Flexi-Sync

Flexible energy system integration using
concept development, demonstration and replication

D5.1 ANALYSIS OF PRICE MODELS

VERSION 1

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Co-creating with partners that help to understand the needs of relevant stakeholders, we team up with intermediaries to provide an innovation eco-system supporting consortia for research, innovation, technical development, piloting and demonstration activities. These co-operations pave the way towards implementation in real-life environments and market introduction.

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EXECUTIVE SUMMARY

Flexibility in the energy system has been studied previously but few results have been implemented in district energy (DE) pricing models. This means that pricing models are not reflecting the system costs, making them less efficient than they need to be. We have studied if and how price models (PM) of DE company can harvest flexibility. A systematic literature search with content analysis of resulting scientific peer-reviewed publications and project reports have been performed. Thereby, the different PMs which have been described in the literature have been aiming at generating knowledge about DE flexibility. Preliminary findings show that most DE grids are slow to recognise and capture flexibility that can be catalysed through end-users, thermal inertia, heat pumps, and other. Similarly, DE companies employ a marginal cost logic to determine whether flexibility should be operationalised, and often their business models and PMs are not oriented towards expressing that value logic to their customers. We identify that there is a potential for DE companies to further capitalise on flexibility in the energy system. By inclusion of flexibility incentives in PMs, a win-win can be established by cutting operational costs for the DE provider and energy consumption of the end-user.

This deliverable also includes a case study, where different PMs have been analysed to see how well they capture flexibility in buildings where both heat pumps and district heating are available as heat technologies. To do this, we apply a demand-side cost optimisation for different PMs, based on real data collected from buildings in two of the Swedish demo-sites, Borås and Eskilstuna. Furthermore, we compare the optimisation results to a baseline scenario which uses the heat pump as baseload for the building's heating demand. Finally, the changes in energy use, economic savings and profits, and carbon emissions are analysed.

The general findings and conclusions from the study imply that higher competitiveness between district heating and heat pump operations with a high temporal resolution reflecting the real costs of heat production would enable flexibility for both the power system and the district heating network and could also lead to lower costs for end-users as well as larger profits for DE companies. Reductions in carbon emissions could be achieved depending on the emission factor of the fuel used in the marginal heat production unit, it would however be interesting to study how a variable electricity emission factor could affect these results.

ACRONYMS

BM	Business model
CA	Content Analysis
CHP	Combined Heat and Power
COP	Coefficient of performance
DE	District Energy
DEH	Direct Electrical Heating
DH	District Heating
DHC	District Heating and Cooling
FET	Flexibility-Enabling Technologies
HOB	Heat only boiler
HP	Heat Pumps
LCOH	Levelised Cost of Heat
MC	Marginal costs
ME	Marginal emissions
MINLP	Mixed integer nonlinear problem
PM	Price model
4GDH	4th generation district heating

1 INTRODUCTION

1.1 Background

The term flexibility as derived from “flexible” is defined as “a ready capability to new, different or changing requirements”. Within the context of energy, flexibility refers to the ability to speed up or delay the injection or extraction of energy into or from a system [1]. The flexibility of energy could be provided from demand-side, supply-side, or grid-side. As a cost-effective means of enabling increased integration of renewable energies, demand-side flexibility captures significant interest from both industry and academia. In terms of demand-side flexibility, the flexibility of energy could mean availability of energy through energy efficiency or some other form of excess energy, shifting of energy or power demand, and reduction of energy or power demand [2].

About 50% of the energy consumed in buildings is for heating and cooling [3]. District Heating (DH) and Cooling (DHC), or more commonly denoted as district energy (DE), is important since it has the potential to use local fuel or heat resources that would otherwise be wasted, to satisfy local customer demands, and has high efficiency [4]. DE has expanded in multiple parts of the world, especially in Europe (DH accounts for 10% of the total heat supply in Europe and is expected to increase to 50% by 2050 [5]) due to its ability to use excess heat. The central idea of DE is utilising a centralised heating/cooling system to distribute heat/cooling to building thermal systems, through a distribution network of pipes as a local marketplace [6] [4].

Currently, low temperature, often referred to as 4th generation district heating (4GDH), is gaining a hold on traditional DHC systems around Europe because of its ability to include low-temperature heat sources, which by extension is conducive to include renewable-based heating and electricity [6]. This system, integrated with renewable heat sources, involves the interaction of smart thermal systems and smart grids, and is considered as one of the cheapest ways to reduce carbon emissions. This technology shift highlights the need for flexibility in the DE sector. Flexibility in the DE sector will encourage the inclusion of low-temperature heat sources, and intermittent renewable energy into the DE grid. Moreover, heat pumps (HP) can be an asset providing demand response to the system. Similarly, flexibility in the DE sector will also aid in energy system integration across the heating and cooling, and the power sectors, thus leading to higher penetration of renewable energy sources, lower investment and grid costs, and less environmental impact [7].

Flexibility can also be a significant source of revenue and profit for both DE grid owners, operators, customers, and end-users, due to increased energy efficiency which cuts down on the expenses for peak-load heat plants, lower overall maintenance costs, etc. Furthermore, flexibility in the DE sector can catalyse and motivate for higher integration in both design and operation of other various energy systems such as biofuels, hydrogen, etc.

Price model (PM) explains how a business gets revenue and continues its existence and defines its relationship with its customers. In many countries, DE businesses are traditional in their outlook and are slow to change their business models (BMs) and PMs, especially when it comes to capturing and making use of flexibility in the DE grid. Despite massive research on the ongoing transformation in DE sector, the question of how current PM capture flexibility remains largely untapped and needs to be redesigned to adapt to a different heat supply mix and provide flexibility.

1.2 Aim of the report

This report aims to narrow the gap by posing the following research questions:

- How has DE flexibility been captured in existing PM?
- What are possible alternatives of PM to better capture DE flexibility?

We are looking to contribute to existing knowledge on how PM in the DE sector capture flexibility, and to take the initial steps in exploring how PM may need to change to critically increase flexibility in the DE sector.

2 METHODOLOGICAL APPROACH

2.1 Approach for reviewing price models

In this study, the method of Content Analysis (CA) is used to review the existing PMs, which were published in peer-reviewed journals on the topic of DE flexibility provision.

CA is the analysis of the implicit or explicit content of any communicated material through classification, tabulation, and evaluation of its key symbols and themes, in order to ascertain its meaning, according to [8]. This approach allows researchers to compress large bodies of textual data into fewer categories, elicit meaning from the data, and draw realistic conclusions from it. Thus, in our study, we analysed the contents of selected scientific literature in order to investigate how DE flexibility has been captured in existing PM and what the possible alternatives of PM are to better capture DE flexibility.

Hsieh and Shannon [9] showed that there are three general approaches to CA such as conventional, directed, and summative. In this study, we chose the directed CA approach, given the brevity and clarity of our research questions. The directed CA process generally consists of the following steps: formulating a research question (in this case, *what are the price models in the DE sector and how they capture flexibility*); selecting the sample; categorisation of data; outlining and implementing the coding process; and analysing the results of the coding process.

2.1.1 Selecting the literature

A systematic, multiple, and concurrent literature search was carried out on SCOPUS with multiple combinations of selected keywords. Given that the focus of this study is threefold, that is flexibility, PMs, and DE (and/or DHC), it was important that an exhaustive search was conducted to not miss any relevant literature. Similarly, a manual Google search was also executed for the same combinations of keywords and relevant scientific reports and conference articles which were not listed in the SCOPUS search results were also included in our literature selection. The detailed list of combination of search keywords executed in SCOPUS and Google are given in Table 1

Table 1 The list of search keywords and combinations.

Keyword 1	Logic Operator	Keyword 2	Logic Operator	Keyword 3
Pricing policies	AND	DE		
PM	AND	DE		
Pricing strategies	AND	DE		
Pricing policies	AND	DHC		
PM	AND	DHC		
Pricing strategies	AND	DHC		
PM	AND	DH	AND	Flexibility
PM	AND	DE	AND	Flexibility
PM	AND	DH	AND	Markets

PM	AND	DE	AND	Markets

These searches were executed in September and October 2020. The results were manually scrutinised by the authors, and the relevant literature were selected. Only literature dealing with flexibility and PMs were selected. Our clear selection criteria meant that in total 38 different articles of literature were chosen to be part of our study. For brevity's sake, we will refer to these articles of literature as articles (art.) from hereon in.

2.1.2 Categorisation of data

The authors implemented a heuristic-based categorisation of data, to answer the research questions elaborated in section 1.2. The authors extracted data from the articles under three broad themes, which are

- Characterisation of flexibility,
- PMs, and
- how they capture flexibility

Characterisation of flexibility is the analysis of how the articles have described flexibility in the different DE grid and sector. The characterisation of flexibility is further categorised in the following three categories: availability of heat/energy, shifting of the heat or power demand in the grid, and reduction of heat or power demand in the grid.

The second theme of PM and how they capture flexibility are extracted from the selected articles and analysed. The different types of connections to PM and flexibility in the DE grid as detailed in the articles are analysed and presented.

2.1.3 Coding process

We manually implemented the coding process, by reading and deductively analysing the selected articles under the categories specified in section 2.1.2. We extracted the data and compiled them in spreadsheets for each of these articles one after the other, and subsequently analysed them. In some instances, the authors who carried out the coding process and deductively analysed the extracted content had to use their judgment as to what constituted a PM.

2.2 Approach for price model analysis

The quantitative analysis performed in this study specifically targeted PMs' impact on demand-side flexibility from multi-family dwellings through load shifting between DH and HP, without affecting the total heat demand of the building. To quantify the utility and savings that could be achieved from this kind of flexibility, a case study was performed for two different Swedish demo-sites: Eskilstuna and Borås, where all results were evaluated against two separate baseline cases for both cities. By using real operational and technical data collected from these demo-sites, two realistic cases could be built, which will be specified in section 5.1.

The PM analysis was carried out in four steps: data collection and modelling, optimisation, comparison, and sensitivity analysis. By iterating between data collection and modelling, the developed model could be adjusted to the available data, and suitable PMs could be tested and implemented in the model. The optimisation step followed, where numerical calculations were run to find the minimal cost of satisfying the buildings' heat demand for different PMs. By comparing these results to a baseline case, in which the HP operated as a baseload for the buildings' heat demand, the utility and savings derived from the demand-side optimised operation could be identified and compared while using different PMs. To understand how different costs of DH could affect these specific cases, a sensitivity analysis of price components' magnitudes concluded the work of the case study.

2.2.1 Data collection and modelling

The work of identifying PMs that capture flexibility in section 2.1 was continued by sending out a survey to DE companies involved in the Flexi-Sync project. The survey included questions on which PM configurations they would like to see included in this study. After collecting the results from the survey, a mathematical model of a heating system was developed, reassuring that the heat demand of the building always was met by either the HP, DH system or both under certain technical limitations. Furthermore, different PMs were modelled and applied to the unoptimised operation of the heating system to establish a baseline.

To be able to perform an analysis regarding the economic and environmental aspects on a system level, production data for both demo-sites were collected and a model for calculating the marginal costs (MC) and marginal emissions (ME) was developed. 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 emissions were calculated by assuming and collecting available techno-economic parameters for each production unit in both demo-sites.

These MC and ME were calculated for each hour (*t*) during the studied time period using the following two equations (1) and (2), in which $C_{fuel,i}$ denotes fuel costs in SEK/kWh (Exchange rate: 1 € = 10,5 SEK approximately) fuel for production unit *i*, $C_{O\&M,i}$ the operation and maintenance costs in SEK/kWh fuel, $H_{increase}$ the increase in heat demand (kWh/h) and $C_{electricity}$ is the electricity spot price in SEK/kWh. The power-to-heat ratio, α 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. The efficiency (η) varies for different heating technologies and different part-loads of the production unit.

$$MC_i(t) = \frac{C_{fuel,i} + C_{O\&M,i}}{\eta_i(t)} \cdot H_{increase}(t) - \alpha_i(t) \cdot C_{electricity}(t) \cdot H_{increase}(t) \tag{1}$$

$$ME_i(t) = \frac{E_{fuel,i}}{\eta_i(t)} \cdot H_{increase}(t) - \alpha_i(t) \cdot E_{electricity} \cdot H_{increase}(t) \tag{2}$$

In (2), costs have been changed to emissions and in this case $E_{fuel,i}$ represents the emission factor in kg CO2eq/kWh fuel of the specified fuel for the production unit and $E_{electricity}$ is the average emission factor for electricity in kg CO2eq/kWh. In reality, the need to start up a new production unit would occur if this method were to be applied to a larger number of buildings, which would lead to start-up costs and emissions. In this study, however, the small amount of heat increase was assumed to be covered by thermal energy storage, and therefore the unit that last changed its production was still considered the unit on the margin.

Furthermore, the methodology of collecting and the sources used to collect specific data are presented in Annex A

2.2.2 Optimisation

With the baselines established and a marginal pricing in place, the demand-side optimisation was modelled for different PMs. The optimisation software package used for this task was the open-source tool PYOMO [10] together with the mixed integer nonlinear problem (MINLP) solver Mindtpy, which in turn combines the linear solver CBC [11] and nonlinear solver ipopt [12].

The general optimisation problem solved for all cases is described in equations (3)-(7) but this general optimisation is specifically modified to suit each individual PM. Equation (3) represents the objective function of the optimisation. In this equation, we want to minimise the sum of the DH cost ($C_{dh,i}$), the cost of operating the HP ($C_{hp,i}$), the fixed cost (C_{fixed}) and the power tariff ($C_{power,i}$) for each day (i) of the year. The HP, DH and power tariff costs are dependent on the DH consumption ($\bar{x}_{dh,i}$) and the electricity consumption ($\bar{x}_{el,i}$) which includes a value for all hours belonging to day i.

$$\min_{\bar{x}_{el,i},\bar{x}_{dh,i}} C_{dh,i}(\bar{x}_{dh,i}) + C_{hp,i}(\bar{x}_{el,i}) + C_{fixed} + C_{power,i}(\bar{x}_{dh,i}) \quad i \in \{0,1,\dots,364\} \tag{3}$$

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

$$C_{dh,i} = \sum_{k=i}^{i+N} x_{dh,k} \cdot C_{heat,k} \qquad i \in \{0,1,\dots,364\}$$

(4)

Analogously, equation (5) describes the cost of HP operation for a whole day containing N hours through a summation of the hourly electricity consumption $x_{el,k}$ and the hourly electricity spot price $C_{el,k}$.

$$C_{hp,i} = \sum_{k=i}^{i+N} x_{el,k} \cdot C_{el,k} \qquad i \in \{0,1,\dots,364\}$$

(5)

Equation (6) calculates the average peak demand ($P_{dh,i}$) of the top 3 peaks (x_{top3}) 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.

$$P_{dh,i} = \frac{\sum_{k \in x_{top3}} x_{dh,k}}{3} \qquad \begin{gathered} x_{top3} \in \underset{x_{top3} \subset \sum_{l \in j} \frac{x_{dh,l}}{|j|}, |x_{top3}|=3}{argmax} \sum_{x \in x_{top3}} x \\ j \in \{[(i+1) - s1 \cdot T, (i+1) - (s1-1) \cdot T], \dots, [i+1-T, i+1]\} \\ i \in \{0,1,\dots,364\} \end{gathered}$$

(6)

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

$$C_{power,i} = C_{peak} \cdot P_{dh,i} \qquad \begin{gathered} \begin{cases} C_{peak} = C_1, & 0 \le P_{dh,i} < P1 \\ C_{peak} = C_2, & P1 \le P_{dh,i} < P2 \\ C_{peak} = C_3, & P2 \le P_{dh,i} < P3 \\ C_{peak} = C_4, & P3 \le P_{dh,i} \end{cases} \\ i \in \{0,1,\dots,364\} \end{gathered}$$

(7)

This objective function needs to satisfy the constraint that the heat demand ($y_{heat,k}$) should be met at all hours (k) of the year, which is described in equation (8), where COP_k is the HP's coefficient of performance (COP).

$$x_{dh,k} + x_{el,k} \cdot COP_k = y_{heat,k} \qquad \begin{gathered} k \in \{i, i+1, \dots, i+N\} \\ i \in \{0,1,\dots,364\} \end{gathered}$$

(8)

The following physical constraints in (9) and (10) also apply to all equations.

$$0 \le x_{el,k} \le el_{\max} \qquad \begin{gathered} k \in \{i, i+1, \dots, i+N\} \\ i \in \{0,1,\dots,364\} \end{gathered}$$

(9)

$$0 \leq x_{dh,k} \qquad k \in \{i, i+1, \dots, i+N\} \quad i \in \{0,1,\dots,364\} \tag{10}$$

The general optimisation problem could be adjusted to suit all the studied PMs in this study. The output of the optimisation gave the cost optimal combination of DH and heat generated by the HP with an optimisation horizon of 24 hours for the specified PM.

2.2.3 Comparison and sensitivity analysis

The comparison consisted in studying the differences between the baselines and the optimisations and finally the pricing models in relation to each other. The aspects considered during the comparison were changes in the heat energy source, electricity consumption, carbon dioxide emissions, costs, revenues and profits of customers and DE company, and system costs. Due to the insecurity of the magnitude in the different price components that were collected from the PM survey, a sensitivity analysis was performed by repeating the baselines and the optimisation with a 10% variation for all price components.

3 EXISTING PRICE MODELS IN DISTRICT ENERGY SECTOR

The findings of the literature review part are presented in this section. First, the general characteristics of the articles, in terms of their geographical scope and the different Flexibility-Enabling Technologies (FET) they have included are presented, followed by how the articles have characterised flexibility. Subsequently, the PMs considered and analysed in the articles are presented.

3.1 General characteristics and characterisation of flexibility

The geographical scope of the articles was overwhelmingly European in focus, either as Pan-European [13] [14], or as Nordics [15] [16] [17] [18], or as individual/dual countries in Europe. Given the preponderance of DHC in Europe, this is not surprising. In the case of [19], the article was country-agnostic, while a case study was based in China, and the article [20] did not specify which country it is based on. The general characteristics of the articles are given in Annex B

An inventorying of FET within these articles showed a wide variety of technologies being used as FET, such as HP [13] [21] [14] [18] [22], thermal storage [13] [14] [15] [17] [18], thermal inertia of buildings [23] [24], Combined Heat and Power (CHP) [25] [26] [27] [23] [28], Direct Electrical Heating (DEH) [29] [30], electric boilers [13] [15] [16] [17], other boilers [31] [32], and end-user behavior [33]. Articles [34] [35] [36] did not specify any FET in their studies, but rather analysed flexibility in a general way.

All the 38 articles included in this report has characterised flexibility as availability of heat/energy. Out of them, 12 articles considered flexibility as shifting demand using FET like heat storage or demand-side management while 16 articles considered flexibility as reducing demand/peak power via FET like HP and energy efficiency improvements. Among those 16, seven articles, e.g. [37] [38] [23], included both demand reducing and shifting as flexibility.

In addition to how the articles captured flexibility, we were also interested in investigating if the captured/exploited flexibility was transferred or transformed into a price or cost shift, in the analyses. In investigating this, we found that a total of 28 articles included an evaluation of the economic value created by flexibility through one or several of the mechanisms mentioned, mainly looking at how it enabled cutting costs from the systems perspective. However, in a few cases, it has also been translated into changes in the price of DH and/or from the point of view of a specific stakeholder.

In 18 of the articles, other aspects of flexibility were highlighted and the predominant themes among these other aspects were the interaction with the electricity system and the possibility for FET to cut peaks in electricity.

Four articles considered flexibility as energy availability through energy efficiency improvements on the customer side [39] [26] [40] [33] and discussed the need for the development of PM to share the value created and thereby incentivise the customers. The proposed PM included different types of motivational tariffs [40] (return temperature, the cooling through the substation, water volume per supplied heat, etc.), basing DH price on MC [26], and implementing a PM based only on actual use (power, flow, and energy components) not including any fixed fees [33].

From the 38 articles, it was evident that the availability of energy was the aspect of flexibility currently dominantly in focus in scientific literature. This also reflected in the current state of PM to capture flexibility.

Only about half of the articles analysed (21) included the impact of using the available heat/energy to reduce demand and/or the possibility of timing of the use to shift the peak-demand. These are important benefits of FET and capturing them ought to be central to the development of PM.

3.2 Pricing logic of heat

Pricing of heat and energy, either in terms of what the DE company charges to its consumers, or the price the DE company offers to pay the prosumers for flexibility provision, is an integral part of its BM. Here, it is important to understand that one is the price charged by the DE company to the heating or cooling they sell, and the other the price they offer to the prosumers for the heat provided by the prosumers. So, in effect, the pricing logic of heat or energy could be what the DE company sells for, and what the DE company pays.

When analysing the articles for how the heat or energy are priced in the case of the DE grid, either nominally or for the inclusion of heat from the prosumers, there are five different ways in which heat or energy is priced. These are:

- Operational parameter-based pricing
- MC pricing
- Seasonal pricing
- Levelised cost of heat (LCOH) pricing, and
- Combination with other price logics

The MC pricing is the pricing logic, which is prevalent in most of the articles. Articles such as [28] [41] [18] [38] [18][42] [31] used MC pricing. In some of the articles, MC was also referred to as operational cost. The significant thing to note is that in MC pricing logic, the investment cost of the heating technologies both in the DE system side and prosumer-side were not considered when the feasibility assessment of prosumer integration was made. In fact, in the articles which used qualitative methods, they explicitly mentioned that using a MC pricing logic disincentivised investment in prosumer-side technologies, since investment costs were often neglected in the MC pricing, which also determined what the DE company was willing to pay the prosumer for supplied heat [21] [43].

In order to counter this, [31] used both a MC pricing and LCOH logic in its study, to look at prosumer integration in a DE system. In this study, the MC price of the DE system unit was compared to the LCOH of the prosumer-side technology to calculate the operational time and monetary benefits.

Seasonal tariffs were used in [44] [45], where the price of heat energy supplied by the DE company was seasonally priced. In the case of [45], the LCOH of the price of the heat also had a seasonal component. In the case of [28] [41], the MC pricing logic was also complemented by studying how it compared to some fixed reference prices. These fixed reference prices consisted of fixed fees or defined as functions of outdoor temperature. These comparisons were made to investigate whether different pricing logics accrue different profits and monetary benefits for the DE company, the prosumers, and the system, in totality. Operational parameter-based pricing was implemented in [46], where the price to be paid to the prosumer was dependent on the temperature and flow rate of their heat supply. This pricing logic was different from all the other articles analysed in our study and places the emphasis on the quality of the heat.

3.3 Price models capturing flexibility

Out of the 38 articles analysed in this study, 24 articles explained different PMs. It needs to be stated here that some articles considered in this study use cost and price interchangeably. While some articles explicitly consider pricing and tariffs (e.g. [44] [22] [47]), the others consider cost and implicitly assume that the cost is transferred as price to the customer.

When analysing the articles which consider cost of DE, two distinct PM themes emerge. These themes are MC PM (e.g. [48] [49]) and LCOH PM (e.g. [20] [32]), as aforementioned. Both these PM themes capture flexibility in the DE grid in their own way.

The MC PM captures flexibility under hourly DE operational conditions and thus only captures the marginal operational cost of heat through different FET. If one FET is less costly for a particular hour, the DE grid, operator or even the customer is incentivised to use that FET, as opposed to the traditional heating technology. The MC PM captures the actual cost of generating a unit of heat, (or cooling) but does not capture the rest of the fixed costs. In other words, MC based PM captures the energy cost of DE, and in some cases the flow cost, but not the load or demand cost [29]. MC based PM captures operational flexibility in the DE grid but according to studies which used LCOH PM, MC PM fails to capture the investment and other long-term costs of the FET, which are associated with the load/power of heat that is supplied to the customer.

Thus, [29] [30] said that a LCOH PM accurately represented the dynamic costs of flexibility and thus captures the value of flexibility better, when compared to the MC PM. In a LCOH PM, the long-run investment and other fixed costs were accounted for as well, over the lifetime of the FET, and enabled faster payback times of investments.

Five of the 24 articles considered both MC and LCOH PM in their analysis (e.g. [50] [51]). In the case of [50] [37] the MC PM was used to look at the flexibility when the DE system was integrated with the electricity/power system through either CHP or other electricity-using (power-to-heat) FET. Thus, the use of both MC and LCOH PM were useful to capture cross-sectoral flexibility (DE and power) specially to determine the cost-optimal heat supply dispatch, given lower MC of electricity. In [35] [51], the studies used both MC and LCOH to capture the full costs of DE grid, especially to consider "dynamic load, energy and fixed cost" components.

In five of the articles, actual tariffs (and their PMs) were discussed. Out of these, [22] [47] proposed a seasonal PM (winter and summer differentiated), where the tariffs were based on the month of heat supply, and in the case of [22], the study also proposed coupling it with price based on peak-demand as well. Here, the tariff model was connected to the dynamic heat demand cost that was accounted for in a LCOH PM. In [17] an energy and fixed fee tariff PM was discussed so as to capture flexibility, whereas in [40] a tariff PM based on three levels of peak-demands per month were analysed, in order to exploit the flexibility in the DE sector. The reasoning for a seasonal and month-differentiated tariff was that in winter month generation of heat is more costly, since peak thermal units may need to be operated by the DE company. Thus, if flexibility can be exploited to reduce the peak-loads and peak energy demand, then the cost of heat should be lower.

The analysis above shows that both the MC and LCOH based PM may capture flexibility in the DE grid, through their underlying logic of calculation. While MC PM captures the value of flexibility in a shorter temporal resolution, and the decision to exploit the FET is on a short-run timescale, the LCOH PM captures flexibility over longer time-range, specifically in the order of magnitude of the lifetime of the different FET [29] [28].

3.4 The marginal cost based pricing for capturing flexibility

In the case of MC PM, the analyses with regards to the cost and revenue perspective were done with respect to the DE company and the variable cost of heat (and in the case of [25], variable cost of electricity) determined the operation of the FET and other heating technologies [52]. But these articles also connected the PM to the BM, with regards to how the benefits of used flexibility may be shared or distributed.

In Article [40], the HP and thermal inertia of the buildings proved cost-effective enough to be used as a flexibility source and provided revenue for the DE company. In this case, innovative BM was analysed where the potential FET on the customers' side is used and how these particular FET may provide additional value to the customers. One such solution discussed was the customer buying "heat as a service". This implies that a fee is paid to the DE company for providing heat and hot water throughout the year for a certain price, while the DE company steers and operates the FET on the customer's side. The proposed BM is that the PM eventually reflects the monetary value of flexibility the customer-side FET may provide the DE company. The PM is based on the MC of providing heat, while also simultaneously using the flexibility provided by the combined FET (both on the customer-side and the supply-side), where the DE company determines the operation of the FET on the customer-side.

Similarly, in Article [25], the PM was based on MC of heat. But the actual monetary value of the price or the price level is determined by whether the DE company may use the FET (HP) on the customer-side. These differential price values are proposed as a way of increasing the use of flexibility in both the DE and electricity sector, and as a way of incentivising the customer to use the FET at their end for the benefit of the DE company of in some cases the benefit of the integrated energy system.

3.5 The Levelised Cost of Heat based pricing for capturing flexibility

Both articles [13] [27] proposed LCOH PM to capture flexibility in their analysis. Yet, the LCOH PM proposed were different from each other. In [13] the authors proposed that two different BM may need to be considered by the DE company, especially with corresponding PM depending on whether they are "big" or "small" FET units. In the article CHP was considered a "big" unit and the cost or pricing logic should be geared towards increasing system-wide optimisation of flexibility. The authors analysed the cost savings through power-to-heat FET such as CHP and through the providing services to the power regulating market. On the other hand, the authors analysed the flexibility effect of demand-side HP and thermal storage, which they considered "small" FET units. Additionally, they proposed the PM which consisted of "negative prices, and certificates of credit", especially for small units such as demand-side HP. While the overall PM remained as the LCOH PM, the design of the PM should also include negative prices for heat to the customer, thus enabling using the customers as a "key flexibility resource".

In Article [27], a different LCOH PM was proposed and analysed. The article analysed the need for seasonal and heating demand effect-based PM, considering that heating demand leads to costly investments for the DE company. The PM and pricing logic then effectively translate to flexibility providers (or owners of FET) becoming key resources to a DE company and the DE company's business logic reflecting this.

3.6 The other price models for capturing flexibility

Besides the MC and LCOH PM, there is another PM and BM capturing flexibility which has been proposed and analysed in the selected articles that is worth exploring. Article [40] proposed motivational tariff for return temperature as a PM, especially to encourage low return temperatures and thereby energy efficiency at the customer-side. Similar motivational tariffs can be constructed for flexibility, by reimbursing the end-user for its provided flexibility, either by decreasing its energy use or by shifting it in time or other heat sources. Therefore, motivational tariff goes beyond the categorisation of MC or LCOH and implies a direct incentive to capture the flexibility that may be provided by customers.

In [34], they also proposed “new forms of relationships and new tariff structures aimed at incentivising network friendly behaviours. For example, DH operators have included in their BMs motivation tariffs, periodical audits at the building installations, tailored contracts, counselling services, training of installers”. They propose a motivational tariff, which re-distributes part of the profit of energy efficiency improvement to the customer, as a way of strengthening the business relationship with a key flexibility resource.

4 EMERGING PRICE MODELS IN THE DISTRICT ENERGY SECTOR

In this chapter we have been studying different PMs and components as well as their impacts on consumer end-uses. Several PMs that exist today but have not been discussed before in this deliverable are presented and analysed in this section. The survey that was sent out to different project partner DE companies aimed to find new and emerging PMs that is not very common today and the results obtained will be presented and compared to the previously described PMs.

4.1 Price model examples

4.1.1 Seasonal price and time-of-use price

The seasonal and time-of-use PMs use a time differentiated price either over a season or within the hours of the day, or both. A variable energy price could create incentives for the customer to use DH at times when demand is lower. This can be used by DE companies to avoid peak loads and being forced to start up expensive peak production units. Over seasons, customers have the possibility of reducing their costs by setting a lower indoor temperature or switching to other alternative heat sources. Within the day this becomes harder, and the customer would need heating technology with smart control to be able to respond to the price signals.

4.1.2 Power subscriptions

Power subscriptions can be used to make sure that the customer never uses too much heat at the same time and try to equalise the load during the year. By using a power subscription, the DE company can secure revenues and also keep their operational costs down by not having to start up expensive peak load production units. Power subscriptions do not necessarily lead to lower peak demand, but by adding a penalty fee if the customer overshoots the subscribed level, extra revenues could be used to cover the increased costs. Power subscriptions are easy to understand, but also hard to control if the customer does not have smart heating technologies or actively control the thermostat.

4.1.3 Power tariffs

Using a power tariff component is a way of incentivising the end-user to even out their heat demand and to avoid peaks. The power tariffs can be calculated in several ways, which can be a bit hard to understand for the consumer. Some of the alternative models include a number of averaged top peaks, where the peaks can be averaged over a day, a month or an hour. Power tariffs are good for securing revenue and keeping down production costs and emissions. However, the DH system has good potential of relieving the power system from load during peak hours, which unfortunately often coincide in time. Power tariffs could in that case lead to an increase in electricity use, which could become a problem.

4.1.4 Power signature

Power signature is a price component that could be used by DH companies to charge the customer for their peak heat demand. It is very similar to the subscription component with the difference in how you calculate it. The power signature is calculated by linear regression and inputting the dimensioning outdoor temperature of the DE network. Power signatures are not as intuitive as a subscription level, but they have the advantage that one single peak does not affect the costs that much, which allows the end-user to provide flexibility to the electricity grid if using multiple heat sources.

4.1.5 Return temperature and flow

The return temperature and flow components are used to incentivise energy efficiency in the heat exchanger. This is an efficient way of both incentivising efficiency and securing revenues but could be hard to understand for the customer. Although the customer only needs to understand whether their heat exchanger is efficient or not, which makes it easy to predict the costs of heating.

4.2 Input on price model elements to capture flexibility

The survey was sent out to 7 different DE companies included in this project and 6 of these replied. The input showed that all DE companies, participating in the survey wanted an energy component to be included in their PMs. The energy component could either be fixed or variable, and in this survey 8 out of 14 suggested PMs included a fixed price. 5 PMs were suggested to include a variable price that change over time and one PM included neither. Furthermore, 4 out of 14 PMs were suggested to include a fixed yearly fee in combination with either a fixed or a variable energy price. Another popular price component was the power tariff, which was included in 5 of the 14 PMs. In Table 2, the input from the survey is presented.

Table 2. The input received from the survey sent out to the DE companies.

Price components	Fixed fee	Energy component - fixed	Energy component -variable	Power component	Return temperature	Flow component
Fixed fee	x	2	2	0	0	0
Energy component fixed	2	x	0	3	0	0
Energy component variable	2	0	x	1	0	1
Power component	0	3	1	x	1	0
Return temperature	0	0	0	1	x	0
Flow component	0	0	1	0	0	x

5 ANALYSIS OF PRICE MODELS FOR FLEXIBILITY

5.1 Case study

As mentioned earlier in this report, this study is an attempt to analyse how different PMs capture demand-side flexibility by firstly conducting a literature review, and secondly by analysing different PMs impact on specific cases using real data to achieve a representative model. The two modelled cases represent one building in either Borås or Eskilstuna, where both DH and HP are installed in parallel as heat sources for the buildings. The analysis has been performed over the three consecutive years 2019, 2020 and 2021 to study how variations in weather and electricity prices over years can affect the results. Electricity prices consist of both hourly spot prices and grid tariffs.

5.1.1 Price models

While we discussed the possibility of implementing all different PMs from the survey, it was considered difficult to use the return temperature and flow components in the study due to the lack of data on temperatures and flows, and they were therefore not included in the study. However, the other components of the study could be modelled. To give this work a certain exploratory character, different DH power tariff components, marginal pricing and time-of-use tariffs were included, inspired by the results of the literature review, implemented, and evaluated to see how they perform against more conventional PMs that were proposed in the survey. This resulted in the following PMs being evaluated shown in Table 3.

Table 3. The names and components of PMs that were included in the case studies.

Price model	Fixed tariff (SEK/year)	Energy price (SEK/MWh)	Power tariff (SEK/kW)	Comment
Fixed price	0	950	0	
Fixed price + tariff	10000	600	0	
Seasonal	0	Winter:1000 Summer: 600	0	Winter: Oct-Apr Summer: May-Sep
Time-of-use	0	Winter peak:1050 Winter off-peak:950 Summer:650	0	Winter: Oct-Apr Summer: May-Sep Peak: 07-11 + 17-22
Power1	0	400	0–30 kW: 900 30–100 kW: 750 100–250 kW: 500 250 kW-: 250	Top 3 peaks of hourly average last 12 months
Power2	0	400	0–30 kW: 900 30–100 kW: 750 100–250 kW: 500 250 kW- : 250	Top 3 peaks of daily average last 12 months
Power3	0	400	0–30 kW: 900 30–100 kW: 750 100–250 kW: 500	Top 3 peaks of hourly average last month

			250 kW- : 250	
Power + fee	10000	200	0–30 kW: 900 30–100 kW: 750 100–250 kW: 500 250 kW- : 250	Top 3 peaks of hourly average last 12 months
Marginal	10000	Variable	0	Dependent on production cost

5.1.2 Eskilstuna

The case-specific details for Eskilstuna mainly include what kind of physical conditions apply to the analysed building and what kind of heat production units that are used in the DH network.

The building’s heat energy demand over a year is approximately 200 MWh and the heat is supplied either by the DH network or a HP with an installed electric capacity of 3.5 kW and an average COP around 3, corresponding to 10% of the building’s peak demand and approximately 40% of the building’s energy demand. The DH production in the network consists of a CHP plant and a heat only boiler (HOB), both fuelled by wood chips from logging residue [53], these resources are complemented by an accumulator tank. As mentioned in section 2.2, the accumulators are assumed to cover the extra heat production if the already running plants cannot increase their production, then the costs of producing the stored heat will be accounted for. There are also other heat plants connected to the network, which are fired by bio- and fossil oils, however these plants are mostly used when the demand is remarkably high.

5.1.3 Borås

In Borås, the analysed building has a much lower heat demand of approximately 60 MWh. The HP installed in the building has an electric capacity of 2.3 kW, but a higher and more stable COP at 4. The reason why the COP is more stable in this building is not clear but could either be that the data collection period for the COP was too short to notice any large variations or that the HP has a more stable lower temperature reservoir (e.g., a ground source HP) than in Eskilstuna. This means that the HP can cover 20% of the building’s peak demand and approximately 80% of the building’s energy demand.

The DE network in Borås is mainly powered by a new CHP plant powered by wood chips but is also complemented by an older CHP-plant with 4 different boilers, two of them use waste as fuel and the other two also burn wood chips. Apart from the two CHP-plants, there are also several pellet- and bio-oil fired boilers to cover the peak loads. Borås DE network also has a large accumulator tank.

5.2 Results from price model analysis

5.2.1 District heating consumption

To understand how well the different PMs capture flexibility, it is important to see how it affects the energy source use, both over time and in volume. Capturing flexibility, in this case, means how well the energy source use reflects the system costs. Therefore, a comparison of the heat energy source use is presented in Figure 1 for Eskilstuna and in Figure 2 for Borås. In Figure 1 we can see that the PMs that include a power tariff component and marginal pricing s are the ones that stand out and affect the energy source use the most. For the building in Eskilstuna, the shift from HP to DH increased up to 40% of the building's DH consumption by optimising the operation after different PMs. The reason why 2019 has a higher relative increase for power 1, 2 and 3 is that the building had a much higher peak demand during spring and autumn compared to other years, which allowed higher DH demand without increasing the power tariff component and led to higher load shifts during these periods. 2021 also stands out because all the PMs result in a load shift. This could be explained by the higher electricity prices during this year, leading to the usage of the HP being more expensive than the DH and the model favoured the DH as heat source.

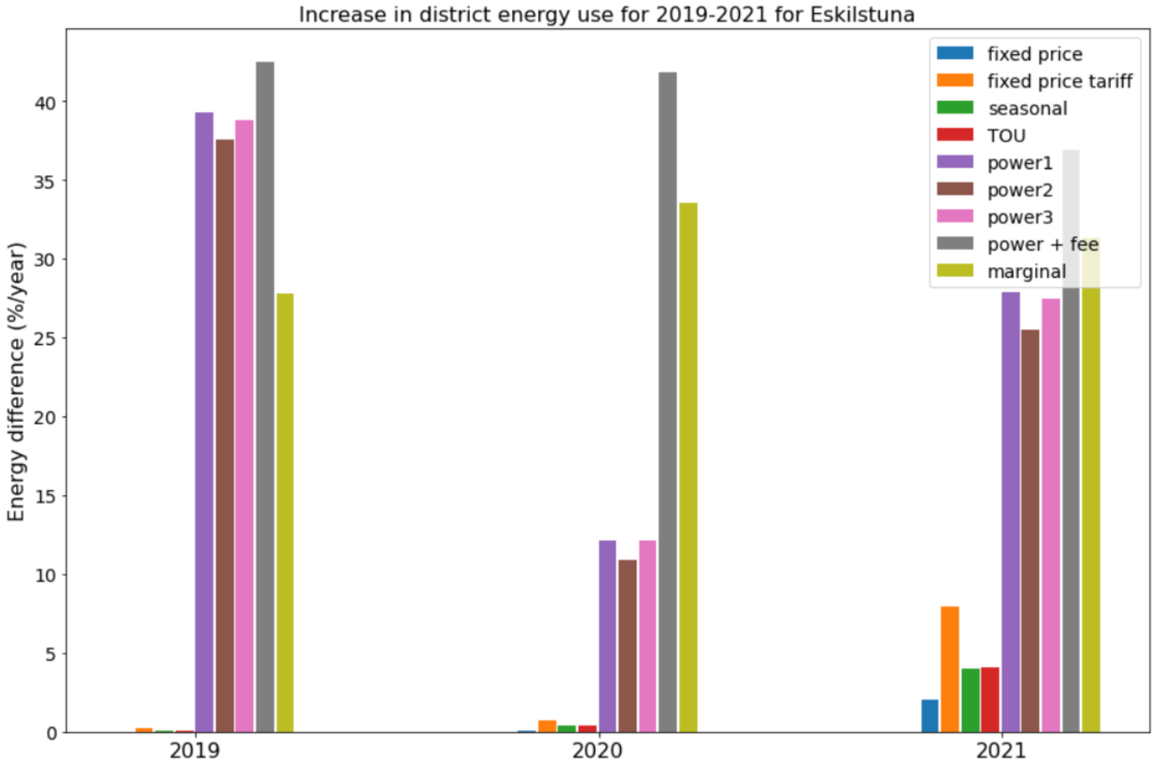

Figure 1. The increase in DE use between the baseline case and the demand-side optimisation for a building in Eskilstuna.

In Figure 2, we can see similar tendencies as for Eskilstuna, where "power + fee" and marginal pricing PMs stand out. In this case, optimising the HP operation after those two PMs can lead to a 75%-150% increase in DH use, reaching approximately 35%-

55% of the buildings total heat demand. The reason why those two PMs shift more load from HP to DH is probably due to the low energy price and increasing their competitiveness against HP.

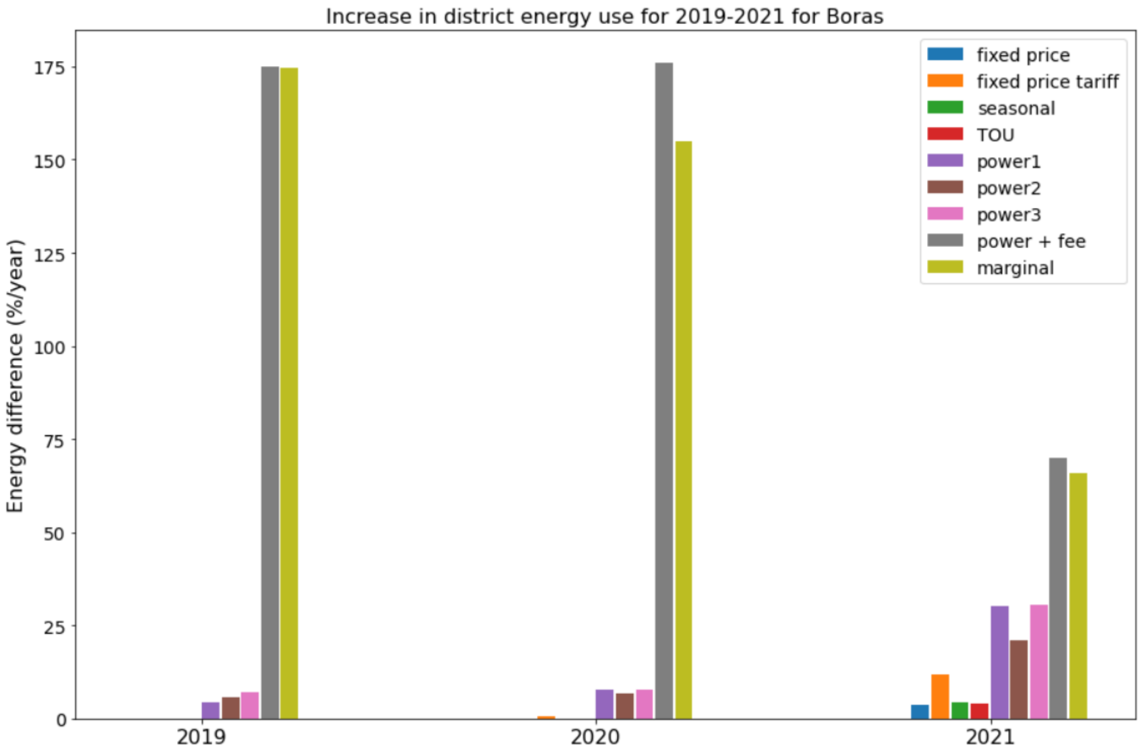

Figure 2. The increase in DE use between the baseline case and the demand-side optimisation for a building in Borås.

It is not only interesting to look at the amount of energy that has been shifted from HP to DH, but also when the energy has been shifted. In Figure 3 and Figure 4, the amount of the shifted energy from HP to DH has been averaged over the hours of the day during which the shift occurs. In the same figures, the normalised marginal production costs are also presented by their hourly average to show how well the different PMs reflect the production costs. In Figure 3 and Figure 4, we can see that the average marginal production cost is lower during the mornings and evenings, which is usually when peak loads occur. The reason why the marginal production costs are lower at these times is probably that the CHP plants produce electricity and can operate at a lower cost by selling electricity during hours with high electricity prices. Another reason could be that the production units reach closer to full load and therefore increase the efficiency of the plant. The total production costs, however, are probably higher during these hours.

In Figure 3, we can see that only 2019 and 2020 have noticeable energy shifts for the PMs including a power tariff component and the marginal pricing, which is in line with the results in Figure 1. There is no clear correlation between load shift and marginal production cost for any of the PMs in 2019 and 2020. For 2021, however, there seems to be a little stronger correlation. But this is probably a result of high electricity prices coinciding with low marginal production costs. For the marginal pricing PM, a clearer correlation was expected, but the reason why that is not the case could be the COP being higher when temperature differences are lower (i.e., during the day), and therefore giving the HP an advantage in the optimisation.

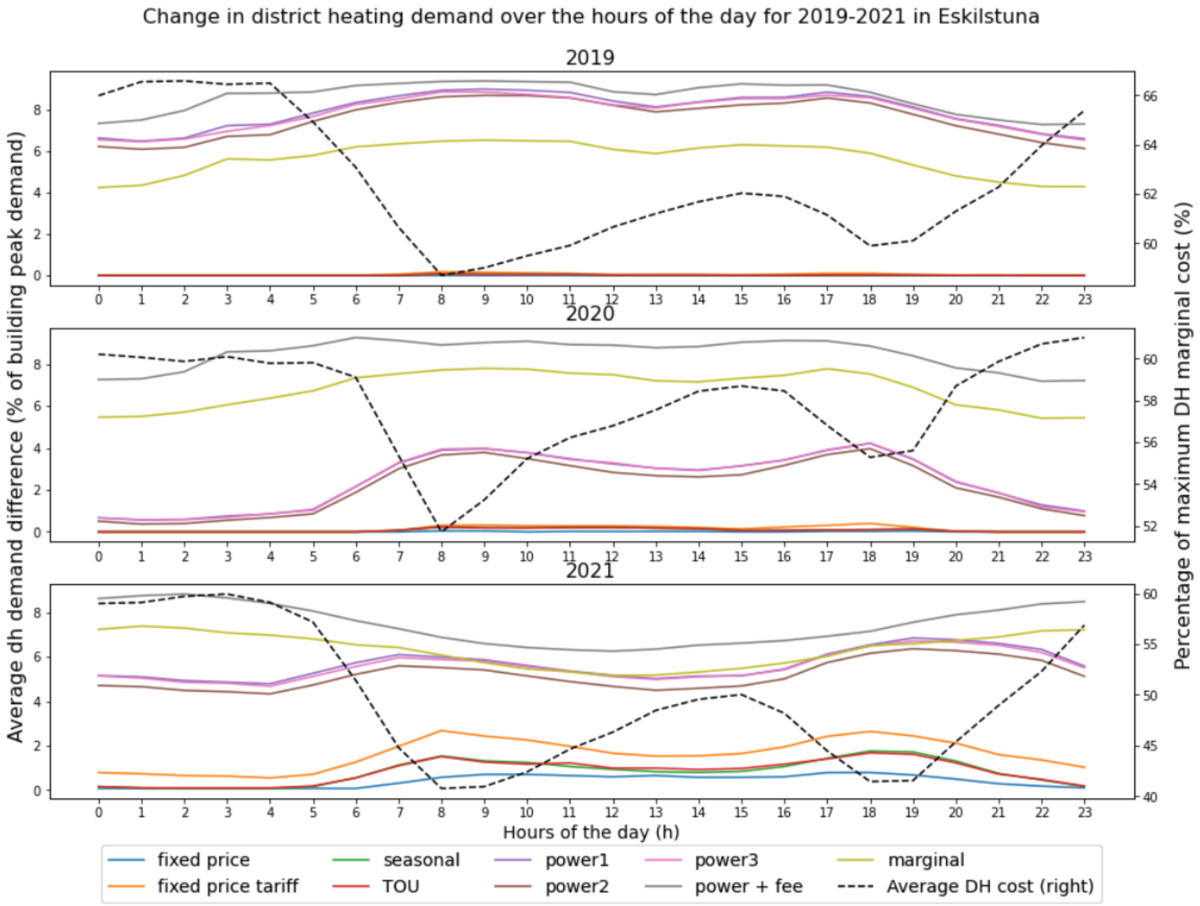

Figure 3. Yearly average change in DE use over different hours of the day in Eskilstuna.

We can see similarities between the load shifts in Eskilstuna (Figure 3) and in Borås (Figure 4) such as the electricity price coinciding with the marginal production cost. For 2021, we can also see larger variations in DH marginal production costs for both Eskilstuna and Borås, which likely depends on the larger variations in electricity price. In Figure 4 it is clearer that the marginal PM reflects the marginal production costs more, but not very much, this is probably due to the HP having a more stable COP.

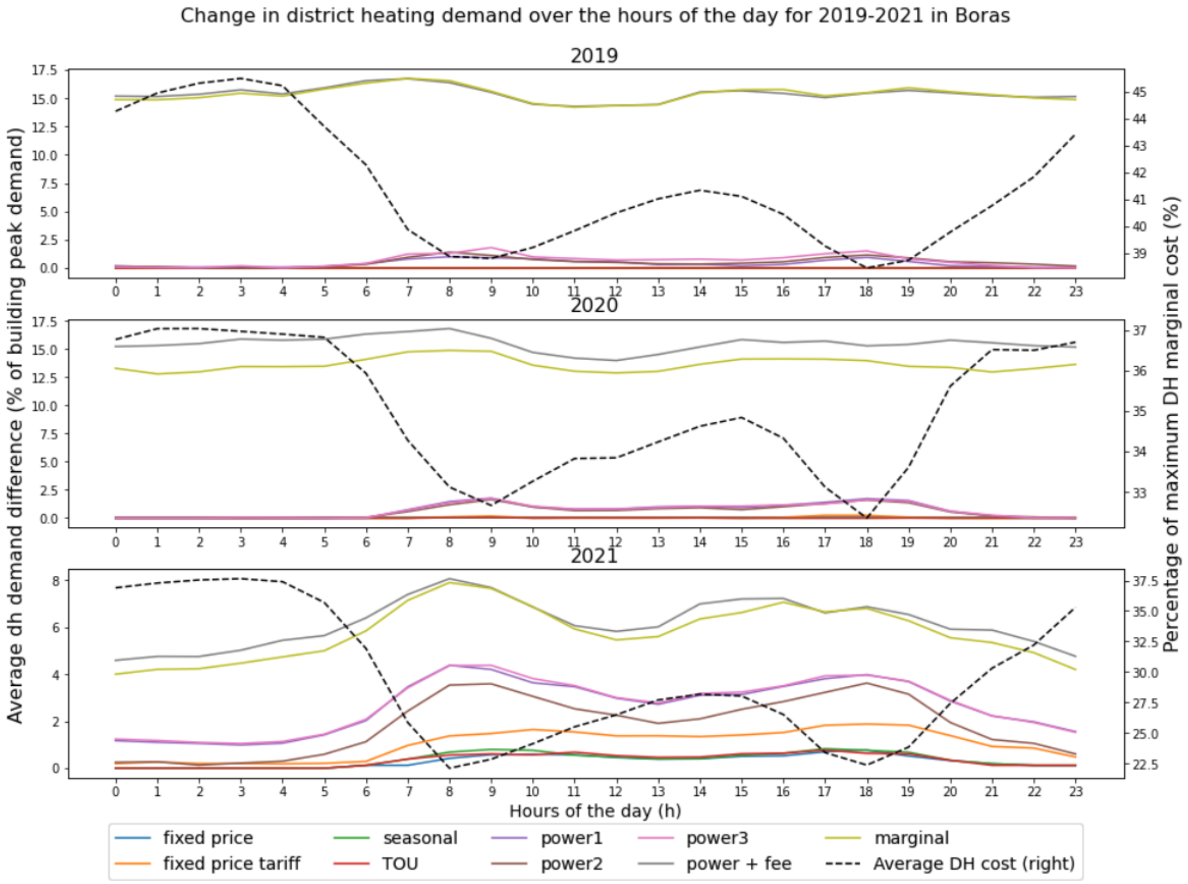

Figure 4. Yearly average change in DE use over different hours of the day in Borås.

5.2.2 Electricity consumption

The increase in DH consumption can also be interpreted as the energy decreased from the HP. To show how this flexibility can be utilised in the electricity grid, the electricity demand change over the hours of the day is presented in Figure 5 for Eskilstuna and Figure 6 for Borås. In Figure 5, it is also clear that the PMs, which include a power tariff component, and marginal pricing models lead to a decrease in electricity use and could result in an average electricity reduction of approximately 5-60% of the installed electric HP capacity at all hours. What is interesting in this figure is that the electric HP capacity utilisation is usually lower in the mornings and evenings, usually when the electricity peak loads appear. This is probably due to the electricity price being higher during these hours leading to a higher HP price.

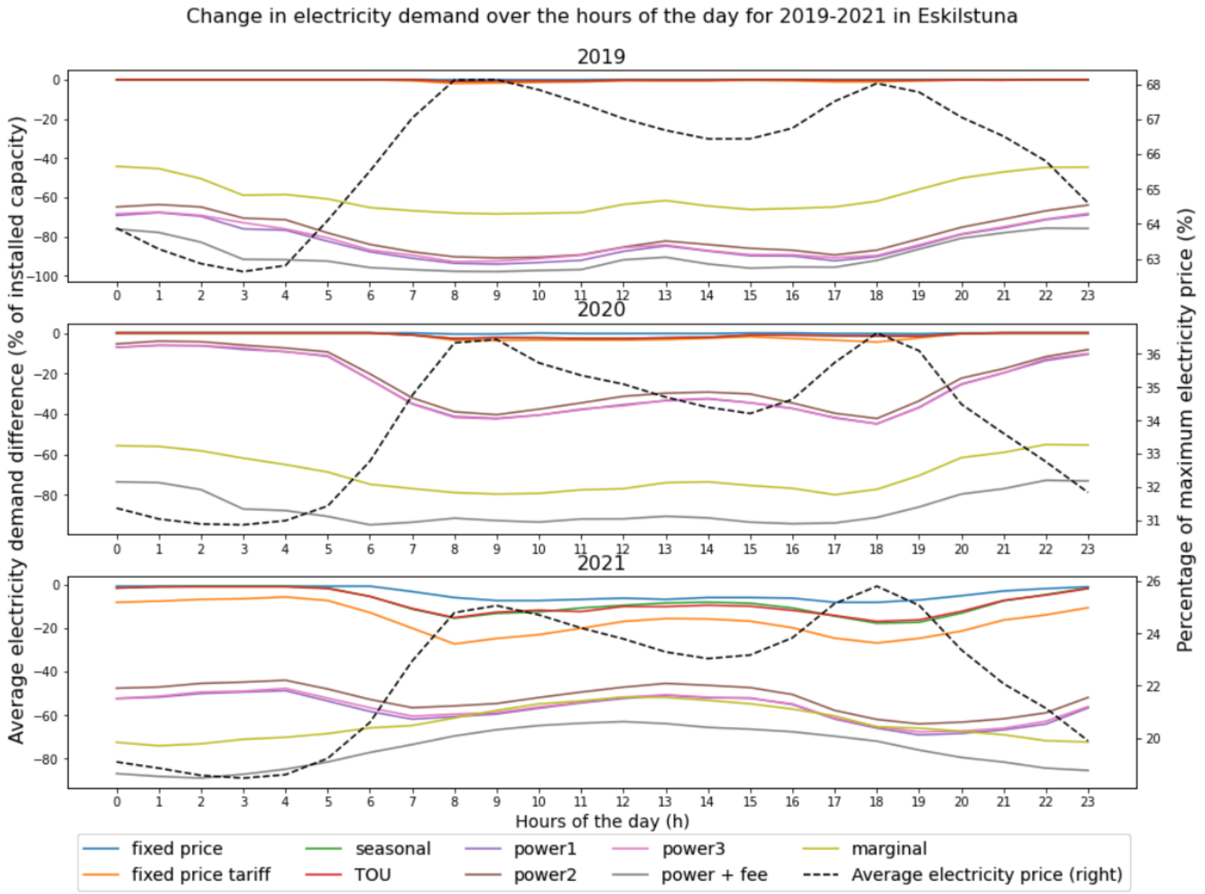

Figure 5. Yearly average change in electricity use over different hours of the day in Eskilstuna.

In Figure 6, we see similar results as for Eskilstuna, but with a smaller amplitude and the average is only ranging between 0-60% for all PMs and hours of the day. We can also see a lot clearer spikes in the mornings and evenings. This can be explained by the fact that the COP of the HP in this building is more stable than in Eskilstuna, allowing the electricity price signals to be clearer without an impact from a variable COP during these hours.

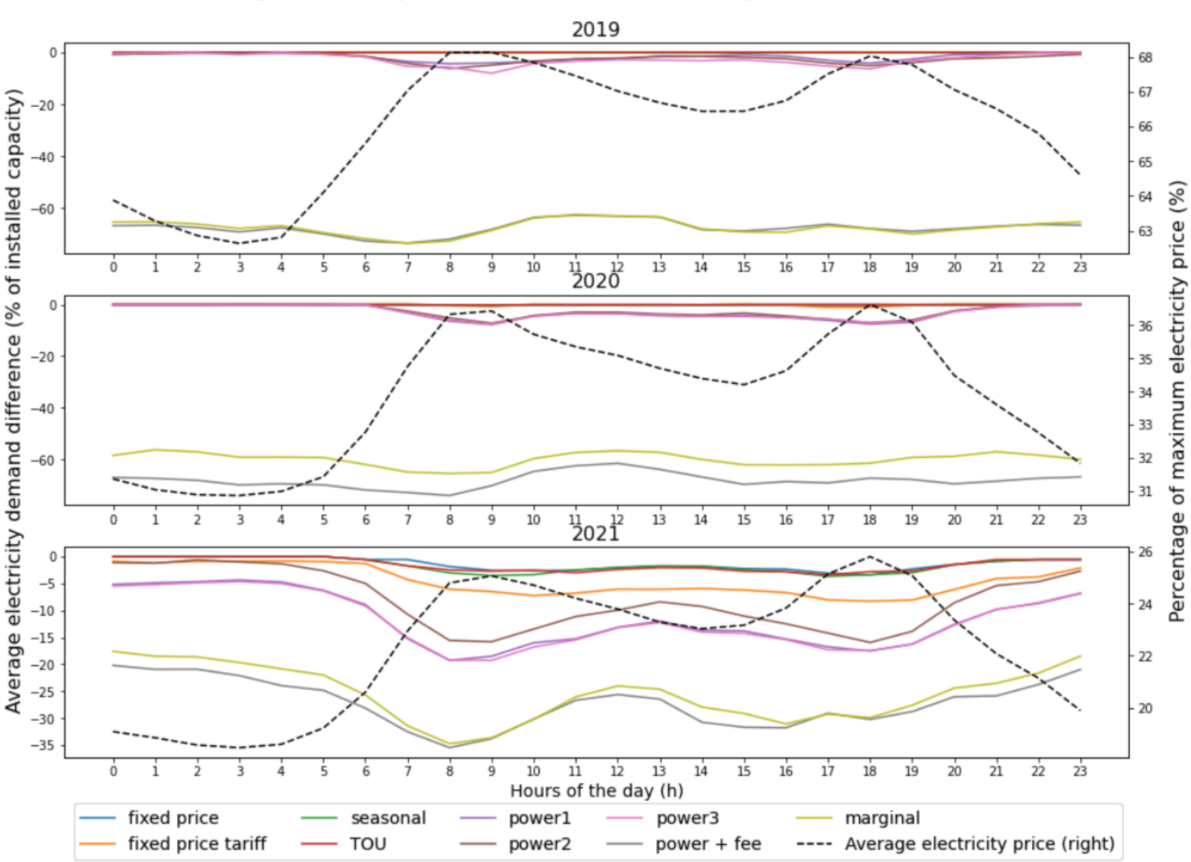

Figure 6. Yearly average change in electricity use over different hours of the day in Borås.

5.2.3 Economic impact

In Figure 7 and Figure 8, the economic results from the demand-side optimisation are presented. By looking at the differences between the baseline and the optimised case, the PMs' economic performances can be compared to each other.

In Figure 7 we can see that the customer costs decrease the most for the PMs, that include a power tariff component, and marginal pricing models for all three years. During 2021, with high electricity prices, some of them reach up to approximately 20% of the total heating costs for the building. We can also see that this shift from HP to DH leads to higher revenues for the DE company and the revenue can increase up to 40% per customer with both heat sources installed. The costs for the extra produced heat are based on the MC of heat production, which usually increase. For 2021, however, the costs of the produced heat can decrease. This is 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 it at a high price.

The system costs represent what the customers pay for operating their HP in addition to what the DE company pays for the heat production. The system costs also seem to decrease in this case and could reach a 25% decrease of the cost of heating this specific building. The company profits represent the difference between the company revenue and the added company costs and always presented positive values for all PMs and years. Profits could be increased by approximately 0-30%, but for the price DH “power + fee” model, we can see that the company profits are negative, meaning that the energy price for this PM was set too low to be able to cover the production costs of the increased heat demand.

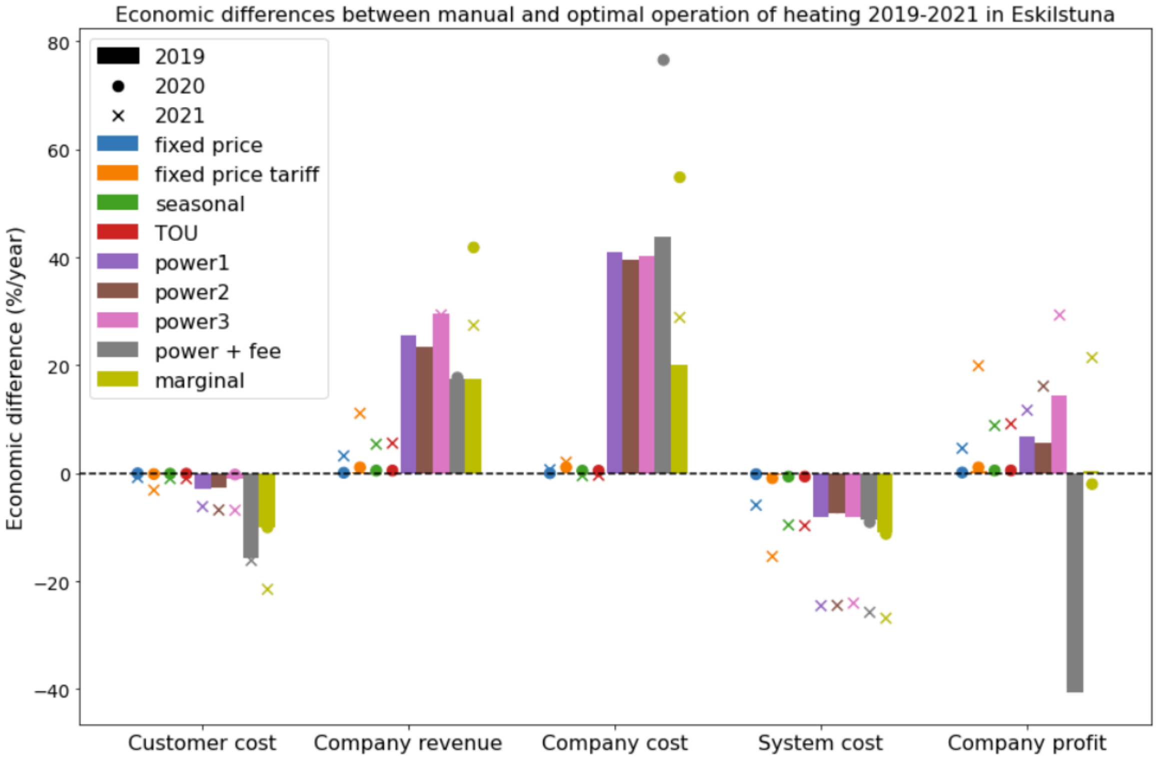

Figure 7. Impact on different economic values from different PMs used for demand-side optimisation in Eskilstuna.

We can see the same tendencies in Figure 8 for Borås, and we get very different percentual values from Eskilstuna. This is probably due to the marginal pricing and “power + fee” models having cheap and competitive prices leading to an increase from 20%-55% in DE use. This led to very high differences in company costs, around 400%. The customers can save up to 40% and the company revenue has the potential of increasing up to 100%. The system costs are the lowest for the PMs with a power tariff component and marginal pricing models, whereas the company profits can increase up to 100%.

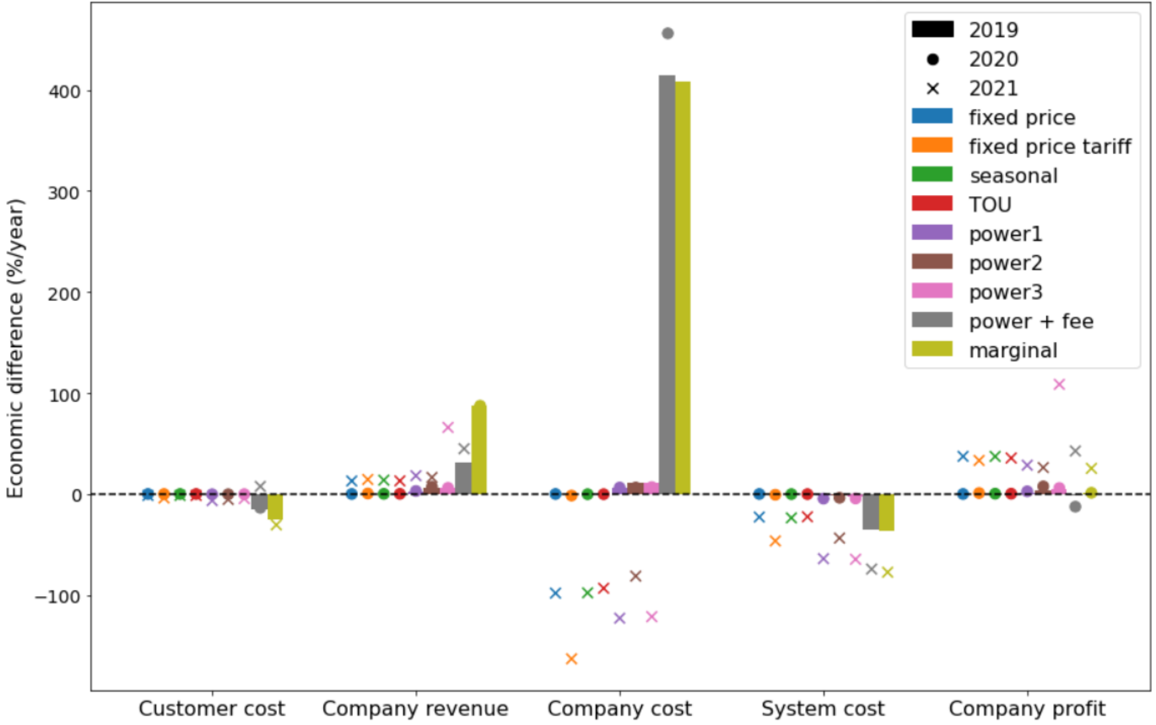

Figure 8. Impact on different economic values from different PMs used for demand-side optimisation in Borås.

5.2.4 Impact on 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. In Figure 9 and Figure 10 the carbon emission differences are presented. In Figure 9, we can see that the PMs with a power tariff component and marginal pricing PMs lead to the highest reductions in carbon emissions for all years and can lead to 3% reduction in carbon emissions. This means that the marginal production unit usually has a lower emission factor than electricity in Eskilstuna.

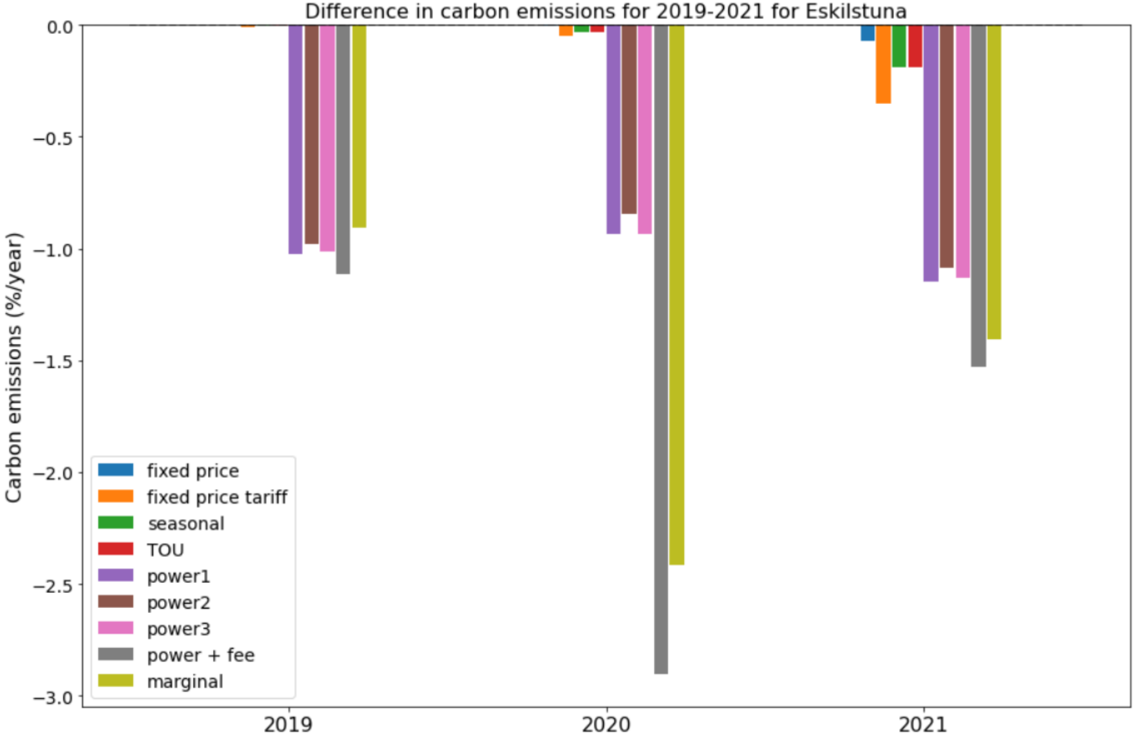

Figure 9. Difference in carbon emissions from demand-side optimisation in Eskilstuna.

In Figure 10, we can see different results with a lower magnitude in emission reductions where the best PM results lead to 0.4% reductions and the worst, up to 3.5% increase in carbon emissions. The largest difference 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 behind this is that the low energy price of these PMs led to large amount of load shifts from HP to DH, which increased the hours of which the load shift occurred. During these hours it is also likely that the waste incinerating CHP often was on the margin, which also has a higher emission factor than electricity.

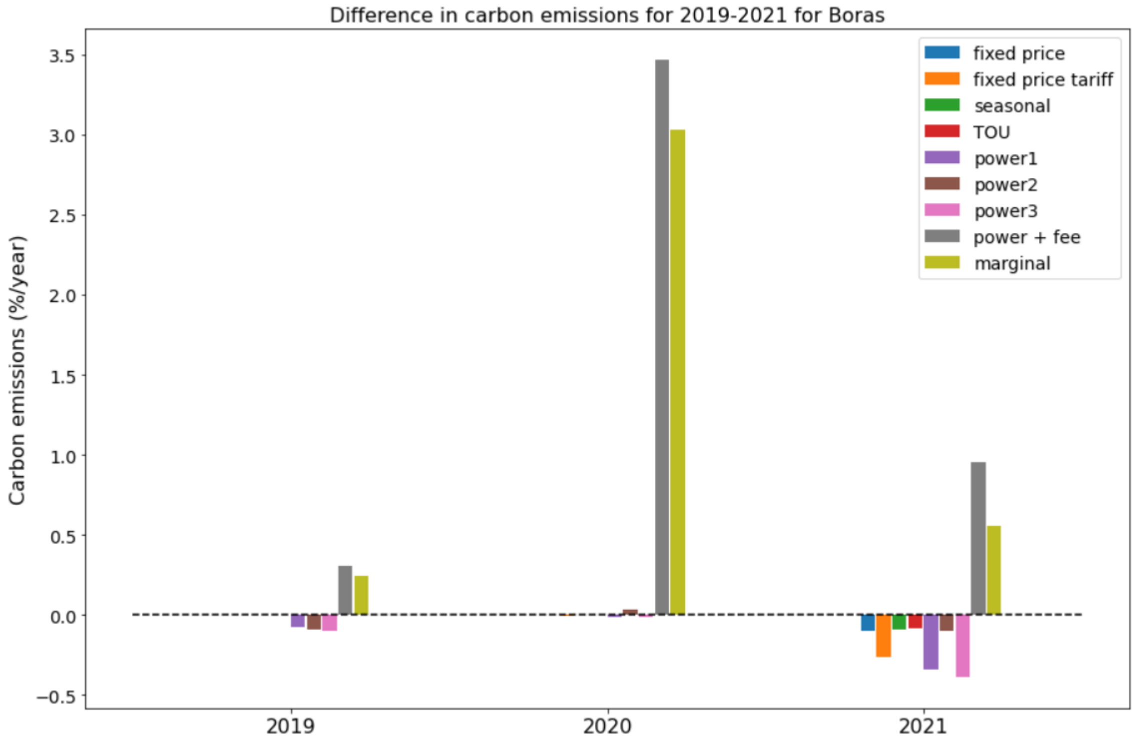

Figure 10 Difference in carbon emissions from demand-side optimisation in Borås

5.2.5 Sensitivity analysis

The competitiveness of DH in this case study is highly dependent on the price value of the price components. Therefore, this section evaluates the impact on the results by varying the price component values. The results in Borås and Eskilstuna are similar, which is why the results for Borås have been moved to Annex C. As can be seen in Figure 11, a decrease in price component value would lead to an increase in DE use, whereas an increase would lead to a lower demand for DH. This is a result of the optimisation choosing the cheapest energy source and if prices are increased for DH, the amount of energy shifted will decrease.

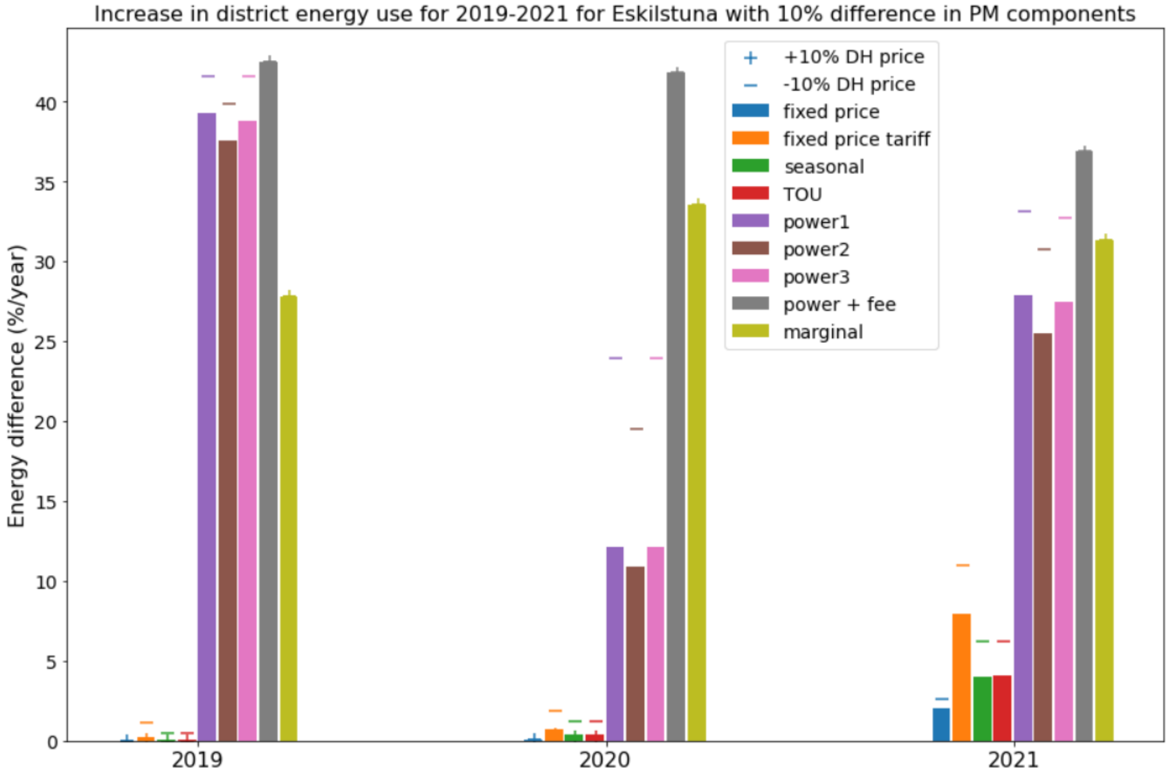

Figure 11. Difference in DE use with +/-10% difference in price component value in Eskilstuna.

In Figure 12-Figure 14, the economic results of varying the price component values by +/-10% are presented for each year between 2019 and 2021. We can see that a lower price usually leads to higher customer savings and a higher company profit, except for the cases with “power + fee”, which decreases the company profits, probably due to the prices being lower than the costs. This indicates that the price component values for DH have been set a bit too high for most of the PMs and by increasing its competitiveness towards the HP, more load shifting can be achieved.

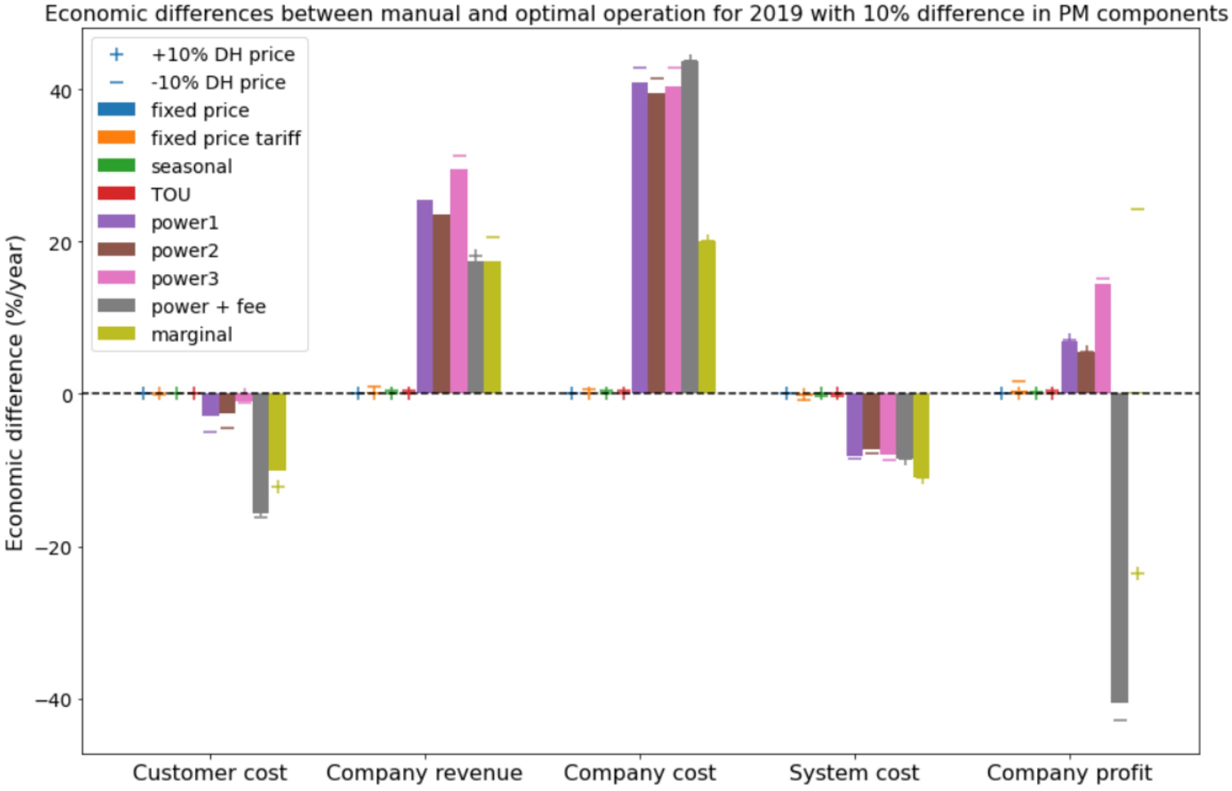

Figure 12. Economic differences with +/-10% difference in price component value in Eskilstuna during 2019.

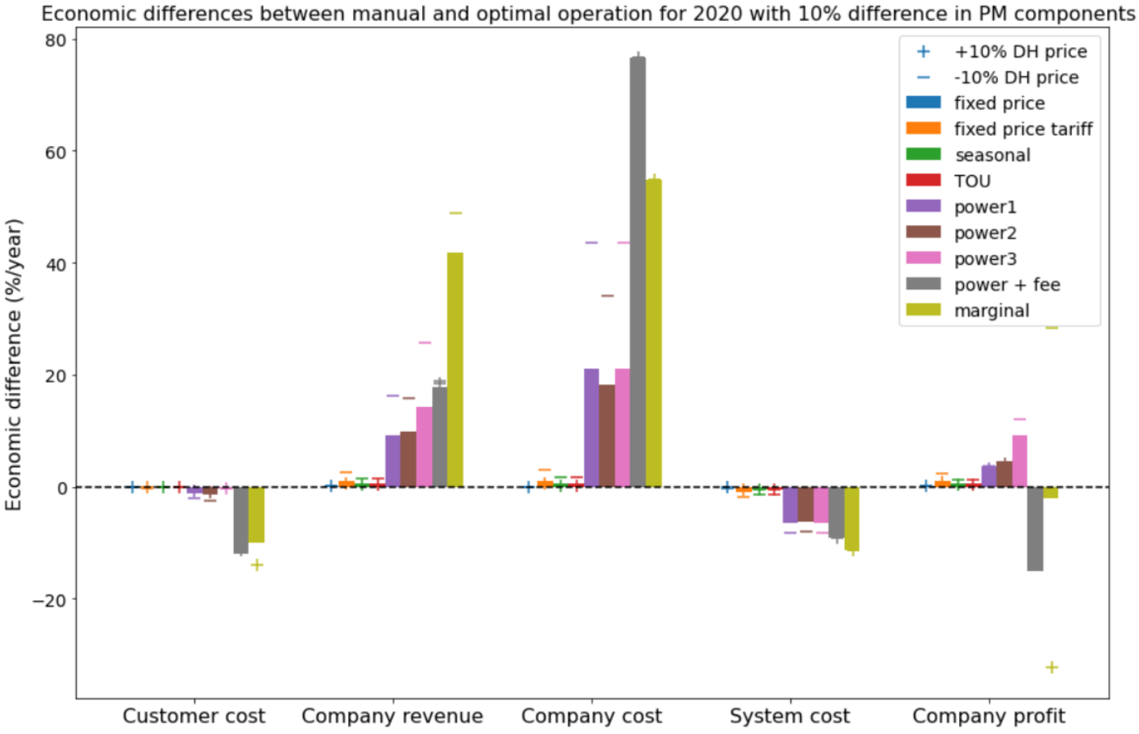

Figure 13. Economic differences with +/-10% difference in price component value in Eskilstuna during 2020.

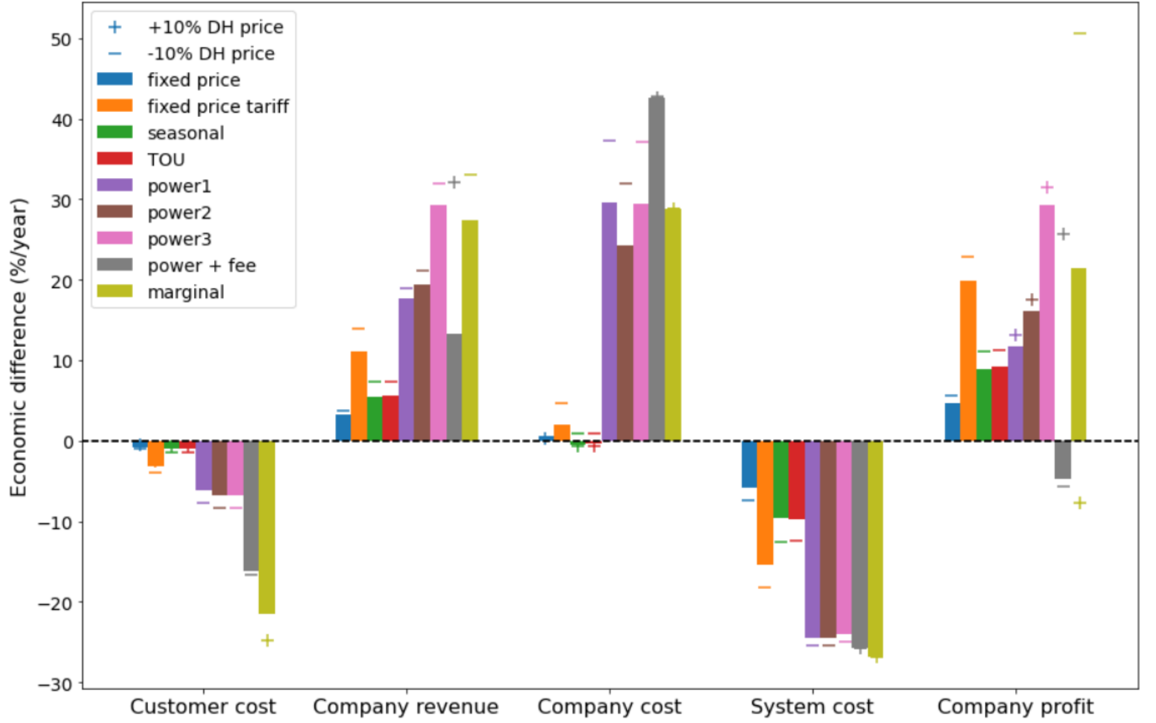

Figure 14. Economic differences with +/-10% difference in price component value in Eskilstuna during 2021.

In

Figure 15, we can see some differences in the carbon emissions, but it seems a bit random whether the lower or higher price would lead to lower emissions. This is probably dependent on which heat production unit is on the margin.

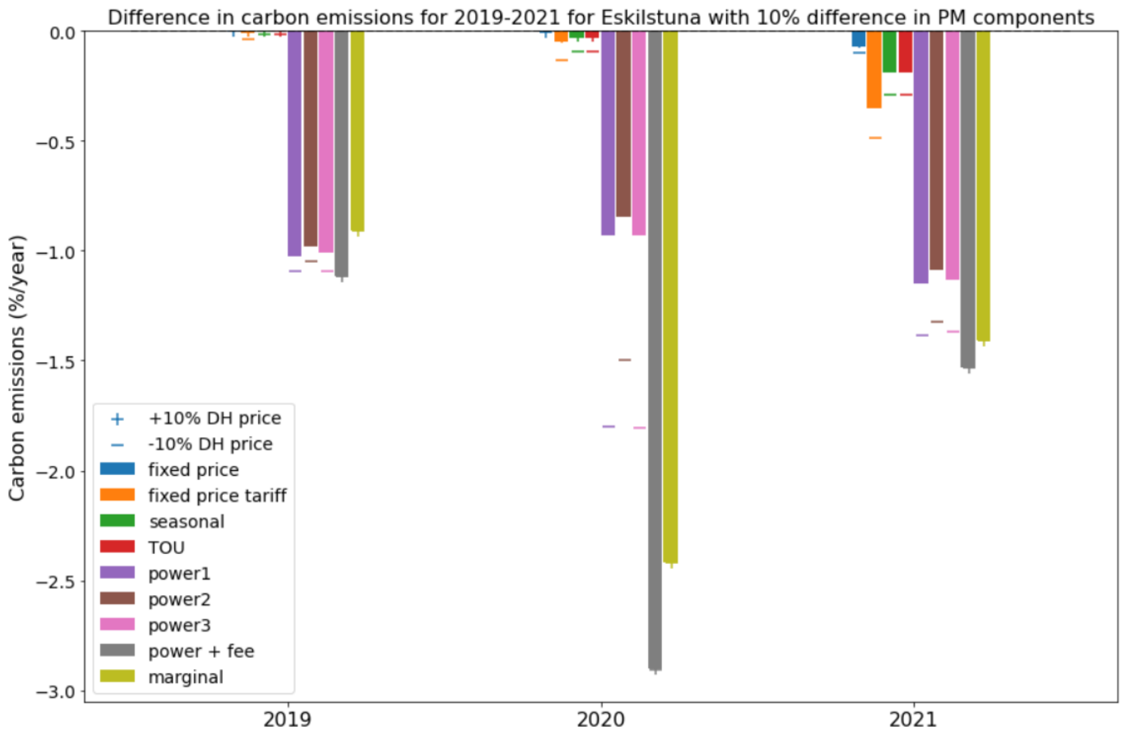

Figure 15. Differences in carbon emissions with +/-10% difference in price component value in Eskilstuna.

6 DISCUSSIONS AND CONCLUSIONS

6.1 Discussions

6.1.1 Literature review

The articles analysing PM for flexibility and the change or shift of costs or price to capture it, all stress current PM lack the ability to transparently convey the value of flexibility. The MC or LCOH are not easily applicable to PM since they are not transparent enough. Furthermore, such PM would be too complex and lack predictability to enable evaluation of how FET, or even energy efficiency improvements, may be translated into monetary value. Analyses in the articles highlight the need for PM to be easily understandable and easy to communicate to the customers. The explanation of how price of heat varies, and thereby how the value of flexibility is captured, should be included while keeping complexity at a minimum, to make it easier for both providers of excess heat and FET installation. Introducing a differentiation of price depending on time of use (season) and components associated with the actual use of heat, such as peak power and return temperature, encourages energy efficiency while enabling a transition towards a price better reflecting the actual cost of heat.

A considerable number of articles integrate and/connect the power sector with the DE sector within the confines of flexibility use. In such cases, it is even more difficult to have transparent PM conveying the flexibility value for the DE sector, as part of the profit or value is created outside of the DE sector.

6.1.2 Case study

The PMs that captured flexibility the best were the “power + fee” and marginal pricing models, which reduced the system cost the most. The most successful PM was the marginal pricing model, which decreased the system and customer cost the most. However, it did not provide a higher company profit, which means that the utility of providing flexibility did not benefit the DH company. The same applies for the “power + fee” PM, but in this case, the DH company had a decrease in profits. The results also indicate that the PMs including power tariff components and marginal pricing shift more load from HP to DH. This does not mean that power tariff components or marginal pricing necessarily induce the shift, but they create other revenues which can allow a lower energy price component.

A lower heat price favoured the shift from HP to DH, and usually increased the company profits as well as decreased the customer costs, with the exception of the “power + fee” model, which decreased the company profits. There are other alternatives to include a power tariff component for securing revenues and decreasing the energy price. Those alternatives include, but are not limited to, a fixed yearly fee, a return temperature-based tariff, a flow tariff or having a peak subscription fee. The advantage of having a return temperature or flow-based price component is that efficiency in the heat exchanger can be promoted and revenues can be secured for the DE company. Using a power subscription component could give the DE company a safe revenue stream and could lead to the end-user consuming less DH energy when demand (also probably total production costs are high). It could however, become a problem for the electricity grid due to the heat and power demand peaks often coinciding and in that case the end-user would use more electricity during these peaks.

Another PM discussed in the literature review is the motivational tariffs, which could be used to reimburse the end-user for being more flexible in their heat use. It has not been included in this case study due to the low interest among the survey participants as well as time limitations. A motivational tariff would, however, probably have the same impact as a time-of-use tariff, but with a carrot instead of a stick. Time-of-use tariffs, if implemented competitively, could be a good way of capturing flexibility if peaks usually occur during the specified times. Motivational tariffs could also be used as a way of compensating customers for “discomfort” (i.e., temperature differences) and using buildings as thermal storages. This is a good way to capture flexibility in both the DH system and the power system, as energy use for both heat sources decrease.

The amount of energy shifted is also dependent on the electricity price and the COP of the HP used. If an end-user has a fixed electricity price or a monthly rate, which is the most common alternative today, the optimisation will not respond on the real hourly price and therefore creates less incentives for flexibility towards the electric power system. By encouraging end-users to have hourly rates on electricity, load shifting flexibility will become incentivised and more flexibility can be enabled between the heating and power systems. For flexibility to be enabled between the DH and power system, it is an advantage that both HP and DH compete on an equal price level and reflect the costs in reality by having a high temporal resolution, which could be achieved by marginal pricing. In that way the demand-side optimised operation would work as an equaliser for both the power and DH system by responding to price signals. To reach this price equilibrium, the energy price component’s magnitude could be adjusted after the COP of the HP and the estimated electricity price. This would however lead to end-users with an efficient HP (high COP) being punished with a higher heat price, which is not desirable. This could possibly be handled by giving end-users with efficient HP a lower price for the power subscription.

As mentioned in the literature review, PMs also need to be transparent and easy to comprehend for the consumer. This means that some of the PMs are not suitable for all customers such as marginal pricing or advanced power tariffs. Fixed energy price or fixed components are easy to understand, but they are unfortunately not very good at sending the right price signals to consumers. Time differentiated price components are however easier to compose to reflect the real heat production costs. Unfortunately, when introducing price components with temporal differentiation, it gets more difficult to understand for the customer, as it needs to be well informed on why and when prices are higher or lower. Although hourly pricing is not very common among end consumers of electricity some innovative electricity trading companies have started offering hourly prices to consumers due to the possibility for the customer to control their own electricity use in their homes and make potential savings. With a growing possibility of controlling building heating through connected and smart heating devices, time differentiated prices could possibly become more accepted among end-users if they see the possibility to make savings.

For the service developed in the Flexi-Sync project, where also thermal inertia in buildings is included, a suitable way of implementing PMs could be to use fixed price components such as return temperature to increase energy efficiency. With a lower energy price component, DH becomes more competitive with the HP in order to provide flexibility to the power system. Lastly, a motivational tariff component could be implemented for decreasing DH use during times when production costs are high. The alternative to the last two components could be to include a time-of-use tariff, which could have the same impact.

The results from this specific case study depend a lot on the local circumstances such as production units, storage, CHP or HP technology and fuel, or electricity prices, and are not directly applicable to the other demo-sites. The fact that these demo-sites are large and include an integrated power and DH system with multiple different production units and heat sources, makes the circumstances different as the production costs of the CHP plants decrease significantly due to the sold electricity. There could however exist some synergies between the Spanish Maria-Laach demo-site and the Swedish ones, due to the similarities in production units. Nevertheless, the general discussion on how different PMs can enable flexibility could be applied to all the other demo-sites in the Flexi-Sync project.

When it comes to carbon emissions, most of the PMs seemed to lead to reductions, except for the ones that shifted large amounts of energy from HP to DH when there were waste-powered production plants in the DH system. This is possibly a result of the heat production plants' fuels mostly being bio-fuelled. Meaning that shifting from electricity to DH usually led to an improvement in carbon emissions. This is not the case in all DH networks, because the emissions are very dependent on which fuels are used to power the DE grid. In a DH grid where waste incineration or fossil oil is used as main heat source, the emissions would probably increase when the heat source is shifted from HP to DH, which makes it important to integrate more bio fuelled production units and CHP plants in the DH mix to reduce the carbon emissions from load shifting flexibility.

6.2 Limitations and assumptions

The case study used several assumptions and limitations to fit within the time frame of this project. The two most impactful assumptions that have been made are assumptions on techno-economic data for operation, costs, and emissions in production units, and the price component values. The latter has been tested and evaluated in a sensitivity analysis, which showed that price component differences can have a large impact on the operation and performance of the heating system.

The former has not been tested and could likely have a large impact on the economic and environmental results in this study. Using other values for O&M and fuel costs, efficiencies, and operation could have had a large impact on whether this solution is cost efficient, environmentally friendly, or not.

Due to little information on production costs and operations, the economic results for the DE company from this study should not be seen as exercisable. However, if DE companies were to use this methodology with their own production data, they could probably evaluate the utility of different PMs to enable flexibility by load shifting between HP and DH. Even though the absolute results might not be reliable, the relations between different PMs indicate what the benefits are for each PM.

For the carbon emissions, the electricity average emission factor has been used. This does not represent the real emissions from producing electricity. Depending on the electricity production mix, import and export of each hour, the values will differ and could yield other results. It is likely that the emissions would be reduced even more if a higher resolution for electricity emissions had been used due to the electricity consumption being reduced during electricity peak hours and likely when the emission factor of electricity is higher. A higher resolution would probably also yield lower carbon emission results. This could be explained by the emission factor for electricity being lower during times when the electricity prices are low, and therefore when it is more advantageous to use the HP as heat source.

6.3 Conclusions and future work

6.3.1 Literature review

Flexibility in DE sector is an emerging field, and the connection of PM and BM to capturing flexibility is not as widely studied as is to be expected. In our systematic study of 38 scientific literature dealing with flexibility in the DE sector, we find that the predominant characterisation of flexibility is as the availability of heat. Only about half of the articles include the demand shifting and peak shifting in their flexibility characterisation, aspects of FET that need to be considered to fully exploit the benefits they can bring to the DE system. Similarly, the two most common PM for DE are MC based PM and LCOH based PM. Our analysis shows that these pricing logics may handle flexibility in different ways. While short-run operational flexibility may be captured by MC PM, long-run dynamics flexibility may be captured by LCOH PM. But the concrete steps or analyses on how to connect these different PM to capture flexibility to the different BM are somewhat lacking in scientific literature.

Out of the 38 articles analysed, only eight dealt with both PM and BM, capturing flexibility in the DE sector. Our findings show that PM need to be connected to BM, especially to catalyse the flexibility that customers may provide to the DE companies. One way of doing this is by selling heat as a service while the operation and steering of FET on the customer-side are undertaken by the DE companies. Similarly, motivational tariffs are also proposed as PM to incentivise customer-side energy efficiency as a flexibility option.

Nevertheless, our analysis also shows that there is a gap in the scientific field to be filled in systematically connecting the different PM, pricing logics and different FET with coherent BM and organisational aspects. Given the policies and regulations which may hinder innovative BM, it is of importance that policy-based barriers and other co-benefits of flexibility in the DE sector are also explored.

6.3.2 Case study

The conclusions that can be drawn from the case study is that the energy price component in DH needs to be competitive against the cost of operating HP to enable flexibility by load shifting between DH and HP. This can be achieved by adding other fixed price components and adjusting their values to the current available technology and conditions. Especially return temperature and flow components could be used to incentivise energy efficiency and would also secure revenue for the DH company with a higher independence of the weather year.

Furthermore, higher temporal resolution in both DH and electricity prices creates better incentives for an end-user with smart heating systems to be more flexible in their heating use. By using prices that better reflect the costs of producing heat, load shifting heat system can be enabled as an equaliser between the two integrated energy systems.

Savings can be obtained by operating a load shifting heating system more efficiently by following price signals. In most cases the customer could decrease its costs of heating and the DE companies could also increase their profits by using PMs that are competitive against the cost of operating HP.

Carbon emissions could be decreased by switching between HP and DH depending on what kind of fuel the marginal heat production unit uses. In this study, a constant emission factor for electricity has been used. But it would be interesting to study a variable emission factor for electricity to see whether carbon emissions are reduced or not.

For future work, it would be interesting to include a study of how scaling the system to include multiple buildings in a city could impact the profits of the DE companies. It would also be interesting to see how a carbon emission minimisation could impact the load shifting between HP and DH.

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ANNEX A

Table A1. The data collected and used in the case study

Value	variable	Method of collection
Fuel costs	C_{fuel}	Estimated from literature and statistics *Energimyndigheten, Energiläget i siffror 2022*
Operation and maintenance cost	$C_{O\&M}$	Estimated from literature *2020, Heltäckande bedömning av potentialen för uppvärmning och kylning, Energimyndigheten*
Electricity cost	C_{el}	Electricity spot price *Nordpool market data hourly spot prices 2019-2021*
Electricity grid fees and taxes	$C_{el,fixed}$	Statistics and taxes *SCB- Elnätspriser för olika typkunder, tidsserie* *Skatteverket- energiskatter* *Skatteverket- moms*
Emission factor for different fuels and electricity	E_{fuel} $E_{electricity}$	National emission factors for fuels and electricity. *Naturvårdsverket-utsläppsfaktorer*
Efficiency	η	Calculated from production data provided by Utilifeed in WP4
Power-to-heat ratio	α	Calculated from production data provided by Utilifeed in WP4
Heat demand	y_{heat}	Monitored by Noda in buildings from the demo-sites
Coefficient of performance	COP	Monitored by Noda in buildings from the demo-sites
Installed HP capacity	el_max	Monitored by Noda in buildings from the demo-sites

ANNEX B

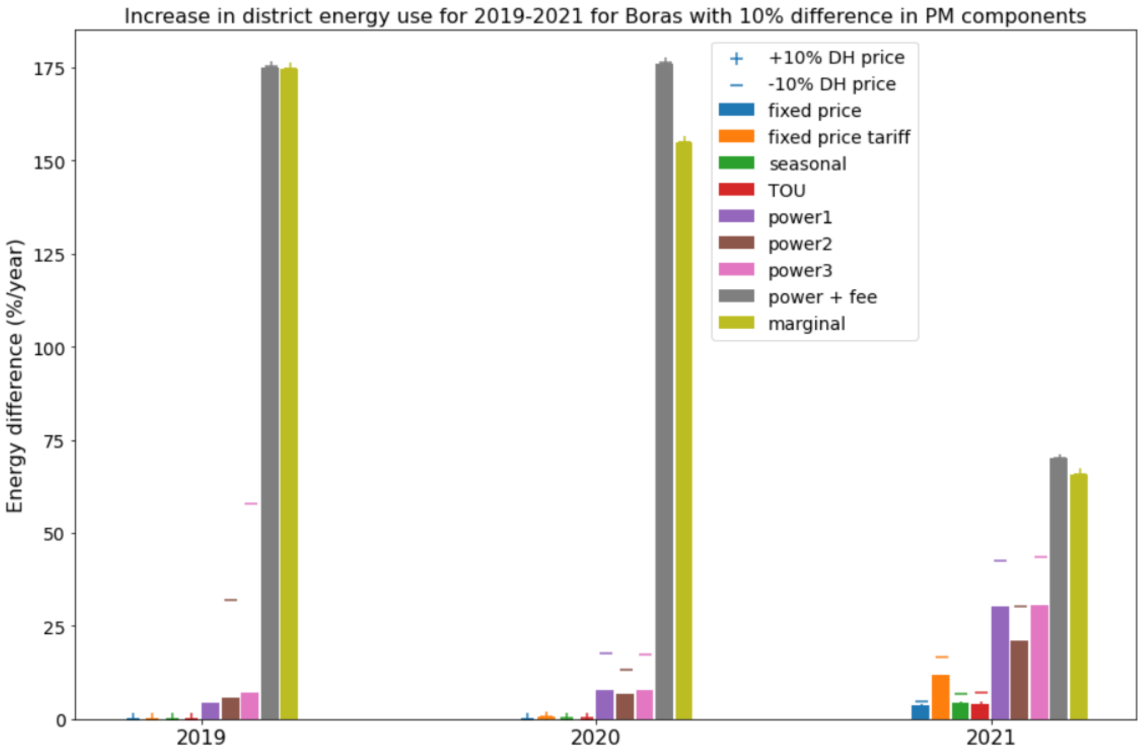
Table B1. The general findings of the selected articles

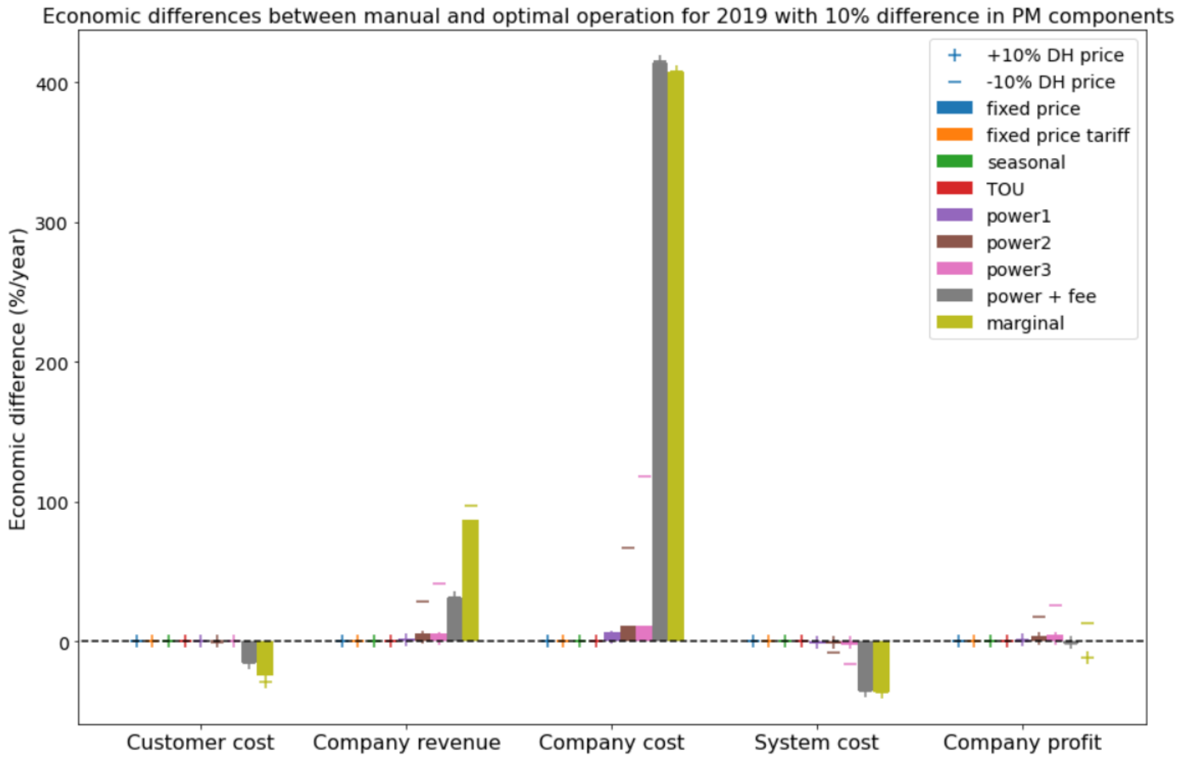
Article	Source type	Regional scope	Flexibility-Enabling technologies
Art. 1[29]	Journal article	Sweden	HP and Direct Electrical Heating (DEH) on the demand-side
Art. 2[30]	Report	Sweden	HP and Direct Electrical Heating (DEH) on the demand-side
Art. 3[13]	Journal article	Pan-European, Austria, Denmark, France, Germany, Italy, and Netherlands	Power to heat source via the Control Market. Solar thermal storage, thermal storage, and HP in the residential heating grid
Art. 4[37]	Journal article	Denmark	HP, thermal energy storage; and biomass straw boiler
Art. 5[19]	Journal article	Geography-agnostic, case study in China	Solar thermal collectors, HP, heat storage, CHP
Art. 6[21]	Journal article	Pan-European, Germany, Sweden, UK, Austria, Denmark	Excess heat from sewage treatment and data center with HP and Solar thermal heat collectors
Art. 7[54]	Thesis	Sweden	End-user behavior and smart grid
Art. 8[52]	Report	Sweden	Ground Source HP, Exhaust Air HP, hot water storage tanks and district heating grids
Art. 9[55]	Journal article	France	*Not applicable*
Art. 10[27]	Journal article	Sweden	HP, Industrial Excess Heat, CHP
Art. 11[32]	Journal article	Latvia	Natural gas boilers with economisers, solar thermal collectors
Art. 12[24]	Thesis	Sweden	HP, thermal inertia of buildings
Art. 13[26]	Journal article	Denmark	CHP on the supply side; hot water tank on the demand-side
Art. 14[40]	Journal article	Denmark, Austria	Temperature of the return flow (from the secondary side). Also, low-temperature heat sources
Art. 15[34]	Journal article	Sweden	Not Applicable
Art. 16[35]	Journal article	Denmark	Not Applicable
Art. 17[15]	Journal article	Denmark, Finland, Norway, Sweden	Heat storage, CHP, wood chip boiler, electric boiler
Art. 18[47]	Journal article	Sweden	Demand-side heat storage
Art. 19[16]	Conference paper	Sweden, Norway, Finland, and Denmark	Electric boilers, District heating
Art. 20[17]	Journal article	Norway, Denmark, Sweden, and Finland	Heat storage, Electric boilers, HP, wood chip boilers, CHP
Art. 21[50]	Conference paper	The UK	HP, Thermal storage, CHP, and electric boiler
Art. 22[20]	Journal article	*Not applicable*	Solar thermal DH system, domestic hot water tank, seasonal storage tank, thermal energy storage, seasonal thermal energy storage.

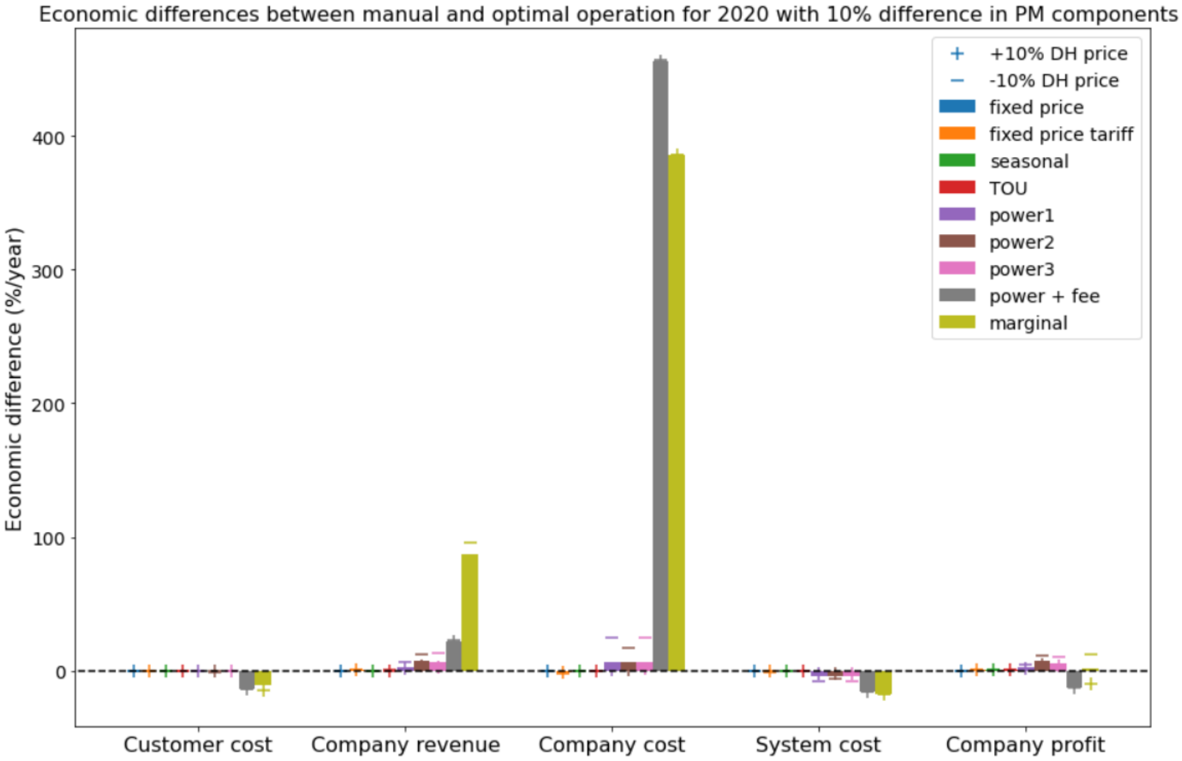
Art. 23[18]	Journal article	Finland/Nordic countries	Waste heat from data centers, often combined with HP and possibly heat storage.
Art. 24[44]	Conference paper	Sweden	HP
Art. 25[22]	Journal article	Finland	HP
Art. 26[38]	Journal article	Denmark/ Finland	CHP, HP, thermal energy storage (pit + hot water tank), waste heat
Art. 27[51]	Journal article	Finland	HP, CHP, and Heat only boilers
Art. 28[25]	Thesis	Sweden	CHP and heating supply-side HP.
Art. 29[48]	Conference paper	Finland	CHP, waste heat HP and solar heating
Art. 30[56]	Journal article	Sweden	HP, switching from electricity to DH as heat source and the fact that cooling is needed primarily in summer.
Art. 31[57]	Conference paper	Pan-European, Germany, Denmark, Spain, and Italy	Reversible HP, chillers in shopping centers/grocery stores. solar thermal heat collectors and ORC
Art. 32[36]	Journal article	Denmark	Not applicable
Art. 33[39]	Journal article	Pan-European (Netherlands, Italy, Belgium, Poland, Spain, Finland)	*Not stated* - uses the term district energy services
Art. 34[31]	Journal article	Romania	Biomass fired boilers, HP, thermal storage (long and short-term), solar thermal collectors
Art. 35[58]	Conference paper	Estonia	HP
Art. 36[49]	Journal article	Netherlands	HP, CHP
Art. 37[23]	Report	Sweden	DH, HP, borehole storage and heat source shifting through thermal inertia of buildings and hot water storage tank.
Art. 38[28]	Report	Sweden	Grocery store and data center excess heat connected with HP, CHP, and water storage tanks

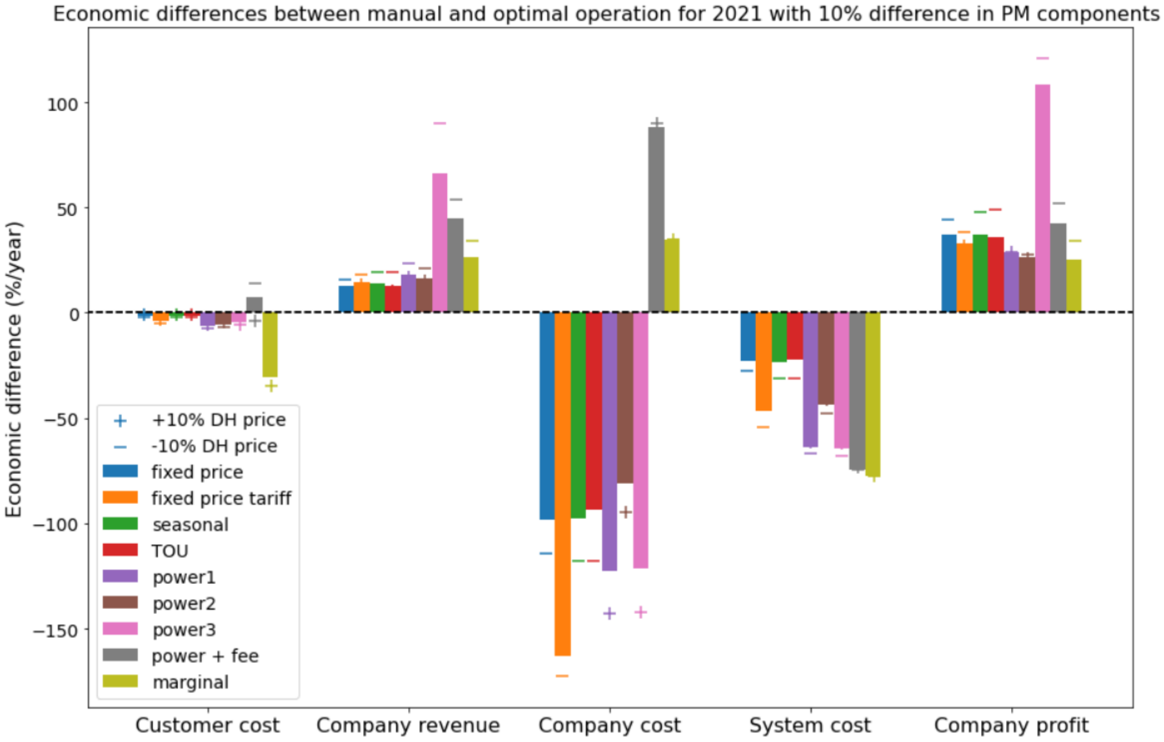
ANNEX C

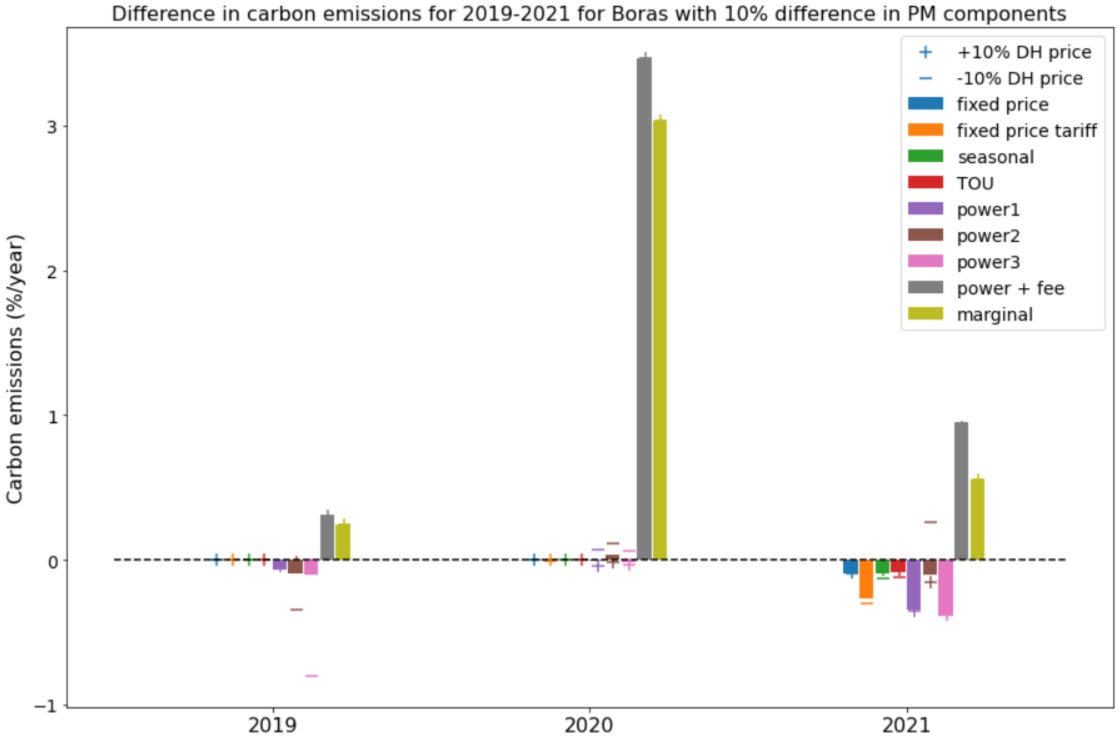
Figures from sensitivity analysis for Borås






Economic differences between manual and optimal operation for 2020 with 10% difference in PM components
Economic difference (%/year)
400
300
200
100
0
+10% DH price
-10% DH price
fixed price
fixed price tariff
seasonal
TOU
power1
power2
power3
power + fee
marginal
Customer cost
Company revenue
Company cost
System cost
Company profit


Economic differences between manual and optimal operation for 2021 with 10% difference in PM components
Economic difference (%/year)
100
50
0
−50
−100
−150
+10% DH price
-10% DH price
fixed price
fixed price tariff
seasonal
TOU
power1
power2
power3
power + fee
marginal
Customer cost
Company revenue
Company cost
System cost
Company profit


Difference in carbon emissions for 2019-2021 for Boras with 10% difference in PM components
Carbon emissions (%/year)
3
2
1
0
−1
2019
2020
2021
+ +10% DH price
− -10% DH price
fixed price
fixed price tariff
seasonal
TOU
power1
power2
power3
power + fee
marginal

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