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Heat source shifting in buildings supplied by district heating and exhaust air heat pump

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Abstract

The heat supply for Swedish multi-family residential buildings is becoming more complex, and today it is fairly common to combine district heating with a second heat source. The most common heat source to combine with district heating in Sweden is an exhaust air heat pump. On average, the exhaust air heat pump covers 31% of the yearly heat load and is given full load priority. There is a missed potential in cost and CO_2 savings when one heat source is given full load priority, since marginal production costs and CO_2 emissions constantly vary in both the electrical grid and the district heating system. The aim of this study is to evaluate how buildings with several heat sources should be operated using hourly energy prices. Hourly heat and electricity prices for Gothenburg have been established for two years based on the marginal costs of heat and electricity generation. These prices have been used to evaluate the most common combinations of heat sources. Results show that the most common combination with an exhaust air heat pump with full load priority does not lower costs compared to the reference case with only district heating. However, having a control system that allows heat source shifting and gives load priority to the heat source with the lowest cost each hour can greatly reduce the heating cost, and systems with larger heat pumps show even greater potential for heat source shifting.

Keywords: Heat source shifting; Exhaust air heat pump; District heating; Hourly pricing

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1. Introduction

The total energy usage in Sweden for the year 2012 was divided among buildings (38%), industry (36%), transportation (24%), and other (2%) [1]. This makes buildings the largest energy-using sector in Sweden, which is also true for the world as a whole. Energy in buildings is primarily used for heating, ventilation, and air-conditioning (HVAC) and secondarily for electrical appliances [2]. The main heat sources for HVAC purposes vary greatly between different countries. In Sweden, district heating (DH) has a market share of 60% [3], and every town with more than 10,000 inhabitants has a DH system [4].

The marginal cost of heat generation (the extra cost per MW associated with increasing the generation) can vary significantly within a single day, and a factor of 2–3 in cost difference is not uncommon in DH systems. All Swedish DH providers have an heat tariff where the price of heat is constant during all hours in one month [5]. Some companies have a tariff that is constant for the whole year, while some provide seasonal pricing. The most common pricing model for electricity in Sweden today is also to have fixed prices over one month or longer periods of time. Costumer prices are set by the electricity traders based on their estimates of the average price for electricity on NORDPOOL, the deregulated electricity spot market for northern Europe. How long the prices are fixed is up to the customer, but the longer the prices are fixed, the larger the risk is for the trader that charges a premium on top of its price for taking the risk. What is true for both DH systems and the electrical system is that having constant prices and large variations in generation costs can lead to suboptimal solutions, since the customer has no incentive to regard his or her heat usage from a system perspective.

Since the need for space heating in buildings can be fulfilled by either DH or electrical heating, primarily with a heat pump (HP), it is also of interest to consider optimizing the two together from a system perspective. Buildings with DH and HP today most often have fixed prices for heat and electricity and utilize the HP for base load and DH for peak load. This is a suboptimal solution, since the marginal production cost of the two systems varies during each day; hence, the system that is best for providing the base load also shifts.

Today it is possible for any customer of the Swedish electrical grid to receive a tariff with hourly prices based on the NORDPOOL day-ahead electricity spot market. This opportunity is seldom seized except by large industries and a few enthusiasts. Hourly prices make it possible for electricity customers to optimize their local systems within a larger system perspective. Load can be shifted to low-price hours to save money, and such actions help to balance the electrical grid. It has been shown in previous studies that shifting heat loads over time is possible by utilizing buildings for thermal energy storage [6-8]. Even greater possibilities can emerge if customers with DH and HP make the choice to switch to hourly electricity pricing and are also provided with hourly heat pricing. This makes it beneficial not only to shift heat loads over time but also to shift loads between DH and the electrical grid. It is these possibilities that are studied in this paper. Adding flexibility in heat sources on the consumer side might increase the interaction between the DH system and the electrical grid, enhancing the possibility of the two systems balancing each other. This can be very beneficial if there is no strong correlation between the marginal cost of heat and electrical generation.

The aim of this project is to study the effects of implementing a heat tariff with hourly pricing for buildings with both DH and HP for space heating. The correlation between NORDPOL day-ahead spot prices and the marginal costs of heat generation in Gothenburg is studied for the years 2013 and 2014. A case study is carried out for a building with both DH and HP and hourly energy prices for both. To decide what type of HP should be used in the case study, a survey of a national building database is carried out. The case study shows how economically beneficial it is to shift load between the two systems and whether they can supplement each other. It is assumed here that the customer pays heat and electricity prices based on the marginal production costs for each; hence, the economic benefit is allocated to the customer. However, the reduced cost for the customer should reflect the reduced cost of heat and electricity generation for the energy suppliers. It should be possible to implement the same control of the heating system with another business model without hourly prices.

DH systems can have very different mixes of heat sources. This study is limited to the DH system in Gothenburg, Sweden, which has a very wide mix of heat sources. A total of 28 heat sources can be grouped into these categories:

- Industrial excess heat
- Garbage incineration combined heat and power (CHP)
- Biofuel CHP
- Natural gas CHP
- Heat pumps
- Bio fueled heat only boilers (HOBs)
- Natural gas HOBs
- Oil HOBs
- Import/export to neighbor DH systems

For the case study, a multi-family residential building is chosen, because it is the most common customer in the DH system, accounting for more than 50% of the heat load. For other building types, the heat load profile might be different.

It should also be stressed that this study is not a comparison of which is the more economical alternative between HP and DH. Such a study would need to take into account investment costs, maintenance, etc. This is a study of existing buildings where the investments are already made, and the study focuses on optimizing the control of the combined space heating system from a system perspective.

2. Methodology

This study can be divided into three steps:

- Survey of residential buildings with several heat sources
- Establishing hourly heat and electricity prices
- Simulation and optimization

The first step in the study (Survey of residential buildings with several heat sources) is to find what heat sources are most often combined with DH and thus what combination of heat sources to further focus on. For this purpose, a database covering Energy Performance Certificates for Swedish properties was used. The database covers the vast majority of multi-family residential properties in Sweden and is further described in [9, 10].

The second step is to find the marginal cost of electricity and heat generation for every hour during the simulation period. The hourly electricity used in this study is based on the NORDPOOL electricity spot market [11]. The electricity trading is split on a day-ahead market, an intraday market, and a balancing power market, with the vast majority of the electricity traded on the day-ahead market. The function of the intraday market is to correct the mismatch in supply and demand that occurs due to imperfect predictions. As a customer, if you want hourly electricity prices, they are based on the day-ahead market; therefore, this data is what is used in this study. Due to transfer capacity limitations in the national and international electricity grid, NORDPOOL is divided into 16 geographical areas. These areas will share the same prices when the transfer capacity in the grid is not limiting, and the prices will differ when the transfer capacity is limiting. Since the building simulated in this project is located in Gothenburg, Sweden, the prices from the associated area SE3 are used. The price a customer with hourly electricity prices pays consists of five components:

- NORDPOOL ELSPOT SE3 day-ahead price
- Electricity tax (294 SEK/MWh)
- Electricity certificate (varies ~35 SEK/MWh for the studied time period)
- Premium to the provider
- Value added tax (VAT) (25%)

The premium to the provider is excluded for both electricity and DH in this study, since the target is to minimize the system cost. VAT is also excluded, so the modelled hourly electricity price consists of the NORDPOL ELSPOT

SE3 day-ahead price, electricity tax, and electricity certificate. This should be an electricity price with a zero contribution margin for the trader.

The hourly DH price is based on the marginal costs of heat generation in the DH system. This data is provided by the operational management group at Göteborg Energi AB (the DH provider in Gothenburg, Sweden). The marginal costs are primarily based on the variable costs for the most expensive heat generation plant that was running each hour, with a few exceptions. One exception is if the plant with the highest variable cost is running on a minimum load and therefore can't be turned off; then the plant with the second lowest variable cost is the one operating on the margin. Another exception is when a plant is in operation because there are tests or pollution measurements at the site. The idea is that the marginal cost in the model should be the extra cost associated with generating, for example, 1 MW extra heat in the DH system. Like the established electricity prices, this should be the heat price with a zero contribution margin. Marginal costs are provided for the years 2013–2014; hence, these are the years simulated in this study. The actual prices are not presented in the figures but all graphs are proportional to the prices.

The third and last part of the study involves analyzing and optimizing a heating supply system in a building with the most common heat source combination found in the study. Based on parameters found in the first part of the study, an average building is established to be used in the simulation. Parameters such as building size, yearly heat use, and year of construction can be found this way. To simulate the building with an hourly resolution also requires having a heat load profile. This profile is based on measurements from a residential building typical for the same time period as the buildings found in the first part of the study.

It is also important to have a model configured with the heating system that represents systems that are actually installed in the buildings. Some of the parameters can be extracted from the building database used in the first part of the study. Yearly electrical input to the heat pumps, yearly bought heat from the DH system, and the division of heat use between space heating and domestic hot water are examples of parameters that can be found this way. However, there are other parameters more difficult to find representative data for. One is the system configuration. Here, practices can vary among different companies, cities, and countries. The system configuration used in this study is based on the regulations from the DH provider in Gothenburg and on experiences of consultants working with such solutions in the city. Two main things stand out that could be different in other cities due to local conditions:

- The heat pump is only used for space heating (no domestic hot water). The reason is that there is a large share of low-cost industrial excess heat in the Gothenburg DH system, and customers pay a seasonal price that is very low in the summer. It is therefore not economically viable to have the HP produce domestic hot water, and the consultants design it this way.
- The heat pump is assumed to be connected in parallel with the district heating substation. This is a part of the customers' contract with the DH provider; if they are to install a second heat source, it should be connected in parallel, so it does not increase the return temperatures to the DH network. The heat pump can still supply heat to the same radiator system as the DH network, and the flow will be split between the two heat sources.

With these constraints, a model for the heat pump is established. Other parameters are kept fairly simple but accurate enough for the purpose of this study. The hot side of the HP is assumed to include the supply temperature of the radiator heating system plus a Δt of 3 °C at maximum load on both the warm and cold sides (decreasing linearly with decreasing load). The supply temperature of the radiator heating system is set to 60 °C at the design outdoor temperature (DOT) of -16 °C, and it decreases at higher outdoor temperatures, following Kärkkinen's equation [12]. According to consultants who were asked, a common design for an exhaust air HP is to allow cooling of the exhaust air down to 5 °C to avoid the need for defrosting, so this condition is used in this study. The amount of exhaust air is set to 0.35 L/m^2s [13].

The parameter with the largest impact on the results is the coefficient of performance (COP) of the HP. Since this value has such a large impact, it is included in a sensitivity analysis. In the base case, it is set to 35% of Carnot COP, which, in the simulations, gives a seasonal COP of around 3.0, in line with surveys of performance of existing systems [14, 15]. These values may seem a bit low, but the existing installations are often decades old and thus not top of the line.

The major part of the study involves the statistical analysis, which is carried out in Excel. The tools provided by Excel are enough to study correlations between electricity and heat prices and also for designing a heating system for a building that switches heat sources depending on which source is the cheapest at the present hour.

3. Results and analysis

This chapter is divided into three sections covering the three steps in the study, as presented in the Methodology section. The first sections study which combinations of heating sources are most common in multi-family residential properties. It also studies how the heat load is shared between the heat sources in these properties. This provides input data for the simulations in the third section.

The second section establishes hourly heat and electricity prices that reflect the cost of heat and electricity production for every hour. The variations in the established prices and their correlation are also studied.

The third section studies the heat load of a residential area and calculates the heating cost based on the established price models. The most common configuration of heating sources found in the first section is used as a simulation case together with reference cases and improved cases.

3.1. Survey of residential buildings with several heat sources

During the year 2013, there were 20,056 properties that were customers of the DH system in Gothenburg. Out of these properties, 4,457 were multi-family residential properties, although they represent >50% of the heat use. This only includes properties with the main application area as “residential” and which also house at least three families. Villas, semidetached houses, and properties where only a minor part of the area is used for residential purposes are thereby excluded. One property can include several buildings, which is fairly common; usually, buildings that share the same yard belong to the same property. Of the 4,457 multi-family residential properties, 170 also have at least one other heat source. These are presented in Table 1.

Table 1. Multi-family residential properties in Gothenburg supplied by DH and at least one other heat source. The DH share is the share of DH of the total energy for heating purposes delivery to the building. The average heat load is converted to an average year using the degree day method.

Extra heat source (all properties also have DH)	**Number of properties**	**Average heat load [MWh/year]**	**DH share [%] (of bought energy for heating)**	**Average year of construction**
---Combination of 2 heat sources---				
HP (exhaust air)	119	591	87%	1956
El (air distributed)	16	910	91%	1967
HP (air/water)	7	429	78%	1965
HP (ground source)	6	260	34%	1962
HP (air/air)	4	418	95%	1935
El (water distributed)	2	2940	97%	1973
Natural gas	1	292	81%	1924
---Combination of 3 heat sources---				
El (direct) & HP (exhaust air)	8	617	79%	2010
Firewood & El (direct)	3	241	99.7%	1934
Natural gas & El (water distributed)	2	211	89%	1933
Pellet & El (water distributed)	1	45	44%	1902
El (water distributed) & HP (air/air)	1	432	83%	1916

From Table 1, it is clear that by far the most common combination of a second heat source in DH-connected buildings is with exhaust air HP. This heating combination is present in 2.7% of the multi-family residential properties in Gothenburg. This can be compared to Sweden as a whole, where this combination is present in 2.2% of multi-family residential properties with DH. It might seem surprising that the DH share of the heat load is on average 87% in these properties, but that is because property owners only report the input electricity to the HP (not the output heat). Assuming seasonal performance factor (SPF) = 3.0 for this category, the average coverage of DH instead becomes 69% of the yearly heat load. Furthermore, in these 119 properties, 21% of the total heat output is used for domestic hot water. Assuming that only DH is used for domestic hot water, on average 61% of the yearly heat use for space heating is covered by DH for the buildings in Gothenburg. For Sweden as a whole, this value is 56%. However, the share of DH is unevenly distributed among the 119 properties in Gothenburg, as shown in Figure 1. It is therefore of interest to study several system configurations in a sensitivity analysis.

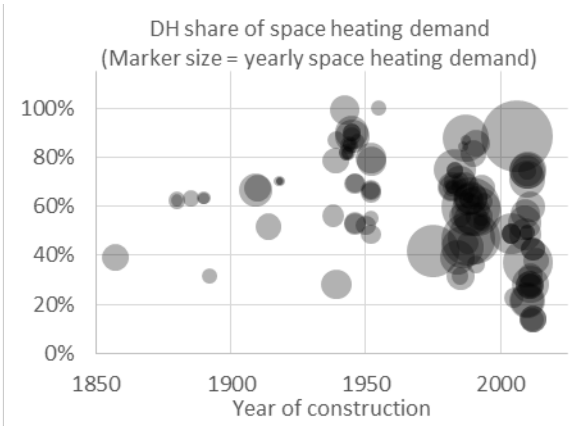

Fig. 1. DH share of space heating demand in buildings with DH and exhaust air HP, assuming all domestic hot water is provided by DH and HP with SPF=3. Markers are transparent, darker color indicates higher concentration of properties.

3.2. Establishing hourly heat and electricity prices

Hourly heat prices for 2013 and 2014 have been established based on the marginal cost for heat generation in Gothenburg and are presented in Figure 2.

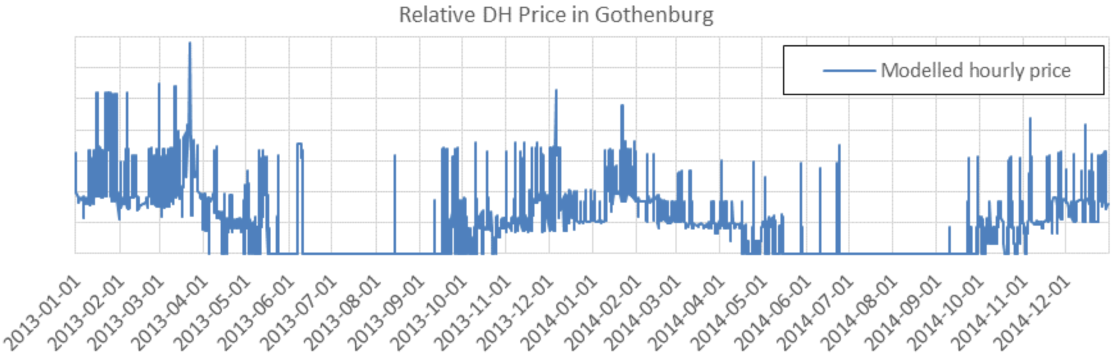

Fig. 2. Modelled hourly heat price and actual consumer heat price in Gothenburg 2013–2014, excluding VAT.

Figure 2 shows that the modelled hourly price, reflecting the marginal cost for heat generation, has a large variation, not only seasonally but also within short periods of time. It is not uncommon that there is a factor of 2–3 in price difference within the same day. It can also be noted that during some hours, the marginal heat production is zero. This is when industrial excess heat is on the margin or when there is an excess of heat in the DH system that needs to be cooled in a river.

Hourly electricity prices for 2013 and 2014 have been established based on the NORDPOOL ELSPOT SE3 day-ahead price, electricity tax, and electricity certificate. They are presented in Figure 3 together with the modelled hourly heat price for comparison.

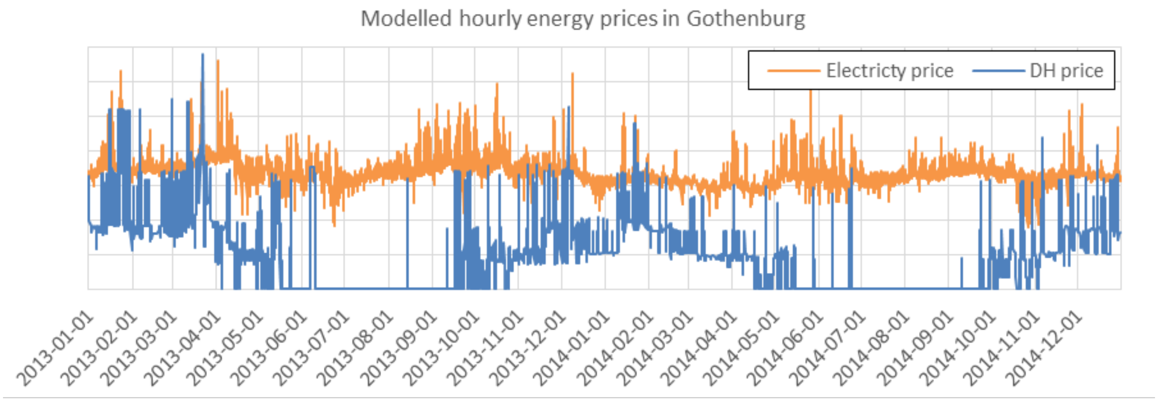

Fig. 3. Modelled electricity and heat price in Gothenburg 2013–2014, excluding VAT.

It is clear from Figure 3 that the variation in heat price is greater than the variation in the electrical price. The heat price has a strong seasonal variation that is not present in the electrical price. There are a few hours when the heat price is higher than the electrical price. During these hours, it would even be beneficial to produce heat with electrical heaters in the DH network. These hours are very few today, but in a future with much intermittent renewable electricity generation, they may become more common. It should also be noted that electricity prices were at a historically low level during 2013–2014 (and were even lower during 2015), due to a number of circumstances on the Swedish electricity market such as e.g. increased efficiency on the consumption side and a recent expansion of wind power. Forecasts of future electricity prices are highly dependent on the rate of decommissioning of nuclear power.

To make a fair comparison of energy prices for a building with HP and DH, the electrical price would have to be divided by the COP of the HP. It is also of great interest to study the price variations in the short term to see whether daily price peaks occur at the same time for heat and electricity or whether there is little correlation. For these purposes, a scatter plot of all data points from 2013 and 2014 was established. The result is shown in Figure 4.

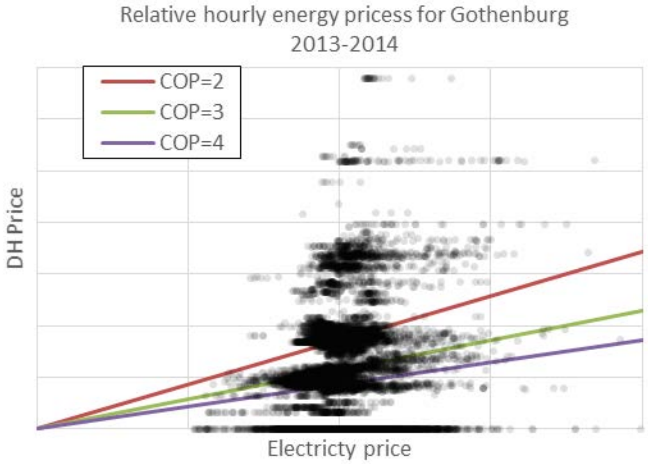

Fig. 4. Scatter plot for modelled electricity and heat price in Gothenburg 2013–2014, excluding VAT. The lines represent the break-even point between heating a building with DH and HP with specified COP.

Figure 4 shows that there is very little correlation between electricity and heat prices. Further, 61% of the points in Figure 4 is below the COP=3 line. This means that the cost for DH is lower than the cost for heat from an HP with COP=3 during 61% of the hours in 2013–2014. For an HP with COP=2 and COP=4, DH is cheaper than the heat from the HP for 76% and 46% of those hours, respectively. Many of the points are quite far away from COP lines, indicating that during these hours, one of the heat sources is significantly cheaper than the other. This result shows that having double heating systems in a building can be very beneficial for the building owner and that both the electricity system and the DH system would benefit from more interaction. However, COP values are constantly shifting depending on the temperatures in the system, and the points are not equally valuable, since the heat load is shifting in the buildings. Therefore, a more detailed analysis is required and is covered in the next section.

3.3. Simulation and optimization

In this section, the hourly prices established earlier are applied to a building with both DH and exhaust air HP for space heating. The heat cost for the building is analyzed for several cases. It should be stressed that this is not an economic comparison between DH and HP as heating alternatives, since neither installation costs nor maintenance costs or other economic factors are taken into account.

The space heating demand in the simulated building is based on measurements from 2013–2014 in a residential building in Västra Gårdsten, Gothenburg. The building is typical for the time period when a large part of the buildings with DH and exhaust air HP are from. It is a three-story building with a structural core of concrete and only tenancy apartments.

The simulations are run in two modes: HP prioritized and shifting priority. HP prioritized should represent how the systems installed today operate, where the HP always delivers as much heat as it is capable of, and DH fills the remaining demand when the heat output if the HP does not meet the total demand. Shifting priority means that the cheapest heat source has load priority each hour. When the DH price is lower than the electricity price divided by COP for the present hour, DH is prioritized, and the HP is turned off. The size of the HP is chosen so that when it is prioritized, it covers 39% of the yearly space heating demand like the average building in the survey of residential buildings with several heat sources. This corresponds to an HP that can cover 9.9% of the heat load that occurs at the design outdoor temperature (DOT) of -16 °C. Results from the simulation are presented in Table 2.

Table 2. Multi-family residential properties in Gothenburg supplied by DH and at least one other heat source. The DH share is the share of DH of the total energy for heating purposes delivery to the building. The average heat load is converted to an average year using the degree day method.

Case	**Prioritized heat source**	**HP share at DOT -16 °C**	**DH yearly share**	**SPF**	**DH price average [SEK/MWh]**	**El. price average [SEK/MWh]**	**Total heating cost [kSEK]**
Only DH (ref)	-	-	-	-	328	-	400
Base	HP	9.9%	61.0%	3.2	375	642	374
	Shifting	9.9%	75.0%	3.0	324 (-14.0%)	642 (±0.0%)	362 (-3.2%)

From Table 2, we can see that the change from prioritizing HP to having a shifting priority in heat sources has a big impact on how the system operates. The share of DH increases from 61% to 75%, and the average DH price drops by 14%. This is a consequence of turning the HP off during the summer and in daytime in spring/autumn when the DH price is very low. However, the total savings are only 3.2%; this may seem small, but it should be noted that there is no material investment necessary—only a change in the control logic. It can also be noted that the savings for installing an HP at all when provided with hourly prices is only 6.5% (9.5% with shifting priority), which is associated with a significant investment. These investments are probably more beneficial for building owners that pay the actual consumer prices for DH today, since they do not benefit from the periodically very low hourly DH prices. How the system operates during a typical spring week is shown in Figure 5.

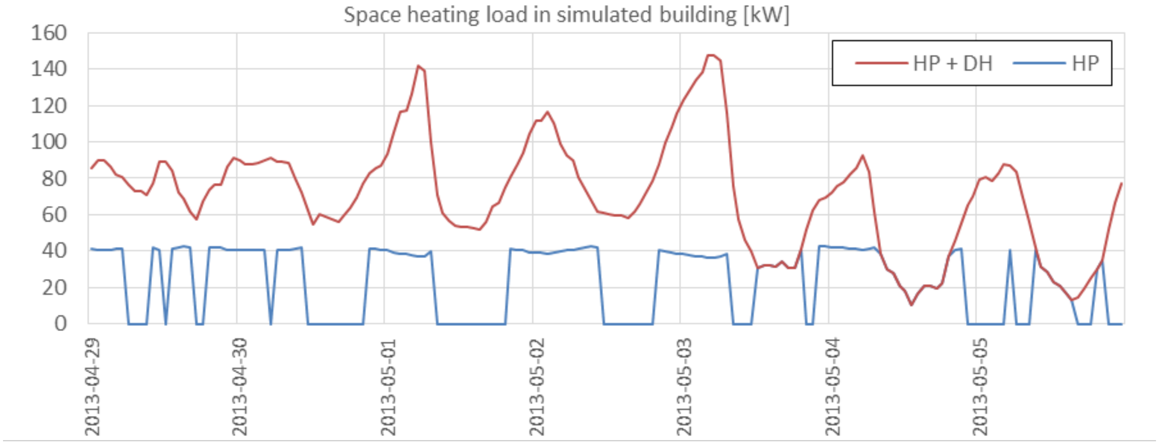

Fig. 5. Operation of the base case heating system with shifting load priority during one spring week (warm days and cold nights).

From Figure 5, we can see that the HP is often turned on during the nights and off during the days. This is a consequence of the DH price usually being high when the load in the DH system is high (cold nights) and low when the load in the DH system is low (warm days). The decrease in SPF from 3.2 to 3.0 occurs because the HP is turned off for many of the hours when the COP is high. It is still economical to do so, since these hours often coincide with very low (or even zero) DH prices. This correlation is further shown in Figure 6.

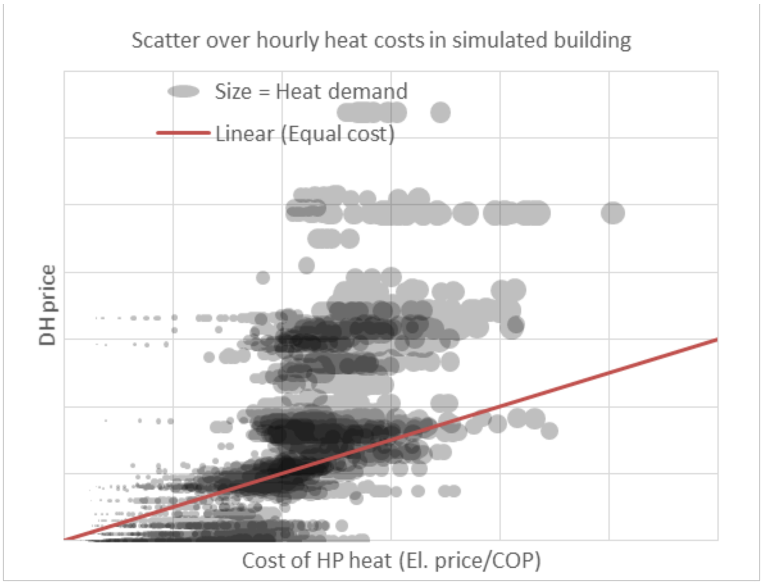

Fig. 6. Comparison of heat cost from the two heat sources where the COP of the HP is considered every hour, 2013–2014. Points below the line indicate that heat from DH is cheaper than heat from the HP.

If we compare Figure 4 to Figure 6, we can see that the data is “tilted clockwise” in Figure 6. This indicates that there is a correlation between COP and the DH price. This pushes many of the points closer to the line of equal cost, reducing the incentives for load shifting. The incentives for heat source shifting could be much more prominent in markets with a more volatile and/or higher electrical price and in systems with less variation in COP (e.g., ground-coupled HP).

Since there are a number of uncertain parameters and parameters that can have a high impact, a sensitivity analysis is carried out. The results of the analysis are shown in Table 3. It is shown that a lower ventilation flow rate increases the total energy cost in the system but also reduces the incentive for load shifting (from 3.2% savings to

2.5% savings). This is because there is less load to be shifted, since the HP covers a smaller share of the total load when it is prioritized. However, having a newer HP with a higher COP decreases the total energy cost and also reduces the incentive for heat source shifting (from 3.2% savings to 2.1% savings), even though there is more load available to be shifted. This is because the cost of the heat from the HP is further reduced during the hours when the DH price is very low. The temperatures of the radiator system also have an impact on the incentive for heat source shifting. Higher radiator temperatures (70 °C at DOT) increase the savings for heat source shifting to 3.6%, and lower radiator temperatures (50 °C at DOT) decrease the savings for heat source shifting to 2.9%. However, all cases significantly reduce the average DH price (between 9.0% and 14.6%) when shifting load priority is applied.

Table 3. Results from the sensitivity analysis.

Case	**Prioritized heat source**	**HP share at DOT -16 °C**	**DH yearly share**	**SPF**	**DH price average [SEK/MWh]**	**El. price average [SEK/MWh]**	**Total heating cost [kSEK]**
Base	HP	9.9%	61.0%	3.2	375	642	374
	Shifting	9.9%	75.0%	3.0	324 (-13.6%)	642 (+0.1%)	362 (-3.2%)
Vent. flow 0.20 L/m2s	HP	9.1%	73.2%	3.0	353	645	385
	Shifting	9.1%	84.1%	2.8	321 (-9.0%)	648 (+0.5%)	375 (-2.5%)
COP=45% of Carnot COP	HP	11.9%	60.2%	3.9	371	644	352
	Shifting	11.9%	68.0%	3.7	333 (-10.2%)	644 (±0%)	344 (-2.1%)
Rad. temp. 70°C at DOT	HP	8.8%	62.4%	3.1	375	642	381
	Shifting	8.8%	79.3%	2.8	320 (-14.6%)	646 (+0.7%)	368 (-3.6%)
Rad. temp. 50°C at DOT	HP	11.3%	59.8%	3.4	375	642	366
	Shifting	11.3%	70.9%	3.2	328 (-12.4%)	641 (-0.2%)	355 (-2.9%)

4. Conclusion

About 4% of all multi-family residential properties in the DH network in Gothenburg have at least one other heat source. By far the most common combination (present in 2.6% of the properties in Gothenburg and 2.2% of the properties in Sweden) is DH combined with exhaust air HP. On average, HP covers 39% of the yearly heat load for space heating and is not used for domestic hot water.

If heat and electricity prices were hourly and were based on the marginal cost of heat/electricity generation, the heat price would have a much greater variation than the electricity price. This is especially true for the seasonal variation but also for the daily variation. There is very little correlation between the established hourly heat and hourly electricity prices.

An average multi-family residential building with the most common size of exhaust air HP and DH would save 3.2% of the heating cost by utilizing the cheapest heat source each hour compared to always using the HP for base load. This would increase the share of DH for space heating in the building from 61% to 75% and reduce the average DH price by 13.6%. These savings can be achieved if the building is provided with hourly heat and electricity prices (or is controlled as if it were). The investment needed to achieve these savings is to update the control system with simple logic criteria.

What limits the savings from heat source shifting is that the costs of the output heat from both systems are often low at the same time. This occurs even though there is low correlation between the DH price and the electricity price, since there is a stronger correlation between DH price and HP COP.

Suggestions for future work include studying other types of installations and building types such as ground source HP and commercial buildings. Future scenarios for heat and electricity prices are also of interest, especially since electricity prices were historically low during this study. Practical tests are also planned.

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