Air-, ground- and dual-source heat pumps: a comparison between energy-efficient systems for a Swedish dwelling.

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Abstract

Air-source heat pumps (ASHPs) and ground-source heat pumps (GSHPs) are the most spread heat pumps nowadays. However, they suffer from drawbacks that could be mostly overcome coupling the two heat sources, i.e., using dual-source heat pumps (DSHPs). In this study, we compared the techno-economic performance of ASHPs and GSHPs for a small Swedish single-family house. We also calculated the performance improvements achieved using dual-source heat pumps, and evaluated the economic conditions necessary to make the dual-source heat pumps economically competitive with the more traditional systems. We found that the GSHPs were more efficient than the ASHP during the first year of installation, but their performance decreased - sometimes dramatically - during their lifetime. However, investing in either systems was always beneficial and no significant differences tended to exist between the investments. The dual-source heat pumps had– sometimes significantly – higher performance than the conventional systems but they might not be economically competitive with the more conventional systems.

Introduction

Heat pumps (HPs) are a promising technology for the decarbonisation of the heating sector. Their heat source often consists of a ground- or air-heat exchanger. During winter, the ground tends to be warmer than the air; therefore, ground heat exchangers typically offer the advantage of higher evaporation temperatures - thus efficiencies – when the heating demand is highest. However, ground heat exchangers are more expensive than air heat exchangers; the ground is typically colder than the air during period of lower space heating demand; and continuous heat extraction from the ground decreases the ground temperature, reducing the advantage of ground source- compared to air- source heat pumps.

Connecting a heat pump to both an air- and ground-heat exchanger allows to overcome the cons of using only one of these heat sources and results in a more efficient system. However, a dual-heat pump is more expensive than an air- only or ground- only heat pump; a techno-economic analysis is necessary to establish whether the additional installation cost is compensated by the lower running cost and the dual-source heat pump can be competitive with the conventional heat pumps.

In this paper, we compare the techno-economic performance of an air-source heat pump (ASHP) and a ground-source heat pump (GSHP) used to satisfy the space heating and domestic hot water demand of a small Swedish single-family house. Moreover, we calculate the technical performance of a dual-source heat pump (DSHP) and the maximum extra cost of this system to make it competitive with the air- and dual-source heat pumps.

Methodology

We have analysed a small Swedish single-family house with an annual heating demand of 15 MWh, including both space heating and domestic hot water. We have calculated:

- One technical performance indicator: the electricity consumption of several HP systems to satisfy the building heating demand;
- Two economic performance indicators: the Net Present Value (NPV) for the ASHP and GSHPs, and the Maximum Additional Cost (MAC) for the DSHPs.

Technical analysis

We have calculated the space heating and domestic hot water demand, and the return temperature from the space heating distribution system with the methodology described by Coronado (2019). We have imposed 50 °C as the return temperature for domestic hot water production.

Then, we have considered three possible types of heat pumps to satisfy the house heating demand:

- Air-Source Heat Pump
- Ground-Source Heat Pump
- Dual-Source Heat Pump

The scheme of the 3 systems is shown in figure 1.

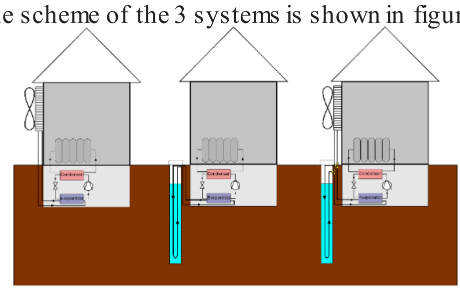

Figure 1: Space heating system coupled to an ASHP (left), GSHP (middle), DSHP (right).

The operation of the GSHP has been simulated using the grey-box model described by Cimmino and Wetter (2017). The model requires as an input:

- the building heating demand;
- the inlet water temperature at the condenser;
- the inlet brine temperature at the evaporator.

The heating demand and inlet water temperature at the condenser were calculated as described above. The inlet brine temperature was calculated using the Finite Line Source (FLS) model (Spitler and Bernier, 2016) to simulate the ground temperature evolution and using the borehole thermal resistance approach to couple the brine temperature to the ground temperature (Javed and Spitler, 2016). More details about the calculation of the brine temperature are given by Coronado (2019).

The operation of the ASHP has been simulated with a similar model. However, for the ASHP, the inlet brine temperature in the evaporator was assumed 3 K lower than the ambient air temperature. Moreover, ASHPs can require defrosting of the evaporator, causing lower heating capacity and efficiency. We slightly modified the HP model using the methodology described by Underwood at al. (2017) for this scope.

Concerning the DSHP, it operates like an ASHP when:

$$T_{inlet,air} > T_{inlet,ground} + 2\,K \quad (1)$$

It operates like a GSHP otherwise.

We used equation 1, rather than the more intuitive

$$T_{inlet,air} > T_{inlet,ground} \quad (2)$$

because, due to defrosting of the air-water heat exchanger, a GSHP tends to have higher efficiency than an ASHP for slightly lower evaporation temperatures.

The control strategy just described for the DSHP can be improved, but given its simplicity we considered it sufficient for the scope of this study.

Simulating the operation of the HPs allowed us to calculate the electricity consumption (electricity used by the compressor and the auxiliary electrical heater) of each examined heat pump system to cover the heating demand of the building.

Economic analysis

The Key Performance Indicators (KPIs) used for the economic analysis are the Net Present Value (NPV) of the air- and around-source heat pumps and the Maximum Additional Cost (MAC) for the dual-source Heat Pump.

The NPV is the difference between the present value of the benefits, B, and costs, C, over the lifetime, L, of an investment. It is calculated as:

$$NPV = \sum_{y=0}^{L} \frac{B_y - C_y}{(1+d)^y} \quad (3)$$

where the subscript y represents the year at which the benefits and costs are calculated, and d is the discount rate. We assumed d = 3%.

To calculate the benefits, we assumed that the HP is installed to replace an electric boiler; therefore, we calculated the benefits as the electricity costs of an electric heater used for heating:

$$B_y = p_{el,y} \cdot W_{EH,y} \quad (4)$$

where $p_{el,y}$ is the price of electricity during year y, and $W_{EH,y}$ is the electricity consumption of the electric heater during year y respectively. The consumption of the electric heater is assumed equal to the heating demand of the building, i.e., $W_{EH,y} = Q_{h,y}$.

The costs include the cost of Installation (I) of the system and the Operation Cost (OC):

$$C_y = I_y + OC_y \quad (5)$$

The operation cost consists of the cost of the electricity to run the HP:

$$OC_y = p_{el,y} \cdot W_{XSHP,y} \quad (6)$$

The investment cost is different for the different types of HPs considered. For the ground source heat pump, we calculated the Investment cost (I) as:

$$I = I_{HP} + I_{Drill}, \quad (7)$$

where I_{HP} is the cost of the HP and I_{Drill} is the cost of the drilling. Both I_{HP} and I_{Drill} include 25% VAT.

We calculated I_{HP} as:

$$I_{HP} = 75920 + 2198.8 \cdot \dot{Q}_h \quad (8)$$

where $\dot{Q}_h$ is the heat pump heating capacity. Equation 8 is the regression line that best fits the data obtained for the HPs of the model NIBE F1245 (NIBE, 2022). It is not clear if I_{HP} includes the commissioning and installation cost.

We calculated I_{Drill} with the equation suggested by Mazzotti (2018):

$$I_{Drill} = 9300 + H \cdot (158.5 + 3.4 \cdot 10^{-4} \cdot H^2 + 100) \quad (9)$$

I_{Drill} includes the costs for the BHEs, manifolds, trench digging for pipe connections to the heat pump, secondary fluid, commissioning and casing.

For the ASHP, we the investment cost, I, only consists of the cost of the HP. We calculated it as:

$$I = 66000 + 1175 \cdot Q_h \quad (10)$$

Equation 10 is the regression line that best fits the data obtained for the HPs of the model NIBE S2125-8 (NIBE, 2022). It is not clear if I includes the commissioning and installation cost.

We did not find data about the costs of DSHPs, therefore, instead of calculating the NPV of these systems, we evaluated the Maximum Additional Cost (MAC) - compared to the equivalent GSHP- that equalizes the NPVs of the DSHP and of the conventional HP with the highest NPV for the scenario considered.

If a GSHP has the highest NPV, the MAC is calculated as:

$$MAC = \sum_{y=0}^{L} \frac{p_{el,y}(W_{GSHP,y} - W_{DSHP,y})}{(1+d)^y} \quad (11)$$

If an ASHP has the highest NPV, the MAC is calculated as:

$$MAC = \sum_{y=0}^{L} \frac{p_{el,y}(W_{ASHP,y} - W_{DSHP,y})}{(1+d)^y} - (I_{ground} - I_{air}) \quad (12)$$

Equations 11 and 12 differ because if the DSHP is compared to the GSHP, the investment costs only differ because of the extra installation cost of the air-brine heat exchanger. If the DSHP is compared to an ASHP, the investment costs also differ because of the purchase of a different HP and drilling for the ground heat exchanger.

Case studies

We have analysed a small Swedish single-family house with an annual heating demand of 15 MWh. For the simulation of the GSHPs and DSHPs it is important to consider the presence of neighbouring installations. We have considered 3 scenarios:

1. *d* → ∞*:* there are no neighbouring installations;
2. *d = 20:* the house belongs to an infinite square grid of identical houses (with identical HP systems). The distance between two consecutive houses is 20 m;
3. *d = 15:* the house belongs to an infinite square grid of identical houses (with identical HP systems). The distance between two consecutive houses is 15 m.

The GSHPs and DSHPs have been coupled to boreholes of lengths:

A. H = 50 m;
B. H =100 m.

The ground and borehole characteristics used for the study are summarized in table 1.

Results

Electricity consumption

The electricity consumptions of the air-source heat pump, and ground- and dual-source heat pumps connected to a 50-m borehole are shown in figure 2.

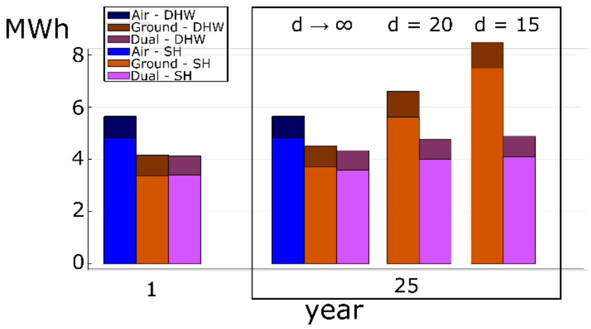

Figure 2: Electricity consumption of the ASHP, and GSHP and DSHP connected to the 50-m BHE. Results for the 1st and 25th year of operation.

It should be observed that the results for the scenarios *d* → ∞, *d = 20* and *d = 15* are the same for the first year of operation. This is due to the negligible thermal influence between the neighbouring boreholes during their first year of operation, thus the identical operation of the isolated borehole and the boreholes in the neighbourhoods.

During the 1st year of operation, the ASHP requires 4.8 and 0.8 MWh of electricity for space heating and hot water respectively (5.6 MWh in total); for the same purposes the GSHP requires 3.4 and 0.8 MWh (4.2 MWh in total); the DSHP requires 3.4 and 0.7 MWh (4.1 MWh in total). Using a GSHP or a DSHP leads to a 26% and 27% saving compared to an ASHP.

During the 25th year of operation the GSHP and DSHP perform differently in the three different scenario. In scenario *d* → ∞, the GSHP requires 4.5 MWh of electricity, 7.1% more than in the 1st year of operation, the DSHP requires 4.3 MWh of electricity, 4.9% more than in the 1st year of operation. In scenario *d = 20* the GSHP requires 6.6 MWh of electricity, 57% more than in the 1st year of operation, the DSHP requires 4.8 MWh of electricity, 17% more than in the 1st year of operation. In scenario *d = 15* the GSHP requires 8.7 MWh of electricity, 107% more than in the 1st year of operation, the DSHP requires 4.9 MWh of electricity, 20% more than in the 1st year of operation.

It can be noticed that in scenario *d* → ∞ both the GSHP and DSHP undergo a minor performance loss during the lifetime of the systems, and still offer significantly better performance than the ASHP after 25 years of operation. However, in scenarios *d = 20* and *d = 15* the performance of the GSHPs drop below the performance of the ASHP. On the contrary, the performance decrease of the DSHPs does not undermine its performance superiority compared to the ASHP.

The electricity consumptions of the air-source heat pump, and ground- and dual-source heat pumps connected to a 100-m borehole are shown in figure 3. Also in this case the results for the scenarios *d* → ∞, *d = 20* and *d = 15* are the same for the first year of operation.

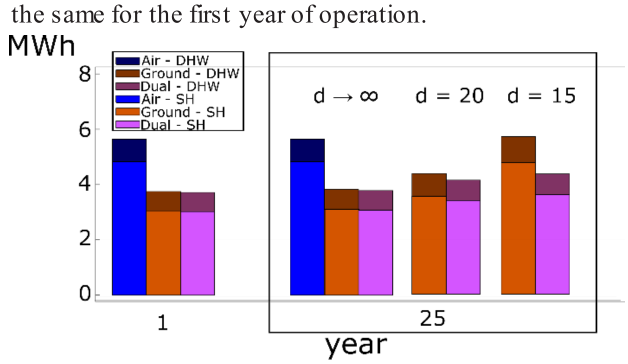

Figure 3: Electricity consumption of the ASHP, and GSHP and DSHP connected to the 100-m BHE. Results for the 1st and 25th year of operation.

During the 1st year of operation, the ASHP requires 4.8 and 0.8 MWh of electricity for hot water and space heating respectively (5.6 MWh in total); for the same purposes the GSHP requires 3.0 and 0.7 MWh (3.7 MWh in total); the DSHP requires 3.0 and 0.7 MWh (3.7 MWh in total). Using a GSHP or a DSHP leads to a 34% saving compared to an ASHP.

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Table 1: Borehole and ground properties

Borehole properties		Ground properties			
Radius [cm]	Resistance [m K/W]	Conductivity [W/m/K]	Density [kg/m^3]	Specific heat [J/kg/K]	Undisturbed temperature [°C]
5.75	0.15	3,1	2300	870	8

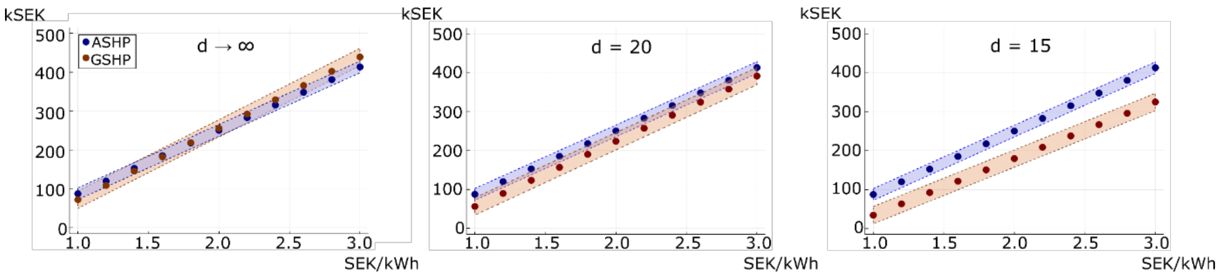

Figure 4: NPV of the ASHP and GSHP connected to the 50-m BHE as a function of the electricity price.

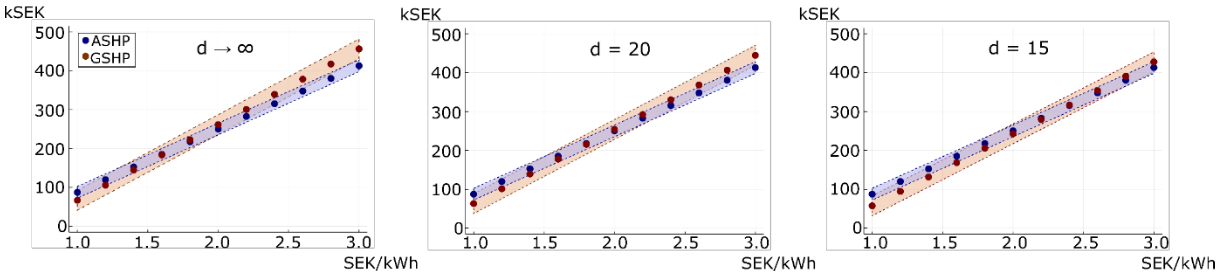

Figure 5: NPV of the ASHP and GSHP connected to the 100-m BHE as a function of the electricity price

During the 25th year of operation the GSHP and DSHP perform differently in the three different scenario. In scenario $d \rightarrow \infty$ the GSHP requires 3.8 MWh of electricity, 2.7% more than in the 1st year of operation, the DSHP requires 3.8 MWh of electricity, 2.7% more than in the 1st year of operation. In scenario $d = 20$ the GSHP requires 4.4 MWh of electricity, 19% more than in the 1st year of operation, the DSHP requires 4.1 MWh of electricity, 11% more than in the 1st year of operation. In scenario $d = 15$ the GSHP requires 5.7 MWh of electricity, 54% more than in the 1st year of operation, the DSHP requires 4.3 MWh of electricity, 16% more than in the 1st year of operation.

Analogously to the 50-m borehole scenario, in scenario $d \rightarrow \infty$ both the GSHP and DSHP undergo a minor performance loss during the lifetime of the systems, and still offer significantly better performance than the ASHP after 25 years of operation. The performance loss is lower than in the 50-m scenario. This is due to the increased length of the ground heat exchanger causing a lower heat extraction load per meter of borehole, thus a lower ground temperature change over time and a lower performance decrease. The lower decrease in underground temperature compared to the 50-m borehole case has an even higher effect on the scenarios $d = 20$ and $d = 15$. In fact, in these scenarios, differently from the analogous scenarios with H = 50, the GSHP still performs better ($d = 20$) or as well ($d = 15$) as the ASHP after 25 years. The DSHP also benefits from a longer GHE, even if to a lower degree then the GSHP. In fact, after 25 years, it performs 12%, 15% and 12% better than the DSHP with the shorter GHE for the scenarios $d \rightarrow \infty$, $d = 20$ and $d = 15$ respectively. On the other hand, for the same scenarios, the performance improvements of the GSHP is respectively of 16%, 33% and 35%.

Net Present Value

The NPVs of the air-source heat pump, and ground-source heat pumps connected to a 50-m borehole are shown in figure 4.

In scenario $d \rightarrow \infty$ the ASHP is more likely to be the most profitable investment for electricity prices < 2 SEK/kWh, while the GSHP is more likely to be the best investment for higher electricity prices. In scenario $d = 20$, the bands taking into account the uncertainty on the investment cost overlap, however, the ASHP is more likely to be the best investment for all the electricity prices considered. In scenario $d = 15$, the ASHP is the best investment for all the electricity prices even considering the uncertainty on the investment costs. The NPVs of the air-source heat pump, and ground-source heat pumps connected to a 100-m borehole are shown in figure 5.

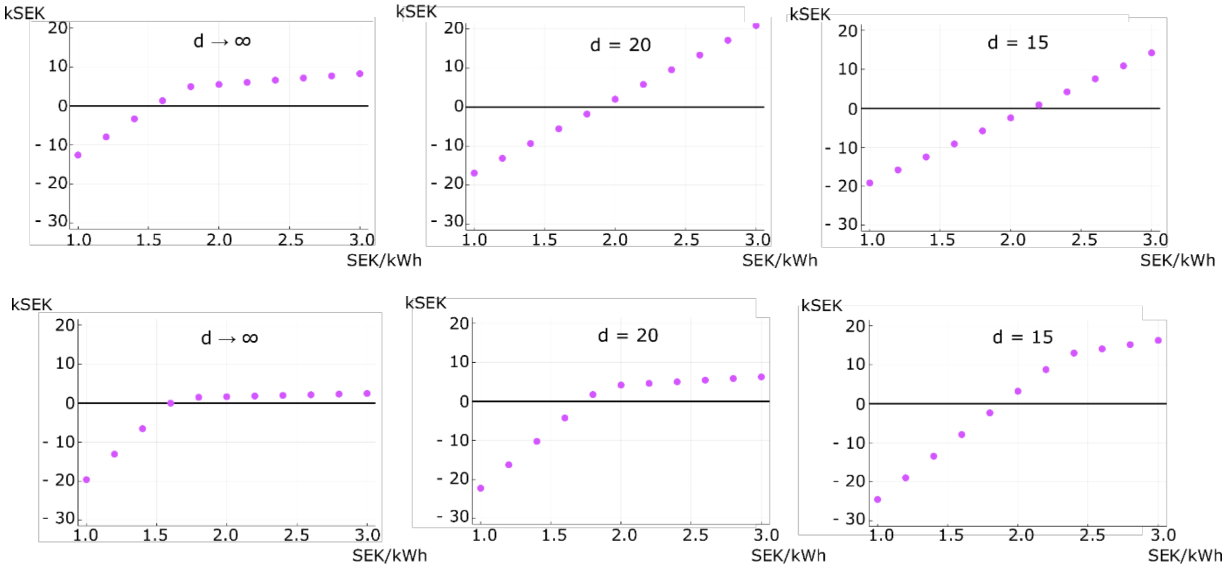

Figure 6: MAC for the DSHP. Results for the 50-m BHEs (up) and 100-m BHEs (down)

In scenarios $d \rightarrow \infty$ and $d = 20$ the ASHP is more likely to be the most profitable investment for electricity prices < 2 SEK/kWh, while the GSHP is more likely to be the best investment for the highest electricity prices. In scenario $d = 15$, the ASHP is more likely to be the most profitable investment for electricity prices < 2.4 SEK/kWh, while the GSHP is more likely to be the best investment for the highest electricity prices.

In general GSHPs connected to 100-m boreholes have a higher NPV than GSHPs connected to a 50-m borehole, meaning that the extra drilling cost is offset by the increased efficiency, thus savings in the operation costs.

Moreover, in all the scenarios, the NPV of either HPs is positive, meaning that substituting an electric boiler with an HP is always profitable in the scenarios considered.

4.3 Maximum additional cost

The MACs of the air-brine heat exchanger installation are shown in figure 6.

The maximum extra cost is always negative for electricity prices lower than 1.5 SEK/kWh and is anyway always lower than 21 kSEK. Given that the maximum NPV of the conventional HPs ranges between 150 and 500 kSEK for electricity prices higher than 1.5 SEK/kWh, the extra investment would lead to negligible economic profit, if any.

One can observe that the MAC increases linearly with the electricity prices in two scenarios, while it has a piecewise linear increasing trend in the other scenarios. To understand the reason behind this behaviour one should remember that for each scenario and electricity price the DSHP is compared to the conventional HP with the highest NPV. If in a specific scenario the same HP (ASHP or GSHP) has the highest NPV for all electricity prices the trend is linear, otherwise it is piecewise linear.

One can also observe that the MAC is lower than 0 in [illegible] has the highest NPV and therefore the DSHP is compared to the ASHP. In this case, the MAC takes into account that the extra investment is not only associated with the installation of a brine-water heat exchanger, but also with the purchase of a GSHP instead of an ASHP (equation 12). Therefore, a MAC lower than 0 can interpreted as follows: investing in a GSHP rather than an ASHP would result in a lower NPV even if the performance of the GSHP were as high as the performance of an equivalent DSHP.

5. Discussion and conclusions

This study showed that the performance of GSHPs vary greatly depending on the design of the systems and presence of neighbouring installations. For example, during the 1st year of operation, the GSHPs performed better than the ASHPs in all the scenarios considered, with a 26-34% lower electricity consumption than the ASHP. However, the performance during the 25th year varied greatly between the different scenarios: the electricity consumption of the GSHPs varied between -32% and +55% of the electricity consumption of the ASHP. Therefore, the often presumed higher performance of GSHPs compared to ASHP is not guaranteed without a proper design that considers the whole lifetime of the system and takes into account the presence of neighbouring installations.

From an economical point of view, it should be noticed that the NPV is positive for all the scenarios analysed, confirming that ASHPs and GSHPs are a profitable replacement of electric boilers for small single-family houses in Stockholm. Our GSHPs tend to have higher NPVs when coupled to the longest boreholes, meaning that the extra installation cost is offset by the improved systems performance. The ASHP tends to be the best investment for the lowest electricity prices considered and the GSHPs tend to be the best investment for the highest electricity prices. However, in most cases the uncertainty bands overlap showing no important difference between the investments in either of the systems.

DSHPs showed a more stable operation than GSHPs, undergoing lower performance decreases over their lifetime. In fact, during the 1st year of operation, the DSHPs had a 27-34% lower electricity consumption than the ASHP. During the 25th year, their electricity consumption was still 12-32% lower than the ASHP. However, the MAC was calculated to be at most 21 kSEK, therefore we consider the extra investment cost associated to a DSHP not justified from an economic point of view for the scenarios considered.

The technical and economic results presented are strongly linked to the case study considered: a small single family-house. We expect GSHPs and DSHPs to be more cost-effective for bigger family houses, and, in particular, we expect the competitiveness of DSHPs to be higher for multi-family buildings and multi-family buildings in densely populated areas. However, further studies are necessary to evaluate these hypotheses.

The input data, including details of the heat loads, the models and functions used for the simulations, and the results are openly available on GitLab (Fascì, 2022).

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