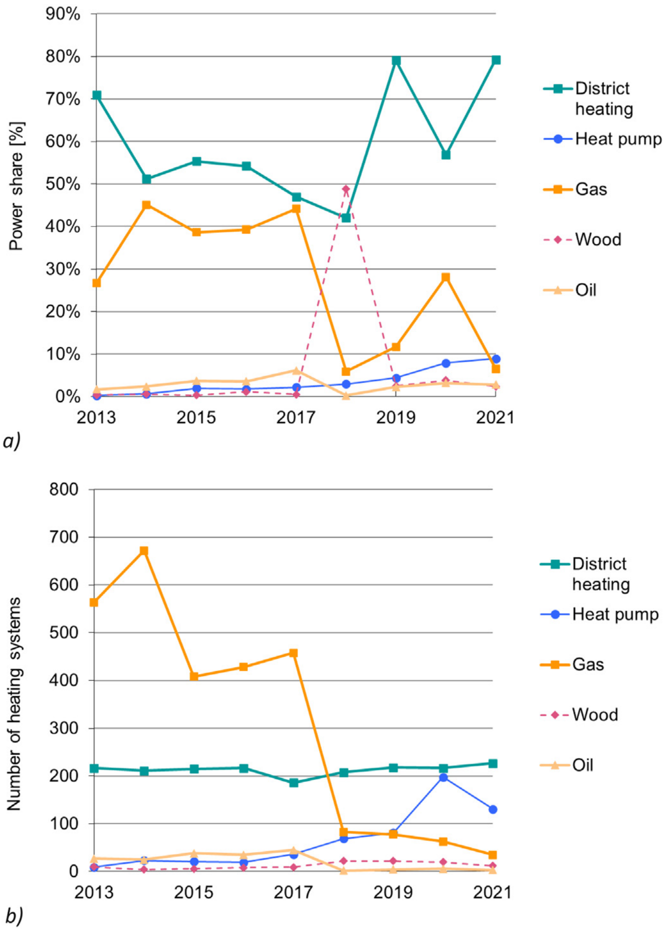

Fig. 1. Decarbonization in Basel-Stadt: Share of installed power of heating systems (a) and number of new/replaced heating systems (b) as a consequence of the new Energy Act implemented in 2017 (Mathys, 2021).

- How can any differences between the cities be explained and what can be learned from the differences?

The novelty of this work lies not only in concrete empirical insights for the two cantons studied, but more generally also in the development and testing of a methodology for assessing the applicability of a successful HP implementation policy.

2. Method and data

2.1. Method

In this work, datasets on building stock characteristics have been used. As a first step, we studied the differences and similarities between the building stocks of the two cantons, comparing the age of the buildings, their size, the current heating systems, and the heating demand. The different efficiency of the buildings is important for the installation of HP, since HP efficiency is reduced in buildings with relatively poor thermal performance, due to the higher water supply temperature which reduces the Coefficient Of Performance (COP) (Dominguez et al., 2020). The thermal performance of the buildings was assessed by studying energy consumption per m^2 based on the Swiss Cantonal Energy performance Certificate for Buildings (CECB) (SIA, 2016), to understand the differences between the building stocks in the two city-cantons. Starting from the total number of residential buildings in Basel-Stadt, we identified for which of these buildings HP cannot be easily installed (for different reasons) and defined a sub-sample of buildings for which it is possible to do so.

The list of perceived barriers that make the installation of HP in buildings more difficult, and thus the filters used in the analysis to identify the final sub-sample, were identified by means of literature, cantonal laws, and the help of experts in the field (e.g. energy utility, installer, energy consultant) (Amt für Umwelt und Energie Kanton Basel-Stadt, 2021; Basel - AUE, 2018; CSD Ingenieurs, 2020; Geneve - ReC, 2019; Lutz, 2019a). First, all buildings currently connected to the district heating network, and with already installed heat pumps, were removed. We dropped buildings with an installed thermal power above 50 kW as there are not turnkey solutions ready for the residential sector (Lutz, 2019b; Märki et al., 2018) (while industrial HPs above this size are commercially available). Moreover, in buildings of this size, it is usually necessary to reinforce the electrical connection if a heat pump is to be installed (Sprecher et al., 2014). A further limitation to install a HP is the dimension and inclination of the roof of the building (Forster and Varga, 2018; Steinke et al., 2018). In many multi-storey urban buildings, there is little or no surrounding space available for the installation of an external HP or its heat exchanger, in which case the roof may be the only option. However, there are architectural, aesthetic, and neighbourhood barriers to installing HP on inclined tiled rooftops in Switzerland. Therefore, all buildings with a sloping roof are excluded in first instance. It makes sense to relax this constraint in additional calculations because HP installation in the attic may well be possible if the statics allow to do so, if it is not occupied by apartments and if it is not used for other purposes. Buildings with flat roof areas of less than 2 m^2 were also removed due to the too limited space for HP installation. The last filter is related to protected buildings,

Table 1
Steps and references used.

Steps	References
1 — All residential	FSO (2017)
2 — Minus District Heating	FSO (2017)
3 — Minus Heat Pump already installed	FSO (2017)
4 — Minus Power more than 50 kW	Amt für Umwelt und Energie Kanton Basel-Stadt (2021), Lutz (2019b), Märki et al. (2018), Sprecher et al. (2014)
5 — Minus buildings with sloped roof	econcept AG (2020), Forster and Varga (2018), Steinke et al. (2018)
6 — Minus the protected buildings	Günther et al. (2020), Varga et al. (2018)

which therefore cannot undergo external changes in the facades or roof, which is usually required when installing an outdoor unit of a HP (Günther et al., 2020). A complete list of the steps, and the respective references are reported in Table 1.

2.2. Datasets

In this section we present the six datasets used for the analysis. They all have in common a key value that allowed to combine these different datasets. This value is the Federal Building Identifier (EGID), a unique identification number for each building in Switzerland, mainly determined by its address.

The main data source for this study has been the Swiss Federal Register of Buildings and Dwellings (RBD) (FSO, 2017). The RBD contains information on all buildings with residential use in Switzerland and their dwellings, and it is continuously updated by communal building departments (last version used for this paper of June 2021). The RBD dataset includes general building metadata (location, closest climate station, construction year), geometry (dimensions, energy reference area (ERA), orientation) as well as type of heating system (fossil, heat pump, solar thermal). This dataset was used mainly to characterize the buildings in the studied cantons as well as to determine the installed heating system.

Another important source for this work has been the Swiss CECB (SIA, 2016). This dataset (Conferenza Cantonale dei Direttori dell'Energia, 2020) reports the energy efficiency of the building envelope and the energy requirements (under the assumption that the building performs in compliance with the standards). This applies both to existing and new buildings. The calculated performance is then categorized into the energy labels A to G (very efficient to very inefficient). The rating is performed based on primary energy demand, including space heating, domestic hot water, and other loads (e.g., appliances). The CECB has been used to compare the energy label distribution (i.e., the thermal performance) of buildings in the two cantons.

In both above databases, information on the installed power of energy systems for space heating and energy consumption are missing. These values were identified using the model developed by Schneider et al. (Schneider et al., 2019). In their paper they present a bottom-up model simulating the hourly heat demand load curve for space heating and domestic hot water production for all buildings listed in the RBD. Their model was calibrated on the actual heat demand load curves of several building types and predicts the demand as function of external temperature and solar irradiation. The model has been found to be very reliable in predicting the installed power, as the aggregated simulated load curve was compared with the measurements from a large district heating network, demonstrating that the peak load was well reproduced.

The Sonnendach database (Klauser, 2016) was used to obtain information about the dimension and inclination of the roofs. This dataset was originally intended to show the degree of suitability of roofs for the use of solar energy, together with the potential yield. The Sonnendach tool provides information on the solar energy potential of buildings. The data is suitable for obtaining initial estimates of the potential for solar energy use on a roof or façade, but it also provides physical data on the roof itself (size, inclination, orientation). This dataset is compiled nationwide and periodically updated.

Finally, we also used datasets containing all protected buildings, which must not be modified or renovated, in the canton of Basel-Stadt (Kanton Basel-Landschaft, 2007) and Geneva (Republique et Canton de Geneve - Office du patrimoine ed des Sites, 2008). These lists are official documents and they have legal value in case of building retrofit.

3. Results

3.1. Comparison of the building stock in Basel-Stadt and Geneva

In this section we present the results of the comparison between the residential building stocks of the cantons Basel-Stadt and Geneva. The findings about the differences and similarities between the building stocks are important in order to understand whether and how the results obtained due to the progressive decarbonization policy in Basel-Stadt are transferable to Geneva or any other location for which the same methodology could be applied. An important advantage of using the RBD dataset is its geographical coverage of Switzerland as a whole. According to the RBD, at the end of 2020, there were 2 million buildings in total In Switzerland of which 1.7 million were residential (of which about 37 thousand in the canton of Geneva and 19 thousand in the canton Basel-Stadt). Of these, 57% were SFH and 26% MFH (FSO, 2017). The residential buildings account for 32% of Switzerland's final energy consumption, representing a total of 67 TWh/y including space heating, cooling, ventilation, domestic hot water, lighting, and general electricity consumption. The largest share of this energy consumption is devoted to space heating and domestic hot water, i.e. 55 TWh/y (Bundesamt für Energie BFE, 2021), representing the focus of this study.

In Fig. 2, the building construction period is compared, showing a large difference between the two city-cantons for buildings constructed until 1960 (and especially between the 1919 and 1945). This can be partially explained by the origins and development of the two cities. Basel has an older and more extended historic centre, while Geneva has fewer residential buildings in the old town. We can only speculate as to the reasons behind the other discrepancies shown in Fig. 2. The more even and stable distribution of buildings in Geneva between the 1919 and 2010 may be explained by the simultaneous steady growth of the city in terms of population and constructed area (Freyre, 2019).

The different urban development of the two cities is also reflected by the comparison of the average building size. According to Fig. 3 showing the distribution of the buildings according to their energy reference area (ERA) that the values are normally distributed around 150 m^2 in Geneva, while a more uneven distribution is found in Basel-Stadt, especially due to its higher share of larger buildings (more than 300 m^2). One reason may be that canton of Geneva includes 44 municipalities with a size between 1 000 and 35 000 inhabitants, and only 40% of all 500 000 inhabitants lives in the city of Geneva (Office cantonal de la statistique - OCSTAT, 2020). In contrast, the canton of Basel-Stadt is essentially urban with almost 90% of the 200 000 inhabitants living in the city and most of the rural municipalities falling into the neighbouring canton Basel-Landschaft (BL) (Präsidialdepartement des Kantons Basel-Stadt, 2021).

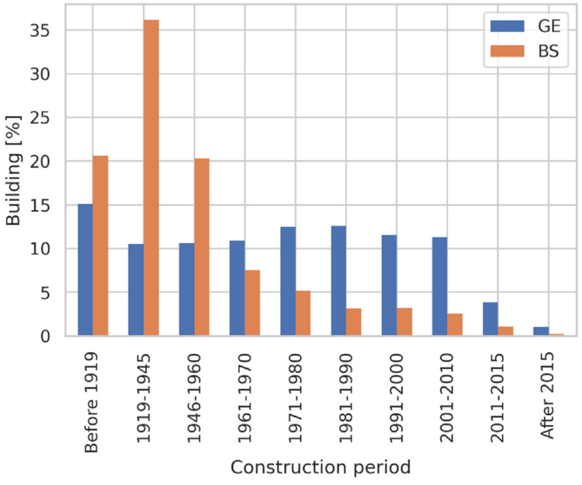

Fig. 2. Comparison share of residential buildings as a function of the construction period between Geneva (blue) and Basel-Stadt (orange). RBD — 2021 (Ferderal statistical office - OFS, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

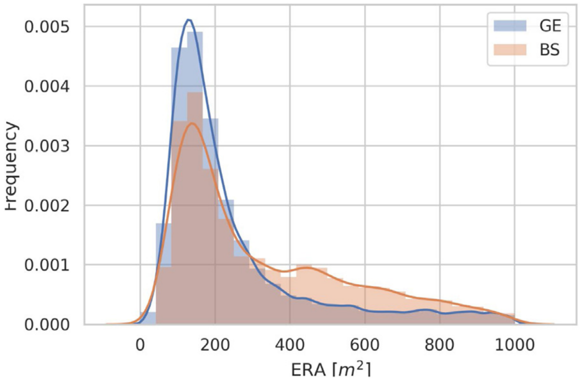

Fig. 3. Energy reference area (ERA) distribution of residential buildings in Geneva (blue) and in Basel-Stadt (orange). RBD — 2021 (Ferderal statistical office - OFS, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

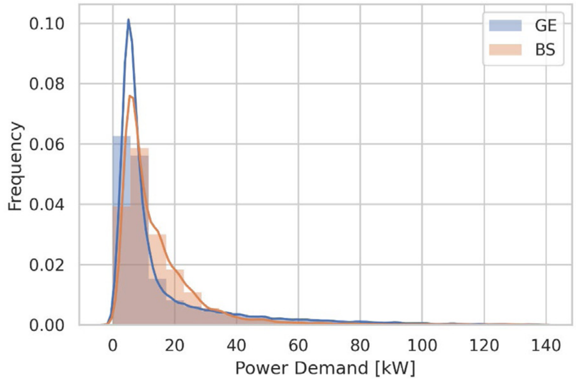

Fig. 4. Distribution of the power of heating systems of residential buildings in Geneva (blue) and in Basel-Stadt (orange). Based on Schneider et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

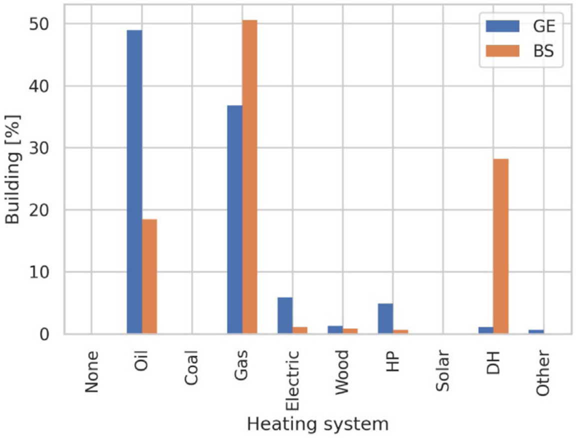

Fig. 5. Heating system type distribution in residential buildings in Geneva (in blue) and Basel-Stadt (orange). RBD — 2021 (Ferderal statistical office - OFS, 2021). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

For this work, the first consequence of the different size of the buildings is the different power of the heating systems (i.e., the greater the ERA the greater the power of the system). Fig. 4 shows the distribution of the power for each building. The trend partly follows the one in Fig. 3: Geneva with a normal distribution around 5 kW and Basel-Stadt with a tendency to higher powers (above 10 kW).

The heating systems and energy sources used to provide these powers are also very different. Fig. 5 compares the heating system used in the buildings in Geneva and Basel-Stadt, revealing some differences. The mismatch for oil and district heating (DH) can be explained with the large DH network in Basel-Stadt (connecting almost 30% of residential buildings), which is currently much less developed in Geneva, where most buildings still have oil-fired boilers. In both cities, the presence of HP is still very minimal.

Finally, another important comparison for this study is the final energy consumption per m^2. Indeed, as reported in several studies (Dominguez et al., 2020; Wingfield et al., 2011), the efficiency of a HP is very different depending on the type of building in which it is installed. In less performing buildings, with higher consumption and losses, the HP works less efficiently and with a lower COP, while in more performing buildings with lower consumption, the COP of the HP is higher. Therefore, the different building stock efficiency (expressed in final energy consumption per m^2) of the two cantons was studied. Fig. 6 presents the energy distribution for the two cantons, and even if distributions are similar, the mean value in Basel-Stadt is lower than in Geneva (these data are climate corrected using the Heating Degree Days in order to be comparable; HDD GE = 1312.0; HDD BS = 1352.3 (Chambers et al., 2019)).

The results in Fig. 6 suggest a higher efficiency – due to lower consumption per m^2 – of the building stock in Basel-Stadt than in Geneva (by approximately 30 kWh/(m^2 y)). To test this hypothesis, we used the energy labels in the CECB certificates. This database contains all the buildings that have been awarded with an energy label in Switzerland. It is important to note, however, that new buildings (with their much higher thermal performance than old ones) typically do not have this energy label. They are instead characterized by compliance with the building codes of a given year/period (SIA, 2016) or by (voluntary) high-performance certification (especially Minergie (Minergie, 2018)). In both cantons, however, new buildings (built after 2015) represent less than 1%, making the building stock comparison using this database (CECB) valid and reliable. Fig. 7 shows the distribution of the number of buildings as function of the energy label in the CECB dataset. In both cantons, most

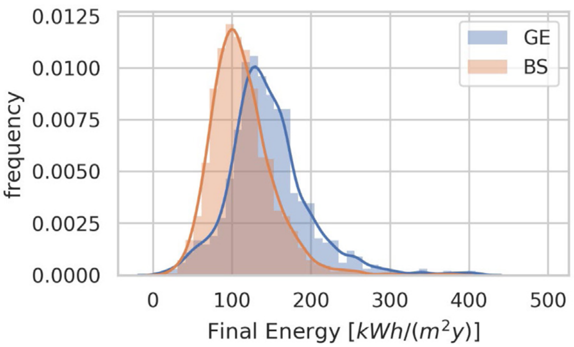

Fig. 6. Final energy distribution (climate-corrected) of residential buildings in Geneva (blue) and in Basel-Stadt (orange). Based on Schneider et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

buildings (more than 30%) have a D label. However, there are clearly more B and C-labelled buildings in Basel-Stadt than in Geneva and the opposite is true for the labels E, F and G. The residential building stock in Basel-Stadt is hence more efficient than in Geneva.

Finally, Fig. 8 shows age and energy label distribution according to the CECB dataset in the two cities. Fig. 8 clearly summarizes how different the buildings in Geneva and Basel-Stadt are, both in terms of age and efficiency/performance.

3.2. Exclusion of buildings based on constraints

In this section, we present the results of the analysis on the number of residential buildings in Geneva for which installation of a HP are expected to be rather straightforward, when applying the same constraints as in Basel-Stadt. As shown in the first row of Table 2, there are currently 36616 residential buildings in Geneva and 18158 in Basel-Stadt, which consume 1825 GWh and 860 GWh per year, respectively.

The first reduction is due to the buildings already connected to the district heating, which will not switch to HPs because they are already connected to a network. As shown in Fig. 9, the difference between GE and BS is very large for the transition from Step 1 to Step 2. Almost 30% of the buildings in BS are already connected to the DH according to the RBD (Ferderal statistical office - OFS, 2021) and therefore do not require a decentralized zero-carbon heating solution, while the reduction in GE is in the order of few percent. The difference is even more evident looking at Fig. 10, where this 30% of buildings in BS count for 40% of the energy demand.

In the transition from Step 2 to 3 we excluded all buildings that have already installed a heat pump. As can be seen from Fig. 9, the impact of this constraint is much more pronounced for Geneva, where the use of heat pumps is more widespread (due to the higher share of suburban and rural areas with single-family houses). The observed impact of this constraint in BS is so small that a lack of completeness in the heat pump installations data cannot be excluded as a reason for the differences.

From Step 3 to 4, we excluded all buildings with an installed thermal power above 50 kW. As shown in Fig. 9, in GE about 10% of the buildings are dropped, however (Fig. 10) they count for about 40% of the total energy demand. This figure is very different in BS, where only 2% of the buildings and less than 10% of the energy are excluded by application of this constraint. The reason is that most large buildings with a power of more than 50 kW$_{th}$ are already connected to the district heating network in BS. In Step 4 to 5 we eliminated buildings that do not have a sufficiently large flat roof to accommodate the outdoor unit of the HP. In this case in GE we lose almost 50% of the buildings but only 20% of the energy, while in BS almost 20% of the buildings and 15% of the energy. This indicates a clear difference in the architecture of the cantons and in the type of buildings. Finally, in the last Step 5 to 6 we removed the buildings that for historical or legal reasons are protected and are therefore subject to major constraints for retrofitting. As shown in Table 2, the effect of protected buildings is negligible in both cantons.

As displayed in Fig. 9, it is rather straightforward to implemented HP in 50% of all buildings in Basel-Stadt and in less than 40% of all buildings in Geneva. However, these findings are much more similar in terms of energy demand: according to Fig. 10 it is rather straightforward to implement HP for almost 40% of the final energy demand both in Basel-Stadt and Geneva. The two figures above are combined in Fig. 11, which shows the reductions in energy and buildings for the two cantons.

The analysis offers a basis for reflection whether the replacement of fossil by zero-carbon decentralized heating systems, as successfully demonstrated in Basel, should also be viable in Geneva. The fact that the percentage of buildings and – even more so – the percentage of their energy use is quite similar in Basel and Geneva after having applied the various constraints represented by the steps discussed above is a first indication of the viability. It implies that decentralized zero-carbon heating systems need to be implemented for buildings representing nearly 40% of the energy demand of the building stock in both locations. However, a number of limitations of this analysis need to be considered which will be discussed in the next section.

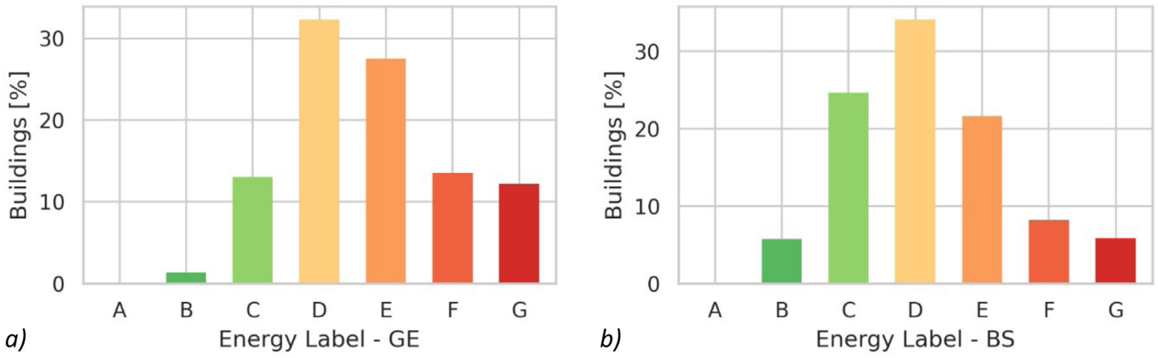

Fig. 7. Energy label distribution by share of residential buildings in Geneva (a) and in Basel-Stadt (b). CECB — 2021 (Conferenza Cantonale dei Direttori dell'Energia, 2020).

Table 2
Remaining residential buildings (number, final energy use and ERA) after application of each constraint (2021). Final energy values are not climate-corrected.

Steps	GENEVA (GE)			BASEL-STADT (BS)		
	Buildings	Final energy demand [GWh]	Total ERA [m^2]	Buildings	Final energy demand [GWh]	Total ERA [m^2]
1 — All residential	36616	1825.1	17113076	18158	860.1	7897651
2 — Minus District Heating	36221	1767.7	16542915	13127	510.5	4647078
3 — Minus Heat Pump already installed	34419	1718.6	15983659	13008	506.1	4592401
4 — Minus Power more than 50 kW	32010	1080.9	10328128	12818	459.6	4167785
5 — Minus buildings with sloped roof	13912	640.9	6159771	8866	321.6	2930789
6 — Minus the protected buildings	13888	639.6	6145811	8820	319.6	2912605

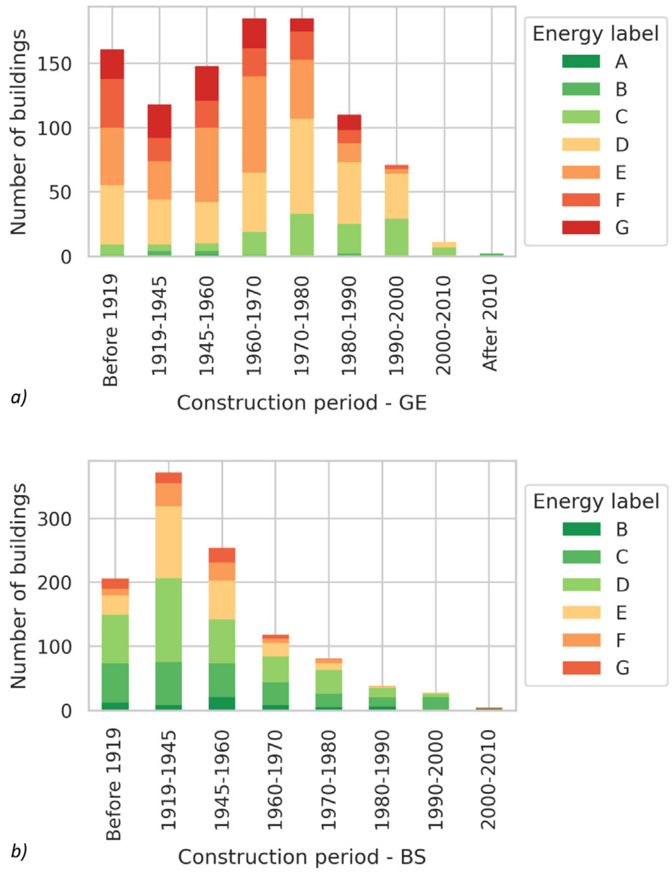

Fig. 8. Energy label distribution of residential buildings in Geneva (a) and Basel-Stadt (b) as a function of construction period. CECB — 2021 (Conferenza Cantonale dei Direttori dell'Energia, 2020).

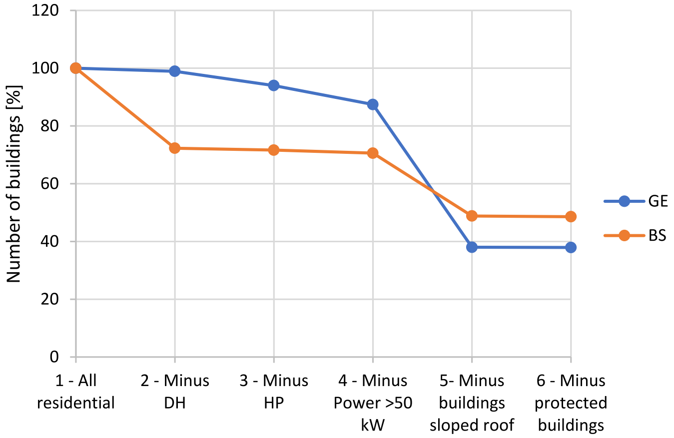

Fig. 9. Number of buildings in % remaining after application of each constraint.

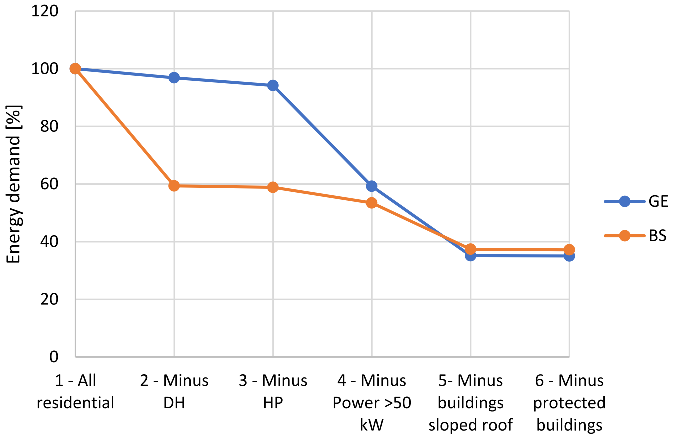

Fig. 10. Final energy demand in % available after application of each constraint.

4. Discussion

4.1. Limitations of the analysis

In order to better understand whether the analysis presented above allows to draw conclusions about the transferability of the successful policy from Basel-Stadt to Geneva, the constraints and the implications for the final results need to be revisited. Step 2 (removal of current DH), Step 3 (already implemented heat pumps) and Step 6 (removal of protected buildings) are not problematic because they reflect facts for which there is little uncertainty. On the other hand, Step 4 (50 kW_{th} power limit) and Step 5 (sloped roof limitation) warrant further discussion.

Two aspects need to be considered, i.e. whether the threshold of 50 kW_{th} is justified and what the implications are for the district heating. First, the 50 kW limit is supported by the technical literature (Günther et al., 2020; Märki et al., 2018): in fact it is relatively easy to find commercially available HP up to 50 kW_{th}. The current problems limiting the power of HP are mainly space availability, visual constraints, and noise. Space is partly addressed by Step 5 implying that HP can only be installed if the building has a flat roof. This entails that heat pumps or – in the case of split-HP – their heat exchangers cannot be installed on buildings with sloping roofs. These are strong assumptions which were chosen to exclude buildings for which it

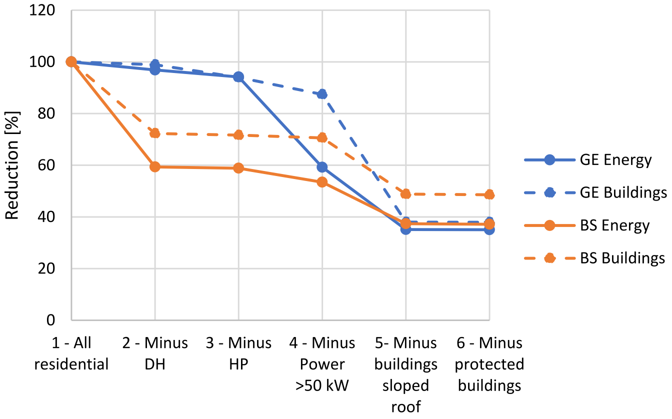

Fig. 11. Number of buildings and final energy demand in % available after each step.

might be more difficult (and expensive) to install a HP. In reality, there are examples of HP installations in attics (sloping roofs), in basements as well as in the surrounding space. On the other hand, even in the case of flat roof, in which availability of space can generally be assumed, statics of the building/roof may make installation impossible, may call for a specific HP configuration, or may alternatively make roof reinforcement necessary. These are the reasons for which this step must be considered very carefully.

A recent study made assumptions and demonstrated how space constraints can be overcome (CSD Ingenieurs, 2020). Five cases were distinguished. These are HP installation on the roof (outside), in the attic, in the basement, outside on surrounding area as well as a split-HP with the core part of the HP in basement and the heat exchanger being placed outside (CSD Ingenieurs, 2020). It would require building-specific information about both the required and the available space in the surroundings, in attics and basements as well as about the accessibility of basements from outside (Lutz, 2019a) to assess whether this set of configurations indeed allows to install HP in practically all residential buildings (also large multi-family houses) under current constraints. No detailed study going beyond singular case studies and instead considering a larger sample of buildings has been conducted on these aspects to our knowledge. Visual and noise constraints are closely related to spatial aspects. To address visual aspects, numerous solutions were developed in Basel-Stadt for different building types with several constraints, therefore accounting for most of the limitations that can occur when installing a HP (Amt für Umwelt und Energie Kanton Basel-Stadt, 2021). Due to the high share of large buildings connected to district heating in Basel-Stadt these solutions concern small and mid-sized multifamily houses, raising the questions about the transferability to other locations. The noise aspect has been addressed with modelling (Jakob et al., 2020) and regulatory (SIA, 2011; Steinke et al., 2018) approaches. Modelling has so far been rather simplified, mainly based on the idea of checking whether the required installed power for HP installation in a given cluster of buildings exceeds the legally defined acceptable noise levels. But this method does not take much account of the improvement in the noise level of the HP. In order to address this gap, we conducted a rough assessment of the effect of different heat pump noise levels for the diffusion potential of air source heat pumps in the city of Basel and the canton of Geneva (see Appendix A). Three noise levels were distinguished, i.e., Low, Medium and High, all of which are far below the levels required according to existing EU noise regulation (Fig. A.1). They partly exceed the ECOLABEL noise thresholds but only up to a heating capacity of 9 kW_{th} for the Medium noise level and up to mere 1.5 kW_{th} for the Low noise level. The calculations show that the diffusion potential of air source heat pumps is only meaningful if they comply with the Low noise threshold levels. Under this condition the heat pumps can be implemented in most parts of the cities and the noise constraint is violated only in the densest urban areas (see appendix for details). If air source heat pumps are foreseen as predominant solution for decarbonizing cities, major efforts will be hence required to avoid noise problems. So far, complementary sound protection measures and noise deflection were the preferred solutions (Steinke et al., 2018) but these are unlikely to be sufficient in the case of large-scale air source heat pump deployment in cities.

With regard to regulatory conditions it has been suggested to develop a standardized measurement procedure for the determination of HP sound data for noise verification, and to then implement it (Steinke et al., 2018). This can create confidence in the sound data and in the quality of the noise protection certification, and it should help to prevent noise complaints. On the other hand, there still seem to be unresolved issues with the night-time silent mode significantly reducing HP efficiency (due to a higher share of direct resistance heating); and a HP manufacturer is reported to take their ultra-silent (and costly) HP from the market due to lack of demand (Omlin, 2021).

There are only few alternative solutions for (mainly large) pre-existing buildings for which decentralized electric heat pumps are not viable. These are (i) the use of biomass as fuel, (ii) bivalent (hybrid) systems consisting both of an electric heat pump and fossil fuel heating and iii) district heating. In Switzerland, biomass as fuel is avoided in dense urban centres for pollution reasons. Hybrid systems may create a lock-in and they may delay the decarbonization of the building stock for some decades. This explains why cities with ambitious climate objectives, e.g. BS, GE and Zurich, aim for a much higher share of buildings connected to district heating (with the heat originating from municipal waste incineration plants, biomass combustion with pollution prevention and large-scale electric heat pumps). To avoid that building owners chose a gas-fired heating system instead of district heating, the city of Zurich decided not only to expand district heating but to also dismantle the natural gas grid (Sprecher et al., 2014)

In order to ensure that the entire building stock is decarbonized, all buildings where the installation of an electric air source heat pump is not straightforward (beyond 50 kW_{th} according to our earlier assumption) could be connected to district heating system. While ambitious district heating expansion plans do exist, we are not aware of systematic GIS-based and economic analyses assessing the viability of district heating systems fulfilling these requirements. In other words, strategies for the expansion of decentralized heat pumps should be aligned to district heating strategies; further work is required in this area.

4.2. Discussion of results

Having discussed above the principal limitations and their implications, we now turn to a discussion of the results and of policy conclusions. Our results indicate that even for a very different building stock situation (Section 3.1), the number of buildings in which HP can potentially be installed is similar in the two cantons and is very large (more than 40% of existing residential buildings). In this work we quantified the number of buildings where it considered to be "rather straightforward" to install heat pumps according to current practice and understanding. However, it is important to highlight that the perception of "rather straightforward" in terms of the building characteristics for installation are somewhat simplistic and that they depend in reality on many other factors such as alternative technologies, maturity of the market, knowledge, and experience of installers. All these factors can be improved, hence increasing the number of buildings that can more easily install a HP.

The first and most important aspect that needs improvement is the regulatory one. As expected, the major obstacles are the construction requirements of the cantons, as well as the noise protection requirements. It is difficult to understand why the outdoor installation of air heat exchangers for cooling purposes is possible without further formality in protected zones, but the same installations for heating purposes cannot be allowed (Sprecher et al., 2014). The approval procedure for HP is currently more complex and the processing time is longer than for other heat generators. On the one hand, the design integration of externally installed HP into the cityscape plays an important role. On the other hand, the noise emissions of HP affect the interests of third parties, which is why compliance with noise protection requirements must be verified and tested. Important suggestions have been made for the further development of the authorization procedure include (Steinke et al., 2018) simplification of the procedure, also to minimize processing time; improved quality of the application material with more support for users; definition of "standard cases" for further development of standard procedures and guidelines; focus on the replacement of fossil fuel-fired boilers; motivation of building owners to plan in advance the replacement of their heating system; more guidance for the applicants to reduce the amount of consultation with the authorities and to reduce the number of rejections; integration of the design into the cityscape; and compliance with the legal requirements as well as respect for the interests of third parties (especially noise protection).

A second very important aspect to make the installation of HP easier is also to raise awareness on this technology and explain the advantages of the HP to the homeowner. A recent study has shown that there is a lack of information on the topic of HP in MFH (Varga et al., 2018). In many cantons, the desire for specific information material on the topic has been expressed, especially for example of "good practice". Unfortunately, such examples can hardly be found in the available studies. To provide a complete example of good installation, it is important that, in addition to the technical system itself, the actual investment costs incurred and the real operating data of the HP are also reported. Moreover, also the bad experiences of the companies involved with difficulties during implementation can be very valuable if adequately shared and communicated (Forster and Varga, 2018).

Another important point raised that requires attention is the low level of knowledge of the average installer (Freyre et al., 2021). It is important to understand the needs of this professional group more precisely and to find new ways of providing them with further training (Freyre, 2019). Research, also across national borders, can possibly reveal innovative approaches (e.g. awards, in-house competitions, bonus models) that promise more success than the usual information and training campaigns (Varga et al., 2018). In Switzerland, the most important energy policy levers are still in cantonal hands. Thus, the Confederation has no direct influence either on the level of subsidies, or on the application of the Article 1.29 from the 2014 MuKEn (Conferenza Cantonale dei Direttori dell'Energia CDE, 2014). However, the Confederation can also have a networking effect here and, for example, show examples of success, information material, tools developed and used in some cantons, so that other cantons could follow.

Finally, there are also economic considerations to be made. In contrast to small detached houses with sufficient outdoor space, the cost of installing a HP in large existing buildings is significantly higher. The cost of the HP is only a fraction of the total costs, which include structural and noise protection measures, often an extension of the electrical connection, and much more. The investment cost is 2.5 to 4 times higher than the cost of directly replacing heating with fossil fuels (Sprecher et al., 2014). Therefore, several forms of subsidies (e.g., from cantons, confederation) should be considered to increase the uptake of HPs.

5. Conclusions

The potential for CO_2 reduction through a change of heating system is generally high in residential buildings, as the majority of them in Switzerland are still heated with fossil fuel sources. Switching to HP system operated with zero or low to very low carbon electricity can significantly reduce the emissions related to space heating and domestic hot water. However, in most Swiss cities, fossil substitution has been the rule, while renewable substitution is the exception. This change is happening very slowly, due to a mix of technical and administrative issues, and some barriers that are perceived as such by all the stakeholders involved.

This study investigated how a strong climate protection law (Energy Act of Basel-Stadt) has managed to overcome resistance to the installation of HPs, which is now observed in some other cantons. In spite of many technical limitations related to the features of the pre-existing buildings the imposition of a law that obliges (with some exceptions) the substitution of fossil fuels with a renewable source has had a very positive impact on the diffusion of this solution. This case study is important because it allows to learn lessons for other cantons, to see if a similar policy can be implemented, how to improve it, and what results to expect. The crucial point is to compare conditions, both from a legislative and a technical point of view. Concerning the first point, almost all cantons are comparable in energy matters. The second point concerns mainly the characteristics of the buildings in the cantons. A direct comparison of cantonal decarbonization policies and achievements would require that the typology of the buildings in the compared canton (in terms of age, size, performance, etc.) is comparable with those of the fore-runner canton (i.e., Basel-Stadt). Since this is hardly ever the case, it is necessary to compare cantons in terms of their building stock. This study is the first of its kind to do so, with the ultimate objective of understanding how and to what extent, the results obtained in one can be extended to the other.

The results indicate that although the two cantons have different characteristics in terms of building stock, and they are starting from very different situations, the potential of buildings where HP installation is considered 'easy' is high in both cases (50% in Basel-Stadt and 40% in Geneva). This is equivalent to 40% (in both cities) of the energy used for thermal use that is currently produced by fossil energy and that could be instead generated with HPs. Considering the different emission factors of fossil fuel systems per MJ of useful heat (e.g. 0.069 $kgCO_2/MJ$ for gas) compared to an HP (0.017 $kgCO_2/MJ$) (KBOB, 2016), the savings in CO_2 emission are very significant. Based on a projection of the emission factors for electricity and gas for 2030 with a conservative (optimistic) forecast, CO_2 savings were calculated to be between 50% and 70% when installing HPs.

The analysis shows that the benefits are indeed clear, and the technical solutions are available too. However, changing the energy system often leads to a comprehensive construction project and therefore requires more (preparation) time, more qualified personnel, more financial means, and many other additional conditions that must be met. The installation of the HP in the attic or on the roof is, in many cases, the only option in urban areas due to the limited space available. However, if static reinforcements have to be carried out, their costs exceed the subsidies received for the HP (if subsidies are granted, which is not the case in all cantons), discouraging property owners. Moreover, increased attention will need to be paid to noise issues in cities if air source heat pumps are the technology of choice. All these factors must be taken into account in order to design effective policies that are truly effective for the extensive installation of HP. However, it is worth remembering that there are many cases where it is already possible to easily install a HP today, and these should be the starting point, without further delay. Further research is required to define in more detail other barriers encountered in other cantons, and to classify a degree of "severity" related to these barriers. Potentially all these barriers can be overcome, but it is important to understand on which buildings to start concentrating efforts in order to spread the use of HP in an efficient and extensive way.

CRediT authorship contribution statement

Stefano Cozza: Conceptualization, Methodology, Software, Writing – original draft. **Jonathan Chambers:** Methodology, Validation. **Roman Bolliger:** Validation, Supervision. **Matteo Tarantino:** Software, Data curation, Writing. **Martin K. Patel:** Validation, Editing, Funding acquisition, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. Assessment of the effect of different heat pump noise levels

In order to assess the constraint of maximum acceptable noise levels for the diffusion of heat pumps at the urban scale, a simplified model was developed consisting of the following three steps:

First, stylized relationships between the heating capacity (power in $kW_{thermal}$) and the sound pressure level for night operation were established. Due to the wide range of noise levels of commercially available heat pumps for a given heating capacity (see blue dots on Fig. A.1) the stylized relationships have rather normative character. They could be seen as anticipating categorization according to noise level labels assigned to heat pumps (such labels do not yet exist to our knowledge). The three noise levels (Low, Medium and High) are far below the levels required according to existing EU noise regulation (see Fig. A.1). They exceed the maximum noise thresholds of the EU ECOLABEL until heating capacities of 1.5 kW_{th}, 9 kW_{th} and 20 kW_{th} for Low, Medium and High noise respectively; but beyond these values, all three levels are below the EU ECOLABEL thresholds.

Second, based on Swiss planning guidelines for HVAC installation, the minimum distance d (in m) between the noise source

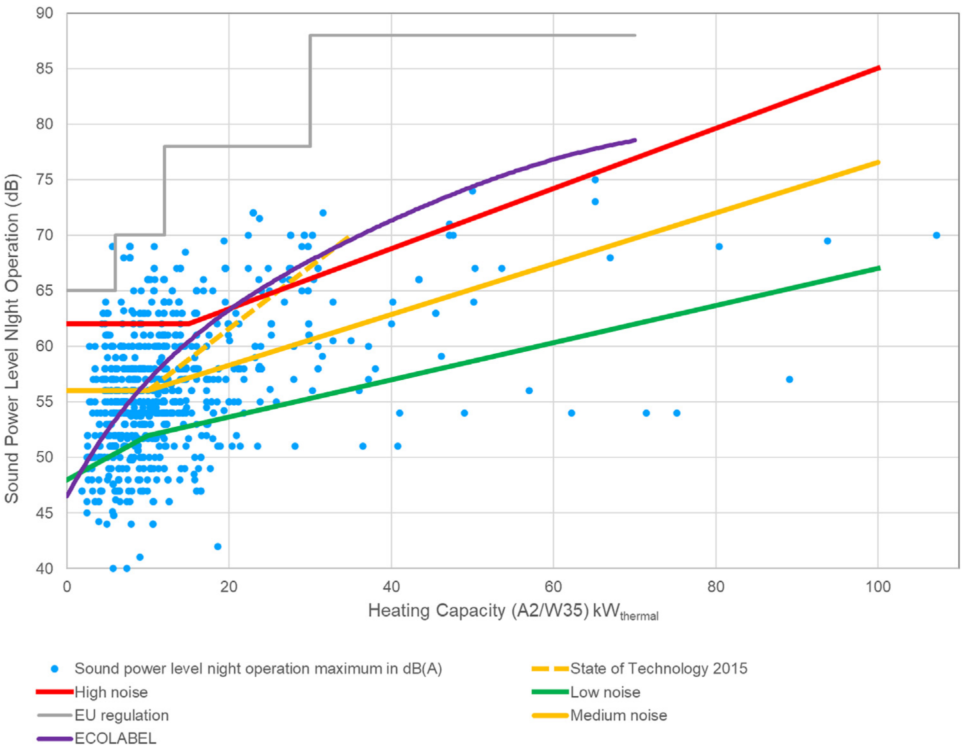

Fig. A.1. Acoustic Emissions from commercially available heat pumps in relation to heating capacity (blue dots; from Swiss Association for Heat Pumps (2019)), assumed noise levels (low, medium and high) and comparison with EU Parliament (2013), Reichl (2021), Stocker (2013).

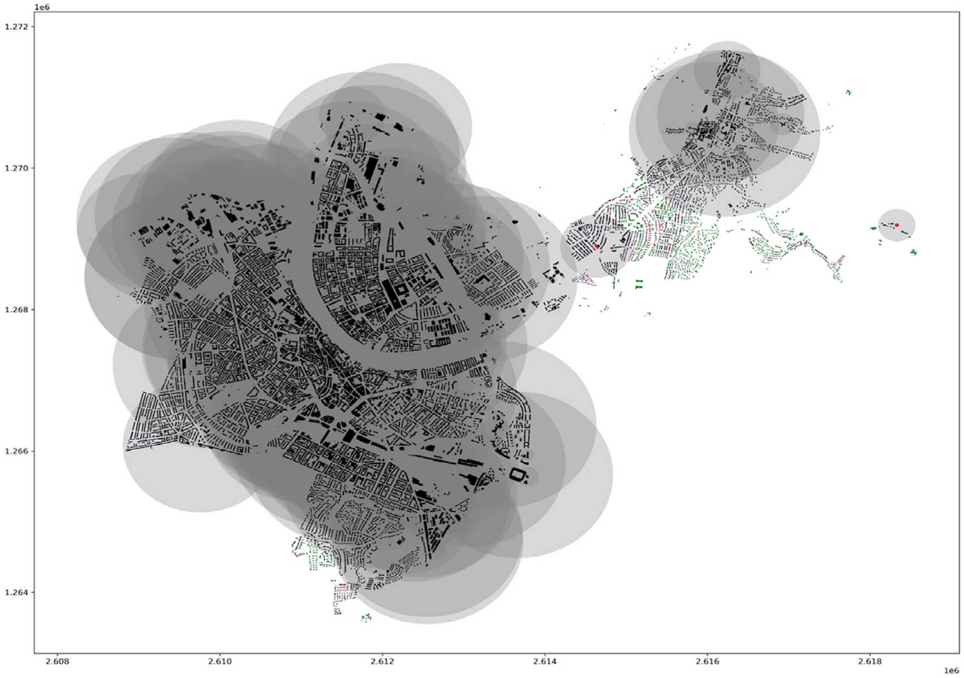

Fig. A.2. Medium noise level scenario results for Basel City.

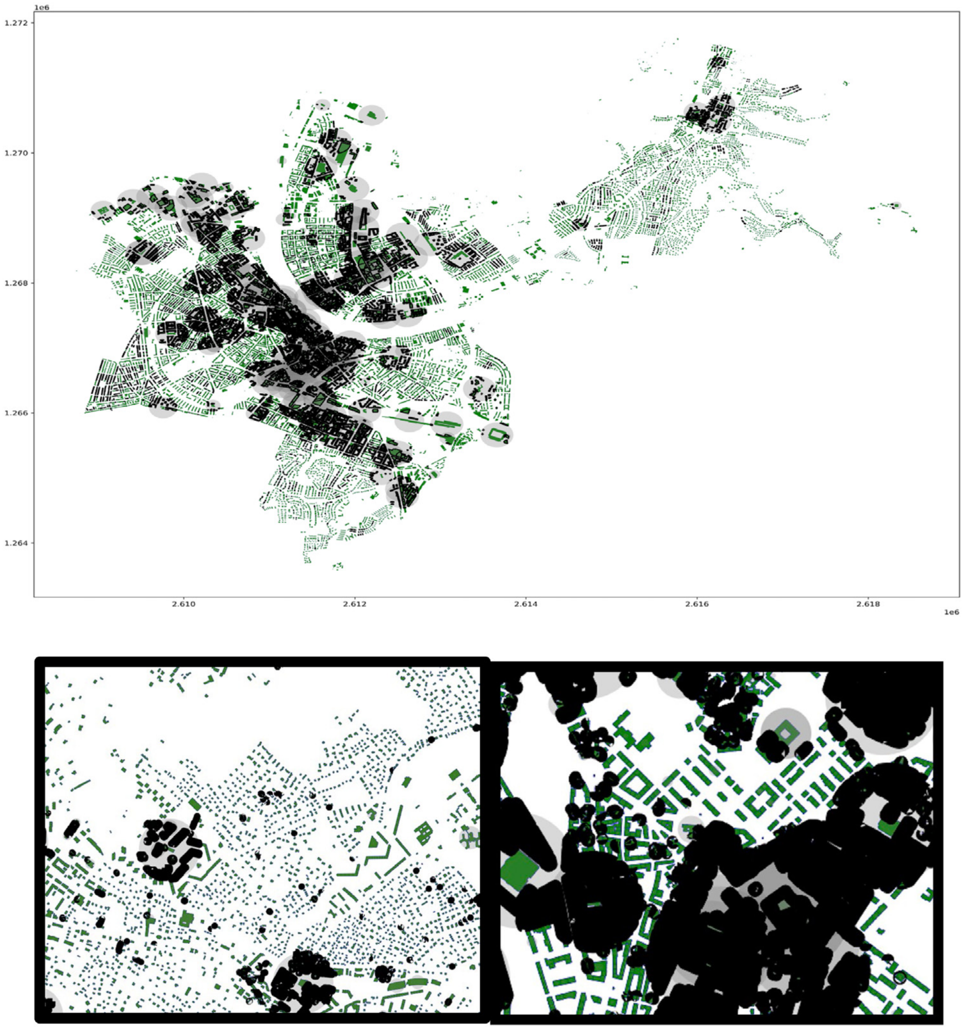

Fig. A.3. Low noise level scenario results for Basel-City with zoom-in areas.

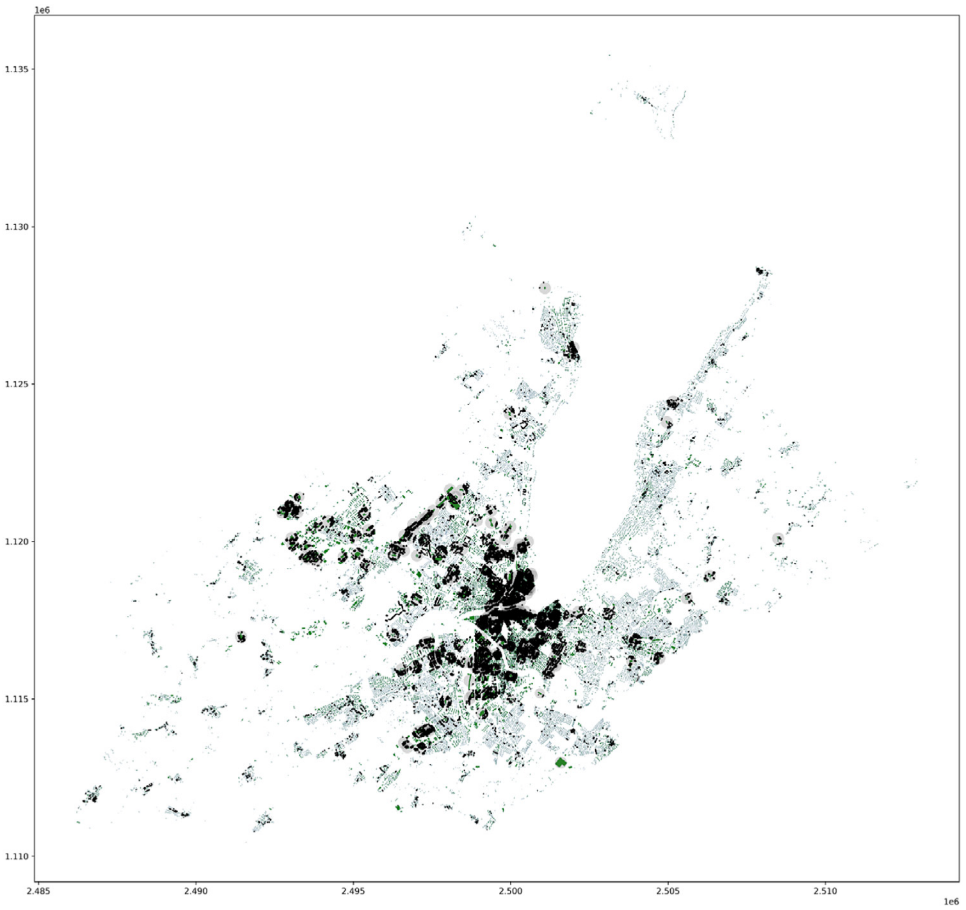

Fig. A.4. Low noise level results for the Canton of Geneva.

and the noise recipient can be calculated according to the equation $d = 10^{(1/20\cdot(SPL-38\text{ dB}))}$, with *SPL* representing the *Sound Power Level* at night in dB (derived from (Swiss Association for Heat Pumps, 2019) for residential areas). In combination with the first step, this equation allows to establish the relationship between thermal capacity (power, in $\text{kW}_{\text{thermal}}$) and the required distance *d*.

Using GIS (and more specifically the Shapely and Geopandas packages of the Python programming language), a circle was then drawn around each heating system, with the radius being the required distance. Buildings for which the circles do not intersect were defined as viable, i.e., these are buildings where a heat pump can be safely installed without causing any noise issues. This calculation was conducted for the three noise levels distinguished in Fig. A.1. In this way, the buildings were identified where heat pumps can be safely installed in the cities of Basel and Geneva. This is based on the assumption that the building on which the heat pump is installed is insulated from its own noise, in line with existing regulation.

When graphically presenting the results, viable buildings are displayed in green, all other buildings are displayed in grey. In the images below, the grey circles correspond to the noise radiuses from heat pumps, whereas the polygons represent buildings. Darker grey areas result from overlap of multiple noise radiuses. As shown in Fig. A.2, hardly any buildings have been identified as viable in Basel-City under the assumption that only heat pumps with medium noise level are installed.

In contrast, at low noise levels, the noise constraint is violated only in the densest part of Basel City (Fig. A.3).

For the low noise scenario, air source heat pumps become viable for 71% of the buildings, corresponding to 45.4% of the floor area. Similar results are found for the canton of Geneva where air source heat pumps are estimated to be become viable for 86% of the buildings and 60.5% of the floor area (see Fig. A.4).

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