Capturing flexibility gains by price models for district heating

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ABSTRACT

Flexibility can support the energy transition and improve the efficiency of heat supply to buildings. This study tests price models for the inclusion of heat pumps (HPs) in district heating network (DHN). Various price models were tested in two cases in Sweden. In Sweden, DH companies are increasingly confronted with instances where building owners invest in a HP and only use DH when it is too cold for the HP to function efficiently. This poses challenges for DH companies due to the high costs associated with peak load production. Potential gains in HP-DHN flexibility and the investment and operational risks of HP-DHN integration are therefore important topics to understand and investigate. Our results show that HPs can increase the flexibility of DHNs, reduce costs and environmental impact. We also identify that the lowest risk exposure to DH companies, in HP-DHN arrangements, is when the building owner invests in the HP and the DH company operates it.

1. Introduction

1.1. District heating

District Heating Networks (DHNs) play a pivotal role in diminishing the reliance on fossil fuels for heating through the utilisation of both renewable energy sources [1] and excess heat [2]. Heating and cooling sectors constitute the largest energy domains within the EU, accounting for half of the final energy consumption. Only 20% of the fuels used within the heating sector are renewable. Expansion of District Heating (DH) can alleviate the dependence of imported energy, lower energy costs and decarbonise the European energy system. In the pursuit of Europe’s decarbonisation objectives, the DH sector is critical and the expansion is attainable considering that only 9% of the European heat supply currently comes from DH [2].

A shift, from combustion-based systems towards using a multitude of locally available waste heat sources in combination with renewable sources in DHNs, is foreseen. This transition underscores the increasing importance of harnessing available flexibility. Flexibility in DHNs has been studied previously but few price models (PMs) have been implemented to harvest it [3]. One reason is that companies do not know which type of model is most efficient to adopt.

1.2. Flexibility

Flexibility is defined as “a ready capability to new, different or changing requirements” [4]. Flexibility in energy is the manoeuvrability of different energy and power demands for optimal operation and design [5]. It could be realized by energy efficiency, excess energy usage, shifting or reducing energy or power demand etc. [6]. Flexibility drivers that are both technical and non-technical have been identified. For example, Heat Pumps (HPs) and thermal storage [6–21] thermal inertia of buildings [22], combined heat and power (CHP) [6,12,13,16–18] [20,23–28], Direct Electrical Heating (DEH), electric boilers [7,12,29,30], other boilers [12,15,19,29] and end-user behaviour [31] are mentioned. Sometimes, demand shifting and energy reduction are included when defining flexibility [6,8,14–17].

1.3. Flexibility (e.g. the possibility to resort to the most cost efficient technology over time) in DH & HP integrated systems

The profitability of integrating HP installations within a DHN, as opposed to relying solely on the DHN has been evidenced [18]. This combination is becoming increasingly common in low-temperature (often referred to as 4th and 5th generation DHC) installations [32,33]. In a case where HPs owned by building owners are incorporated into a DHN, the DH companies must make sure the HP is operated in a desirable way. It is important to establish the responsibilities of each

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part, clarify supply conditions, and determine mitigation strategies to manage potential deviations from the newly established business conditions [34]. In Ref. [8], the inclusion of a HP into the fuel mix of a DH company was analysed by shifting the boundary conditions between the parties’ business arrangements. New business concepts and models of DH & HP combinations in the low temperature DHN context were suggested [35]. Innovative ownership and operation of HPs have been discussed by introducing a third-party ownership concept where DH companies exercise control over the HPs [36]. A business model for DH & HP integrated systems was presented, wherein an aggregator hosts the HPs, owned by end-users, and the heat is directly purchased by the end-user from the aggregator [37]. The aggregator can buy electricity from the wholesale market for HP inputs and sell electrical load flexibility in an ancillary market. Third-party ownership of HPs was addressed and the economic viability of providing flexibility was identified (Ibid). In Sweden, there is a trend amongst building owners to invest in a HP and rely on DHN exclusively during peak load periods. This operational approach poses challenges to DH companies given the substantial costs associated with peak-load production. For efficient integration of HP and DHN for DH companies, it is important to understand how to work with customers who own or consider installing a HP [36].

The integration of distributed HPs into DHNs challenges traditional DHN business model design. Conventionally, DH business models are product-oriented (the DH companies sell heating to customers and get paid based on the amount of delivered heat: measured in kilowatt-hour, kWh). This kind of business model is, however, inadequate for addressing a flexible DH demand and supply system. To capture flexibility, the adoption of an alternative business model that offers heat as a service could be relevant. A service pyramid has been identified when studying energy offers to customers [38]. It distinguishes between two tiers of services: product-focused aimed at ensuring the functioning of a delivered product, and customer process-oriented designed to facilitate enhancement of customers’ operational processes [38]. The value proposition of a service can be categorised at three levels: (1) input-based; the supplier provides the customers with information, (2) performance-based; linked to operational performance; and (3) result-based; centred around joint (customer and energy supplier), desired, outcomes such as reduced energy consumption. Most energy services offered by Swedish DH companies are input-based, situated at the bottom of the pyramid. These services encompass the installation and maintenance of DH systems (service) and the provision of heat (product). As companies transition into the performance-based service tier, their offers evolve from products to services in the category of smarter control, optimisation, preventive maintenance, remote monitoring, advisory, training, and other customer supports. For result-based services, the highest level of customer engagement is ensured by guaranteeing specific outcomes that result in a win-win situation. To harvest flexibility, energy services that span across all three levels of the service pyramid are needed.

### 1.4. Business model and price model

A business model (BM) outlines what value is offered to a customer, how the company interacts with the customer and what customer segments are targeted. It also addresses what resources, activities and relationships are needed to deliver the value. As a result of resources being acquired and activities undertaken, costs are incurred that are met by charging the customer for the value that is generated (the price model, PM, component of the business model) [42]. When the BM changes, for example when a product-oriented business model shifts towards increasing service orientation, the configuration of the business model shifts. The change can lead to a new customer value, segment, relationship as well as a setup of resources, activities and partnerships. When BMs change so does the risk exposure. When a HP is included as a heat source in a DHN, the operational risk for the DH company increases (if the HP is not operated efficiently) and including it in the fuel mix might be unprofitable.
One facet of the BM is the price model (PM), designed to align the costs associated with delivering customer value with corresponding revenues. Incentivising and harvesting flexibility can be achieved by adjusting the PM. The motivations alert customers of inefficiencies in their assets (secondary system) and incentivises them to make improvements [39] that they gain from. Motivational components can be incorporated into DH PMs in different ways. Common components include flow (m3/MWh) where the customer pays for the amount of water passing through the substation per the amount of heat consumed [40] (large flows characterise inefficient systems as a high flow in the substation increases the return temperature [41]). Bonus-malus components include percentage variations of the heat price, or one of its components, according to the offset between a measured key parameter (return temperature, cooling performance through the substation, the water volume per supplied heat) and a reference value [40]. With bonus-malus, customers with return temperature below a reference value get a bonus, while customers with return temperatures above pay a fee [41]. A discount for return-line heat is sometimes applied, motivating customers to install low-temperature systems such as floor heating and instant domestic hot-water preparation. A feed-in tariff can also encourage waste-heat suppliers to supply the DHN with heat [40]. Tariffs are also linked to the size of the installation (referred to as power) to minimise use at peak load [39].

The installation of HPs in multi-family houses, a growing trend in Sweden, is leading to an increase in the peak load heat demand for DH companies. To understand what PM is needed to harvest flexibility in the secondary system (i.e., using a HP) to benefit the primary system (i.e. DHN), particularly when a building owner has a HP installed, is important. DH companies need to be proactive and engage in dialogue with customers that have or are about to invest in a HP. Operational and investment arrangements of the HP installation can reduce the risk of HP as DH technology. In this paper, two questions of research have been studied:

**Research question 1.** What PMs are most effective (e.g., cost effective and/or able to reduce CO2 emissions compared to a base case) when a building owner has an HP installed?

**Research question 2.** How does the risk exposure of DH companies shift when HPs in secondary systems are resorted to as DH technology?

In section 2, the methods applied to perform the analyses, formulas for simulations and the cases studied are presented. In section 3, the results are outlined. In section 4, the results are discussed. The paper is ended by a concluding section 5.

### 2. Method

A PM is one component in a BM. PM configuration is decisive for business model revenue generation. Our point of departure has been to identify what configuration of PM is most efficient in terms of cost savings and reduction of CO2 emissions. Next, the efficient configurations were used to show what kind of BM concepts are needed to match the efficient PM configurations. Hence, the scope of the paper is to identify the efficiency of alternative PMs and based on results, identify relevant BM risk characteristics.

Two cases have been studied (2.1). A quantitative analysis has determined what PMs are efficient for harvesting flexibility (2.2–2.3). A qualitative method has been used to identify how the risk exposure of DH companies shifts (2.4).

#### 2.1. Cases

To quantify the value of the flexibility (electricity consumption and CO2 impact) two Swedish sites were studied: Eskilstuna and Borås. Both sites encompass a residential building equipped with a HP. Operational and technical data were collected from the sites for a time period of 3 years (2019–2021). The flexibility options include the switching between DH and HP and leveraging the thermal inertia of buildings. The analysis was performed at the Business-to-Business level (building owner & DH company). Technical specifications are summarised in Table 1.

#### Case 1. Eskilstuna

The annual heat demand is 200 MWh, the HP has an installed electric capacity of 3.5 kW at an average coefficient of performance (COP) of 3. The HP covers 10% of the building’s peak demand and approximately 40% of the annual heating demand. The DH production consists of a combined heat and power (CHP) plant and a heat-only boiler (HOB), both fuelled by wood chips, complemented by an accumulator tank. Other boilers are also connected to the network: fired by bio- and fossil oils; these plants are peak load units.

#### Case 2. Borås

The annual heat demand is 60 MWh, the HP has an installed electric capacity of 2.3 kW and a COP of 4. The HP covers 20% of the building’s peak demand and approximately 80% of the annual heating demand. The DHN is powered by a new CHP plant fuelled by wood chips in combination with an older CHP plant (four different boilers, two of them use waste as fuel and the other two wood chips). There are also several pellets- and bio-oil-fuelled peak boilers and an accumulator tank.

#### 2.2. Demand/Supply balance

A service (in this paper referred to as “digital tool”) was developed combining the flexibility potential of the enabling technologies. It optimises multiple parameters of heat supply and demand, all managed through a cloud-based platform. It contains data on production unit availability, fuel and electricity prices, heat demand, and available flexibility. Mixed-integer non-linear programming (MINLP) was performed targeting to minimise operational costs of HP-DHN system. On the supply side, several plans were generated including production plans (indicating which production units should operate at specific hours) and storage plans (guiding the operation of hot water storage tanks). On the demand side, a demand flexibility plan was generated.

The digital tool diverges from the existing business logic of DH
companies, the product logic, which revolves around delivering and being compensated for delivering a specific heat volume. The traditional DH objective involves expanding the DHN by increasing customer numbers or overall consumption (leveraging economies of scale). Historically, interaction between DH company and their customers has been limited. However, the introduction of the digital tool transforms this dynamic. DH companies must transition from delivering a single product (heat) to offering a system solution that integrates both primary and secondary energy systems. Two different BMs for HP inclusion are tested. Fig. 1, describes the existing DH and HP utilisation approach (top part of the figure), and the new, integrated system (bottom part of the figure).

The digital tool resorts to 4 key stakeholders: the provider of the digital tool, an aggregator, the DH company, or the building owner. The digital tool supplier provides the DH company with software and system for balancing heat demand and supply (at a cost). Data essential to the process are sourced (by the digital tool supplier) from an aggregator. The aggregator collects data from consumers at the building level, (e.g., building owners) and feed them to the demand-side of the balancing service. With this input, the DH company makes operational plans that harmonise supply and demand, a task executed by the digital tool. Signals indicating the utilisation of assets (flexibility) are either conveyed through the aggregator or the DH company to the building owner who, subsequently, acts in response to the signal. In Fig. 1, BM1 reflects a BM scenario where a party other than the DH company manages the HP, while BM2 depicts a BM scenario where the HP is operated by the DH company.

It is presumed that the building owner, aggregator and DH company are all driven by commercial incentives for engaging in the HP-DHN integration. In Table 2, we outline what responsibilities the stakeholders can take in a HP-DHN integration system.

Table 2

<table>
<thead>
<tr>
<th>Stakeholders’ responsibilities in a HP-DHN integration system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment in the digital tool</td>
</tr>
<tr>
<td>DH company</td>
</tr>
</tbody>
</table>

As depicted in Table 2, the DH company is presumed to invest in the digital tool, while various stakeholders have the potential to invest in and operate the HP. The rationale behind a building owner’s investment in a HP is to maintain control over the secondary system, thereby allowing control over indoor comfort for tenants. An aggregator might choose to invest in a HP if granted operational rights, effectively positioning itself as an active influencer of energy consumption. A DH company’s investment aims at enhancing the efficiency of both primary and secondary systems, consequently reducing the risk of their DHN becoming a peak load solution only. Although a joint ownership is feasible, such introduces another layer of complexity. For example, such an arrangement might require accommodating different parties with different payback criteria. Shared operational responsibility is not seen as feasible as it is challenging enough to have one party efficiently responding to signals of the tool. Therefore, the concepts of shared ownership and operation are excluded from the BM discussions in this paper.

2.3. Quantitative analysis of price model efficacy

A PM assessment was conducted in four steps: (i) data collection and modelling, (ii) optimisation, (iii) comparison to base case and (iv) sensitivity analysis. Through an iterative approach that alternated...
between data collection and modelling, the model was fine-tuned to align with the available data, enabling the representation of appropriate PMs. By comparing the results to a baseline scenario, the advantages and savings derived from the demand-side optimised operation were identified for different PMs. In the baseline scenario, HP functioned as a baseline for the buildings' heat demand, reflecting the current operational state of both cases. This baseline scenario served as a point of reference for evaluating the improvements resulting from demand-side optimisation. A sensitivity analysis encompassing various price components closed the quantitative analysis.

2.3.1. Possible price models

An extensive literature review was undertaken to understand the factors influencing flexibility within DHNs [43]. To enhance this understanding through empirical insights, a survey was designed and distributed to seven Swedish DH companies. This survey aimed to understand the most efficient PM configurations for flexibility from the practitioner’s perspective. All participating companies indicated that an energy-related component was pivotal, which could assume either a fixed or variable nature. Furthermore, the inclusion of a dynamically changing price component over time was recommended. A combination of a fixed annual fee alongside a fixed or variable energy price was pointed out as a candidate of relevance to test. Survey findings emphasised the significance of factors beyond conventional elements in the context of HP-DHN integration. Particularly, the ability to reduce peak loads (referred to as “power”) was important. Other price structures such as marginal pricing and time-of-use (TOU) were also included inspired by the results of literature review. A comparative analysis was conducted between the conventional constituents of DH PMs and different combinations of the power-related components (Table 3). The prices in Table 3 encompass the cost of heat delivered to customers, thereby accounting for transmission, distribution, and heat loss.

The conventional PMs (including “fixed price”, “fixed price + tariff”, “seasonal price”, “time-of-use price”, and “marginal price”) consist of a fixed tariff part which is paid by the consumers per year (e.g. “fixed price + tariff” and “marginal price”) and an energy price component measured and paid per kWh. Depending on the price strategies, some DH companies prefer to apply a zero fixed tariff combined with a variable energy price, illustrated in models such as “seasonal price” model and “time-of-use” PMs. In such models, energy prices fluctuate across different seasons and time periods. Conversely, some DH companies prefer a fixed tariff combined with a fixed energy price, seen in the “fixed price” and “fixed price - tariff” models. Another approach entails a fixed tariff combined with a variable energy price, aligning with production costs, as observed in the “marginal price” model.

The flexibility-addressing PMs (including “power1”, “power2”, “power3”, and “power + fee”) consist of more than just fixed tariff and energy price components; they also incorporate a capacity fee. This fee can be calculated in different ways. In this study, three different ways are proposed: selecting the top 3 peaks of hourly averages over the past 12 months, top 3 peaks of daily averages over the last 12 months, and the top 3 peaks of hourly averages from the previous month.

Considering the variability in the magnitude of different price components collected from the PM survey, a sensitivity analysis was performed by recalculating the baselines and the optimisations while introducing a 10% variation in all price components.

2.3.2. Price models analysed

The first step was to analyse the economic and environmental aspects at the system level. To accomplish this, production data were collected, and a model was developed for calculating the marginal costs (MC) and marginal emissions (ME). The production unit that had changed its production most recently was assumed to be the marginal production unit. If the changes for multiple units coincided, the unit with the highest MC was assumed to be the marginal production unit. The MC and ME were calculated by collecting available techno-economic parameters for each production unit in both sites. For the carbon emissions, an average emission factor for electricity was used. This factor served as a general approximation and does not exactly mirror the emissions stemming from electricity generation. Depending on the electricity production mix, import and export per hour, the values differ. It is important to note that utilising a higher resolution for electricity emissions could lead to even greater emissions reductions.

The MC and ME were calculated for each hour (t) during the studied period using equations (1) and (2). In equation (1), $C_{\text{fuel}}$ denotes fuel costs in SEK/kWh (Exchange rate: 1 € = 10,5 SEK approximately) for the production unit $t$, $C_{\text{O&M}}$ denotes operation and maintenance costs in SEK/kWh for the production unit $t$, $H_{\text{increase}}$ denotes the increase in heat demand (kWh/h), and $C_{\text{electricity}}$ is the electricity spot price in SEK/kWh. The power-to-heat ratio $a$ denotes the share of electricity produced for each share of heat, where 0 means that no electricity is produced and 1 means that electricity and heat production are the same. This assumption is intentionally conservative and for the purpose of simplification. The efficiency ($\eta$) varies among different heating technologies and different loads of the production unit.

$$MC_u(t) = \frac{C_{\text{fuel}} + C_{\text{O&M}}}{\eta_u(t)} \cdot H_{\text{increase}}(t) - a_u(t) \cdot C_{\text{electricity}}(t) \cdot H_{\text{increase}}(t)$$

### Table 3

<table>
<thead>
<tr>
<th>Price model</th>
<th>Fixed tariff (SEK/year)</th>
<th>Energy price (SEK/MWh)</th>
<th>Power tariff (SEK/kW)</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional 1. Fixed price</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Fixed price + tariff</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Seasonal, differing in winter and summer:</td>
</tr>
<tr>
<td>Winter: Oct–Apr</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer: May–Sep</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seasonal price</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Time-of-use (TOU)</td>
<td>Y</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer: May–Sep</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak: 07–11 = 17–22</td>
<td></td>
<td></td>
<td></td>
<td>Variable energy price, dependent on production cost.</td>
</tr>
<tr>
<td>5. Marginal</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexibility- Addressing 6. Power1</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Intervals:</td>
</tr>
<tr>
<td>Y &amp; Y Y Y Y Y Y Y Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Power3</td>
<td>Y</td>
<td>Y</td>
<td></td>
<td>Intervals, same as &quot;Power1&quot;:</td>
</tr>
<tr>
<td>Top 3 peaks of hourly averages last 12 months.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Power + fee</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Intervals, same as &quot;Power1&quot;:</td>
</tr>
<tr>
<td>Top 3 peaks of hourly averages last 12 months.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[ \begin{align*}
ME_a(t) = \frac{E_{\text{fuel},a}}{\eta_a(t)} \bullet H_{\text{increase}}(t) - \alpha_a(t) \bullet E_{\text{electricity}} \bullet H_{\text{increase}}(t)
\end{align*} \]  

(2)

In equation (2), \( E_{\text{fuel},a} \) represents the emission factor in kg CO2eq/ kWh fuel of the specified fuel for the production unit and \( E_{\text{electricity}} \) is the average emission factor for electricity in kg CO2eq/kWh. In practice, implementing this method on a larger scale, encompassing numerous buildings, would require initiating a new production unit. This, in turn, would result in start-up costs and associated emissions. However, in this study, the marginal increase in heat demand was presumed to be accommodated through thermal energy storage. Consequently, the production unit that most recently underwent modifications continued to represent the marginal unit.

With the baselines established and marginal pricing in place, the demand-side optimisation was modelled for different PMs. The optimisation refers to that numerical calculations run to find the minimal cost of satisfying the buildings’ heat demand for different PMs. The optimisation focuses on the system level, aiming to minimise the cost of the HP-DHN system. The optimisation software package used for this task was the open-source tool PYOMO [44] together with MINLP solver MindyPy, that combines the linear solver CBC [45] and nonlinear solver Ipopt [46].

The optimisation problem solved is described in equations (3)–(7) but this general optimisation is modified to suit individual PMs. Equation (3) represents the objective function of the optimisation. In it, the sum of the DH cost (\( C_{\text{dh}} \)), the cost of operating the HP (\( C_{\text{hp}} \)), the fixed cost (\( C_{\text{fixed}} \)) and the power tariff (\( C_{\text{power,i}} \)) for each day \( i \) of the year are minimised. The HP, DH and power tariff costs depend on the DH (\( x_{\text{dh},i} \)) and electricity (\( x_{\text{el},i} \)) consumption for all hours belonging to day \( i \). \( \tau \) denotes the average value.

\[ \begin{align*}
\min_{\tau_{\text{dh}},\tau_{\text{el}}} & \quad C_{\text{dh}}(\tau_{\text{dh},i}) + C_{\text{hp}}(\tau_{\text{el},i}) + C_{\text{fixed}} + C_{\text{power,i}}(\tau_{\text{dh},i}) \\
& \quad i \in \{0, 1, \ldots, 364\}
\end{align*} \]

(3)

Equation (4) describes the DH costs for a whole day containing \( N \) hours by summing up all DH consumption (\( x_{\text{dh},i} \)) at hour \( k \) multiplied by the hourly heat price (\( C_{\text{heat,i}} \)).

\[ C_{\text{dh}} = \sum_{k=1}^{i+N} x_{\text{dh},i} \bullet C_{\text{heat,i}} \quad i \in \{0, 1, \ldots, 364\} \]

(4)

Equation (5) describes the cost of HP operation for a whole day containing \( N \) hours by summing up the hourly electricity consumption \( x_{\text{el},i} \) and the hourly electricity spot price \( C_{\text{el},i} \).

\[ C_{\text{hp}} = \sum_{k=1}^{i+N} x_{\text{el},i} \bullet C_{\text{el},i} \quad i \in \{0, 1, \ldots, 364\} \]

(5)

Equation (6) shows average peak demand (\( P_{\text{a},i} \)) of the top 3 peaks (\( x_{\text{peak},p} \)) up until (and including) day \( i \), using the average values based on the averaging period \( j \), starting from \( s1 \) averaging periods back with the averaging time \( T \).

\[ P_{\text{a},i} = \frac{\sum_{k=s1}^{i+T} x_{\text{peak},p}}{3} \]

(6)

Equation (7) determines the cost of the power tariff, where the peak price (\( C_{\text{peak}} \)) depends on the power interval of the average peaks.

\[ \begin{align*}
C_{\text{peak}} = C_{\text{p},1} & \quad 0 \leq P_{\text{a},i} < P_1 \\
C_{\text{peak}} = C_{\text{p},2} & \quad P_1 \leq P_{\text{a},i} < P_2 \\
C_{\text{peak}} = C_{\text{p},3} & \quad P_2 \leq P_{\text{a},i}
\end{align*} \]

(7)

This objective function satisfies the constraint that heat demand (\( y_{\text{heat},i} \)) is met at all hours \( k \) of the year, which is described in equation (8) where COP\(_3\) is the HP’s COP.

\[ \begin{align*}
x_{\text{dh},i} + x_{\text{el},i} \bullet \text{COP}_3 = y_{\text{heat},i} \quad i \in \{0, 1, \ldots, 364\}
\end{align*} \]

(8)

The constraints in (9) and (10) apply to all equations. \( \varepsilon_{\text{max}} \) is the maximum hourly electricity consumption.

\[ 0 \leq x_{\text{el},i} \leq \varepsilon_{\text{max}} \quad i \in \{0, 1, \ldots, 364\} \]

(9)

\[ 0 \leq x_{\text{dh},i} \quad i \in \{0, 1, \ldots, 364\} \]

(10)

An important assumption is that DH system can consistently meet the entire energy demand of the building. The optimisation process yielded the most cost-effective blend of DH and heat generated by the HP, considering a 24-h optimisation horizon.

2.4. Qualitative analysis - risk exposure

The foundation of the supply/demand balancing service is built on efficient operational response to flexibility signals, which refers to the switch between DH and HP systems. This implies that an effective operation of the HP is necessary. To explore risk exposure shifts for DH companies based on varying HP operation setups, two distinct BM concepts have been formulated. One concept reflects the HP operation conducted by an external party such as an aggregator or building owner (referred to as BM1 in Fig. 1). The second concept reflects HP operation conducted by the DH company itself (referred to as BM2 in Fig. 1).

The owner of the HP can impact how it is operated, therefore who invests in the HP is of importance in understanding if the service is efficient or not. A systematic evaluation has been conducted to assess the DH company’s risk exposure under the two BMs and diverse HP ownership arrangements.

3. Results

The main results from different PMs (3.1) and the analysis of risk exposure (3.2) are provided.

3.1. Results from price models

3.1.1. DH consumption

To understand how different PMs capture flexibility, it is important to see how it affects the energy source use (over time and volume). A comparison of the utilisation of heat energy sources is presented in Fig. 2 for Eskilstuna and Fig. 3 for Borås. In Fig. 2, PMs featuring power tariff and marginal pricing are the ones that affect the usage of energy sources the most. For Eskilstuna, the shift from HP to DH increased up to 40% of the DH consumption, by optimising the operations. A higher increase for “power 1”, “power 2” and “power 3” occurred in 2019 because the building had higher peak demand during spring and autumn compared to other years. Consequently, this facilitated greater DH demand without increasing the power tariff, which in turn led to higher load shifts. In 2021, across all PMs, there was a shift towards greater DH usage due to higher electricity prices during that year.

Similar results are found for Borås, where “power + fee” and
“marginal pricing” PMs stand out (Fig. 3). Optimising the HP operation after those PMs leads to a 75%–150% increase in DH use, satisfying 35%–55% of the heat demand.

The HP-DHN shift takes place when flexibility is available. In Figs. 4 and 5, the energy shifted from HP to DH is averaged for the hours of the day when the shift occurs. Concurrently, these figures also illustrate the normalised marginal production costs on an hourly average basis, depicting varying production costs corresponding to different PMs.
These two figures highlight that the average marginal production cost is comparatively lower during the mornings and evenings, which coincides with peak load periods. This is attributable to CHP plants generating electricity and subsequently selling it at higher electricity prices. During these periods, the production units attain their maximum load, enhancing plant efficiency. It’s important to note that despite these efficiencies, the overall production costs tend to be higher.

In Fig. 4, only the years 2019 and 2020 display energy shifts in conjunction with PMs, featuring a power tariff component and marginal pricing, aligning with the results shown in Fig. 2. No correlation is found between load shifts and marginal production costs for any PM in 2019 and 2020. However, a correlation emerged for the year 2021, where high electricity prices coincide with low marginal production costs. This was anticipated, especially for the marginal pricing PM. Nonetheless, the absence of this correlation could potentially be attributed to a higher COP when the temperature differences are lower (i.e., during the day). Therefore, during these periods, a price increase gives DH an advantage.

Similarities are found in the load shifts in Eskilstuna (Fig. 4) and Borås (Fig. 5), where the electricity prices coincide with the marginal production costs. Both cases for 2021 show larger variations in DH marginal production costs due to larger variations in electricity prices.

3.1.2. Electricity consumption

The increase in DH consumption corresponds to a decrease in energy supply from the HP. To show how this flexibility can be harnessed within the electricity grid, the variations in electricity demand throughout the day are presented in Fig. 6 for Eskilstuna and Fig. 7 for Borås. In Fig. 6, it is shown that the PMs including a power tariff component, and marginal pricing models decrease electricity use. This could lead to an average reduction in electricity consumption of approximately 5%–60% of the installed electric HP capacity over a day. Interestingly, the utilisation of the electric HP capacity is lower in the mornings and evenings, coinciding with electricity peak loads periods. This phenomenon can be attributed to the higher electricity price during these hours, which, in turn, leads to higher HP operating costs.

In Fig. 7, similar results as observed in Eskilstuna. The average reduction ranges between 0% and 60% for all PMs and throughout the day. Evident spikes appear during the mornings and evenings. This finding can be explained by the COP of the HP in this building being more stable than in Eskilstuna, allowing the electricity price signals to be clearer without the impact of a variable COP.

3.1.3. Economic impact

In Figs. 8 and 9, the economic results from the demand-side optimisation are presented by examining the differences between the baseline and the optimised case.

In Fig. 8, customer costs decrease the most for the PMs, including a power tariff component and marginal pricing. During 2021, with high electricity prices, the impact of some PMs is up to 20% of the heating costs. Additionally, the transition from HP to DH is seen to enhance the revenues for the DH company, with potential increments of up to 40% with both HP and DH employed. The costs for the extra produced heat are based on the MC of heat production. For 2021 the heat production costs decreased, due to the assumption that CHP plants in the network increase their electricity production with the same power-to-heat ratio when increasing their heat production and sell electricity at a high price.

System costs encompass expenses related to operating both HP and DH heat production, and these expenses also exhibit a reduction of 25%.
The DH company profits have positive values for all PMs and years, except for "power + fee" (2019). There is a potential to enhance profits by approximately 0%–30%. However, in the case of the "power + fee" model within the DH pricing structure, the company’s profits are negative. This implies that the energy price set for this PM was inadequately low to cover the production costs linked to the increased heat demand.

Similar results (Fig. 9) are observed for Borås but at different percentage values than Eskilstuna. Notably, the marginal pricing and "power + fee" models, characterised by cost-effective and competitive pricing, contribute to escalated DH usage, with increase ranging from 20% to 55%. The increase led to differences in company costs by around 400%. The building owner can save up to 40%, and the DH company can save up to 100%. Among the various models, the lowest system costs are associated with PMs that integrate a power tariff component and marginal pricing models.

In considering the economic impact, it is important to remember that the analysis is made on HP operation (as per equation (3)). The fact that an initial investment required for procuring the HP is not included in the assessment of economic effects.

### 3.1.4. Carbon emissions

The impact from demand-side cost-optimised heat supply on carbon emissions is dependent on whether the electricity has a higher emission factor than what is emitted from the produced DH. This article does not consider the emissions from electricity. Figs. 10 and 11 show the carbon emission differences. In Fig. 10, the PMs with a power tariff component and marginal pricing PMs lead to the most substantial reductions in carbon emissions across all years, resulting in a 3% reduction. This finding means that the marginal production unit has a lower emission factor compared to electricity in Eskilstuna.

In Fig. 11, the best PM results lead to 0.4% reductions, while the least favourable scenarios exhibit potential increase of up to a 3.5% increase in carbon emissions. The most noticeable distinction between Eskilstuna and Borås is that some PMs result in increased emissions. In this case, it is the "power + fee" and marginal pricing PMs that lead to increased carbon emissions. The reason is that the comparatively low energy price of these PMs triggers a significant volume of load shifts from HP to DH, thereby increased the hours during which the load shift occurred. During these hours, the waste incinerating CHP often was at peak load (resorting to fossil fuel peak load units), which has higher emission factor than electricity.

### 3.2. Business model risk exposure analysis

#### 3.2.1. Business model 1- HP operation- party external to the DH company

The first BM revolves around optimising the use of the service (as a "product" itself). The DH companies sell a bundled package of hardware and software to the customers. Derived from actual cases, two sub-concepts are developed based on distinct choices. As discussed earlier, either the aggregator or the building owner could respond to the flexibility signals by managing heat demand through the control of HPs (turning the HP on and off). The motivation behind an aggregator controlling HPs is to extend its business beyond data extraction and demand optimisation, stepping into the realm of system operation. The motivation behind a building owner controlling HPs is to control the flexibility signals by managing heat demand through the control of HPs (turning the HP on and off). The motivation behind a building owner controlling HPs is to control the flexibility signals by managing heat demand through the control of HPs (turning the HP on and off).
The building owner takes charge of HP operation.

The risks are the result of information asymmetry, where different stakeholders do not have full information on each other’s activities. The risks can be mitigated by different parties assuming the investment risk of the HP. The DH company or the building owner can assume the investment risk of the HP. When the DH company invests in a HP, the risk of poor operation diminishes, because the DH ownership ensures that the HP operates in a way that is beneficial to the DH system (which applies to the HP operation of both aggregator and building owner). On the other hand, if the building owner invests in the HP, it surrenders the right to control the way the HP is operated, but still has a say in its use which mitigates the risk of an aggregator unintentionally operating the HP inefficiently. The party taking on the investment has a further exposure to risk: if the combination of an HP and a DHN means that the HP is operated fewer hours per year than if it is used without DH its payback is prolonged. Such an effect needs to be counteracted by the total DHN increasing its efficiency, thereby compensating for the longer payback of the HP. In the two cases studied, a HP was already installed but in other situations where the building owner is considering investing in a HP, it is important to understand what risk exposure the HP ownership leads to.

A feasible combination of an investment and operational arrangement for the BM is listed below (Table 4).

3.2.2. Business model 2- HP operation by the DH company

In a performance contract model (also referred to as “heat as a service”), DH companies sell an agreed level of warmth rather than a volume of heat. The contract ensures the customers are satisfied with the provided comfort level and heating bill.

For a service offer, the DH company operates the HP, which cancels the risk of a non-response to the operational signal. The DH company operating the HP mitigates the risk that building owners do not trust the operation of it: it is assumed that the HP is operated in an optimal way for the DHN. The customer perception of losing control over the tenant comfort remains. In this case, the two risks that were significant in BM 1 (HP not operated by the DH company) are no longer important. Instead, the building owner accepts the supply/balancing service and is willing to invest in the flexibility gain (owning the HP or not). The risk in focus is the investment risk. For the DH company, outsourcing the ownership of the HP is interesting if the control over its operation remains with the DH company.

If the DH company both invests in the HP and operates it, all the equipment risk is assumed. The DH company improves the efficiency if its DHN and the building owner is given an incentive (lower price for example) for agreeing to the implementation of the supply/demand balancing service. This necessitates trust between the DH company and the building owner as the latter might perceive a risk to lose control over tenant comfort.

If the aggregator invests in the HP but the DH company operates it, the risk perceived by the customer is similar to the DH company owning the HP case. It is in the interest of the DH company that it operates the HP for DHN efficiency, and the building owner has no reason to assume that the ownership of the aggregator negatively impacts the operation of the HP. A concern to lose control over the comfort of the tenants might remain.
Fig. 7. Yearly average change in electricity use over different hours of the day in Borås.

Fig. 8. Impact on various economic values from different PMs used for demand-side optimisation in Eskilstuna.
If the building owner invests in the HP, there is still a need for mutual trust. The output of the collaboration is a win-win solution where the DH company operates the HP efficiently. The perception of not having control over the comfort of the tenants is reduced (Table S).

Feasible combinations of investment and operational arrangements for the business concept are shown below.

Compared to the conventional BM, the DH company includes a HP in its technology supply and operates an asset owned by the building.
owner, the aggregator or the DH company itself. The fact that the HP is operated by the DH company shifts the boundary condition of the BM going beyond the substation of the building. The DH company assumes the operational risk of the HP. If the DH company owns the HP, it also assumes investment risk. The alternative with the least risk exposure for the DH company is where the building owner is interested in the demand/supply service and invests in the HP, but the DH company operates it.

4. Discussions

The supply/balancing service (the digital tool) works. Large-scale HP-DHN combinations can provide a balance between district energy markets and electricity markets through fuel flexibility in heating. It can create a competitive advantage by leveraging cost-effective economies of scale. In Sweden, some building owners use both HP and DHN. In such cases, only when the HP capacity is insufficient to meet the full building heating demand, DH is used. This means DH is used to meet peak demand, which challenges the DHN. It appears relevant for DH companies to engage in dialogue on the possibility to resort to existing HPs (invested in by building owners) or to jointly implement such a solution. When a building owner has an HP installed, a discussion on how to balance the possibility of a longer payback period of the HP when used in combination with DH is relevant. The building owner should be compensated from the flexibility gains generated from the HP-DHN setup.

HP inclusion can reduce CO2 emissions. Most of the PMs led to reductions. Shifting from electricity to DH (CHPs on biofuels) led to an improvement in carbon emissions. But it is not always the case. In a DHN where waste incineration or fossil oil is used as the main heat source, emissions increased when the heat source is shifted from HP to DH. So, for green flexibility CHPs on biofuels are important.

Operational and investment choices impact the risk exposure of the DH company. Two risk exposures need to be managed: operational and investment risk. Reviewing the risk exposure of various arrangements of operator and investor in the HP, it is identified that for some configurations there is a risk that the building owner is not interested in flexibility. Other configurations have a more beneficial risk exposure where the best one from the point of view of a DH company is to operate the HP (removing the risk of flexibility signals not being captured) and to have an engaged building owner by the latter investing in the HP. Thereby the DH company does not have any investment risk but still controls the operation of the HP. PMs designed and tested are complex and necessitate a building owner well familiar with how DH and HPs work. It is a challenge to simultaneously introduce complex PMs into BMs as the risk exposures shift from what both the DH company and customers are used to. A main driver for increased risk exposure is information asymmetry between partners which adds a risk premium to using the HP as a DH technology.

Other insights. The efficiency of resorting to HPs as heat source in DHNs will be linked to the heat supply in the DHN. Therefore, the local circumstances will determine how efficient a replication is.

Strengths and limitations of this study. We identify that the main strength is that we have, with real life data as a basis, been able to shed new light on how PMs can be established to foster flexibility between primary DHN systems and secondary HP systems. The integration of both technical and economic disciplines in our approach allows us to provide meaningful insights to this real-world challenge. The gains from enhancing DHN- HP flexibility can be significant and should be considered both by DH companies and owners of local HPs.

The main limitations of the study are that there is a bias in the results since we have studied two cases, rather than a full population. Furthermore, the results are influenced by certain assumptions, one example is the assumption of a constant efficiency of the HP. Hence the results are not fully reflecting reality. Therefore, the findings should be interpreted with a degree of caution, understanding that they offer a conceptual framework rather than a precise reflection of reality.
5. Conclusions

Revisiting the research questions, the PMs that best captured flexibility were the “power + fee” and marginal pricing models, primarily due to the significant load shift from HP to DH. Among those, the marginal pricing model demonstrated the highest success in notable reductions in both system and customer costs.

In terms of risk exposure, addressing operational risk and the investment risk is important to ensure an efficient HP-DHN integration. For DH companies, the risk of not having the operational control of the HP is the most important one. Lowest risk for DH companies is to manage the HP operation but have another party invest in the HP. How to manage HP investment in buildings is important to DH companies to manage HP investment in buildings is important to DH companies and DH companies have another party invest in the HP. How to manage HP investment in buildings is important to DH companies and DH companies have another party invest in the HP. How to manage HP investment in buildings is important to DH companies.

Table 4
The scenarios for HP investments, HP operations, DH companies’ risks and the consequences, based on business concept 1.

<table>
<thead>
<tr>
<th>HP Investment</th>
<th>HP Operation</th>
<th>DH Company Risk</th>
<th>Risk Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aggregator</td>
<td>Aggregator</td>
<td>Building owner does not trust aggregator</td>
<td>Building owner is not interested in supply/demand balancing service</td>
</tr>
<tr>
<td>Building owner</td>
<td>Building owner</td>
<td>Building owner does not respond to flexibility signal</td>
<td>Building owner is less interested in the supply/demand balancing service</td>
</tr>
<tr>
<td>Building owner</td>
<td>Aggregator</td>
<td>Building owner may feel the control over tenant comfort is jeopardised and thus must handle complaints</td>
<td>Business partner (aggregator) may find it demotivating for high investment on HPs unless convinced about its profitability potential</td>
</tr>
<tr>
<td>DH company</td>
<td>Aggregator</td>
<td>Building owner does not trust aggregator</td>
<td>Building owner is not interested in the supply/demand balancing service</td>
</tr>
<tr>
<td>Building owner</td>
<td>Building owner</td>
<td>Building owner may feel the control over tenant comfort is jeopardised and will have to handle complaints</td>
<td>Building owner motivation for investment in HPs without controlling it is low</td>
</tr>
<tr>
<td>DH company</td>
<td>Building owner</td>
<td>Building owner does not respond to flexibility signal</td>
<td>Building owner is less interested in the supply/demand balancing service</td>
</tr>
<tr>
<td>DH company</td>
<td>Building owner</td>
<td>Building owner may feel the control over tenant comfort is jeopardised and will have to handle complaints</td>
<td>Business partner (aggregator) may find it demotivating for high investment on HPs unless convinced about its profitability potential</td>
</tr>
</tbody>
</table>

Table 5
The scenarios for HP investments, HP operations, DH companies’ risks and the consequences, based on business concept 2.

<table>
<thead>
<tr>
<th>HP Investment</th>
<th>HP Operation</th>
<th>DH Company Risk</th>
<th>Consequence of Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH company</td>
<td>DH Company</td>
<td>Building owner does not trust DH company</td>
<td>If the building owner is not interested in the supply/demand balancing service, then the investment in the HP is forgone</td>
</tr>
<tr>
<td>Building owner</td>
<td>DH company</td>
<td>Building owner may feel the control over tenant comfort is jeopardised and thus must handle complaints</td>
<td>If HP operation fails, it negatively impacts the tenants and the efficiency of the DHN</td>
</tr>
<tr>
<td>Building owner</td>
<td>Building owner</td>
<td>Business partner (aggregator) may be demotivated to invest in HPs unless convinced about its profitability potential</td>
<td>Building owner is less interested in the supply/demand balancing service</td>
</tr>
<tr>
<td>Building owner</td>
<td>Building owner</td>
<td>Building owner may feel the control over tenant comfort is jeopardised and thus has to handle complaints</td>
<td>Building owner is less interested in the supply/demand balancing service, then the investment in the HP is forgone</td>
</tr>
</tbody>
</table>

both in the dialogue with customers that own a HP already and with customers considering investing in an HP. If such an investment occurs without DH company involvement, the building owner tends to reduce resort to DH for peak load heat provision. Inclusion of HPs in secondary systems appears to be a strategy for maintaining DH market share.

CRediT authorship contribution statement

Kristina Lygnerud: Conceptualization, Formal analysis, Funding acquisition, Writing – review & editing. Ying Yang: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The results in the paper come from the Flexi-Sync project acknowledged in the paper. In addition, the analysis on risk exposure was added to this paper, this part is therefore novel.

We have no conflicting interests to declare.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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