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District Cooling – assessment of price models supporting the efficiency

M. Jangsten, T. Lindholm, J-O. Dalenbäck

Abstract—District cooling is an energy efficient cooling supply technology compared to building individual solutions. However, many district cooling systems suffer from low return temperatures, which usually originate from the buildings' systems and substations and cause increased operating costs for the district cooling company. One potential solution to this problem is to ensure the district cooling price model sufficiently incentivizes the district cooling customers to maintain well-performing substations. The aim of this study is therefore to assess district cooling price models which reward well-performing substations. The study is based on operational data from an actual district cooling system located in Gothenburg, Sweden and 26 of its connected buildings. Four price models were designed based on the existing price model's components power, energy, and flow along with either a delta-T or a return temperature component. The new price models resulted in lower costs for customers having substations with high delta-Ts compared to the reference price model. The results of this study showed a delta-T, or a return temperature component are more effective in providing economic incentives for customers to maintain well-performing substations compared to utilizing only a flow component. Moreover, it was shown the strongest incentives are realized with both a flow and a temperature component.

***Keywords*—district cooling, high return temperatures, low delta-T syndrome, price model, price component**

I. INTRODUCTION

IN A GLOBAL CONTEXT, the cooling demand is expected to increase more than any other building energy end-use [1]. To supply this increased cooling demand, district cooling (DC) is one solution [2]. However, many DC systems suffer from low return temperatures, called the "low delta-T syndrome". The low return temperatures usually originate from the connected buildings' and cause increased operation costs for the utility company and ultimately the customers, due to increased chilled water flow rates and less free cooling possible to use. Moreover, individual cooling technologies constitute a competitor to DC since customers have the possibility of choosing local chillers for example, to supply their cooling demands and thereby disconnecting from the DC system. The counterpart to DC, district heating (DH), also faces competition with building individual technologies. Moreover, the development of lower temperatures in DH systems have brought upon new challenges [3], for example lower delta-Ts. Several previous studies, reviewed in the next section, have therefore been conducted to investigate and develop the business and price models of DH systems. However, DC, which is closely connected to DH from a technology and ownership perspective, has received little attention. For DC systems, low delta-Ts are a major challenge and there is a need to ensure proper incentives through the price models are provided to DC customers as well.

Literature review

In a Swedish context, DC has been developed and is offered by DH companies. Pricing DH can be done by two different approaches depending on if the market is regulated (meaning the DH utilities are owned by the municipalities and the DH price is controlled by the government) or deregulated. In a deregulated DH market, the price models are cost-based with marginal-cost heat prices [4,5]. A cost-based price model for DH should as a minimum consist of three components: 1) a fixed annual price, 2) a fixed capacity price based on measured power and 3) a variable energy price with differentiation based on two or three seasons where the price level is based on the marginal cost of the heat production. A possible fourth component and complement to the price model, is a fee based on either the flow, return temperature or the delta-T [4,6]. Since DC is part of DH companies, the development of DC price models has typically been done with knowledge and inspiration from DH, although individual contracts and pricing schemes are still common.

DH price models are not standardized, whereby several hundred different DH price models exist across Europe and Sweden. Surveys of price models in Swedish DH systems have been conducted [7–13] to understand what price component combinations exist. Song et al. [7,8], identified 237 different DH price models among 80 DH

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companies. The different price components found among the surveyed price models were a fixed annual price in 60%, a fixed capacity price in 87%, a variable energy price in 100%, and a flow component in 50%. The price level of the variable energy cost can be determined in many different ways [9,14–17], where seasonal differentiation and peak/off-peak pricing are two approaches [18]. Based on the component structure of DH price models, rationale for the design of DC price models in Swedish DC systems is provided.

Many customers perceive the best price model only contains a variable energy component and thereby solely charges for the energy consumption [6]. Contrariwise, the DH utilities prefer a high share of fixed costs due to the high investment and maintenance costs of the DH system. For this reason, the shares between fixed and variable costs should be carefully determined to balance the need of producers and the preference of customers [12,17,19,20]. The shares of price model components have not previously been investigated for DC price models.

A price model component charging for the flow, return temperature, delta-T, or flow per delivered MWh is not always used by the DH companies. One reason could be its complexity and sometimes difficultly for the customers to understand [19]. However, such a price component is what provides the customers with incentives to maintain well-performing substations and improving the return temperature [21,22]. Peterson and Dahlberg-Larsson [23] assessed 203 Swedish DH systems and found 55% have a flow price component (or similar). A slight majority of these systems apply the flow price during the entire year and the remainder only during the high demand season. If the flow is charged per cubic meters used during the entire year, and the DH system supply temperature varies throughout the year, customers will be punished for higher flows due to lower supply temperatures. This can be avoided by the utilizing a correction factor, for example adjusting the flow based on the monthly average supply temperature. Another option is to charge for the return temperature instead of the flow. A return temperature price component can be arranged in a revenue neutral way for the DH company, where customers with a monthly average return temperature greater than the network average is charged a fee, and customers with a return temperature lower than the network average receive a bonus [21,23]. Seventy-one percent of the Swedish DH systems with a flow price component as part of the price model charge per cubic meter of flow and 29% use a return temperature price component [23]. The return temperature component has been shown to be effective to achieve low return temperatures in DH systems [13].

Previous studies on price model evaluations have been conducted for DH but very few have investigated price models for DC [24,25] and the knowledge about DC pricing has been identified as low [26,27]. Chan et al. [28] and Abdullah et al. [29] investigated different electricity tariffs with on/off-peak pricing schemes to evaluate the profitability for ice thermal storage in DC systems. Another possibility for thermal storage in DC is to use the building structures by supplying night cooling from the DC system. For this to be cost-effective, incentives through the DC price model are needed, where discounts on the energy and/or the flow component are one solution [30]. To the authors' knowledge, only one publication about DC system price models exists [24,31]. The price model is used in Singapore Marina Bay Business District and consists of the following five components:

1) Contract capacity charge. The needed capacity is declared by the customer.
2) Usage charge. Based on the metered energy consumption.
3) Capacity overrun charge. A daily fee charged if a capacity higher than the declared capacity is used. The fee is 1/10 of the monthly rate for the contract capacity charge.
4) Return temperature adjustment. An upward adjustment of the usage charge by 3% for each °C of the monthly average return temperature below 14 °C.
5) Supply deficiency rebate. A discount equal to twice the amount for the corresponding contract capacity charge. Paid to the customer when the average DC supply temperature for any hourly interval fails to meet the specifications of 6±0.5 °C.

For DC systems it is recommended to as a minimum include capacity and consumption price components in the price model. To address poor delta-T an "excess flow" penalty can be applied, which is based on the difference between actual and target delta-T [32]. In Sweden, 36 energy companies offer district cooling alongside district heating. Although DC comprises a much smaller share of the utility company's product portfolio compared to DH, it is growing rapidly. To date, no survey of Swedish DC systems' price models has been conducted, mainly since most DC utilities determine the customers' contracts and prices on an individual basis [33]. Of the 36 DC companies, four have disclosed their DC price models and price lists online [34–37]. These price models include different variations of the price components energy and power. Also, two of the price models include a flow component and one a bonus/fee-based return temperature component. The flow price components are charged based on either the monthly used cubic meters [34] or as an average of the three hours with the highest flow rates for each of the months June, July and August [36]. For the price model with a return temperature component, it is calculated as the energy weighted average return temperature from each substation, compared with the network average and applied only during the months May through September. Customers with a return temperature above the average receive a bonus of 1 €/(°C·MWh) and customers below the average are charged a fee [35].

Based on the literature review of DH price models studies it can be concluded DH customers are incentivized to improve the performance of their substations through the price model components charging for the flow, return temperature or delta-T. Moreover, prior studies have solely focused on incentives for the implementation of energy efficiency measures. Previous studies on the district cooling system in Gothenburg [38,39] indicated economic incentives are needed for the customers to improve the function of their substations and increase the return temperatures. However, there is little information available, and to the authors' knowledge no evaluations have been conducted on the most effective price component to provide such incentives in DC systems.

Aim of study

Based on the above literature review and identified knowledge gaps, the aim of this study is to investigate DC price models which provide incentives for DC customers to improve the performance of their substations and increase the return temperature. One objective is to identify a price model which rewards customers with well-functioning substations and provide incentives for customers with poorly functioning substations to improve them. Also, the higher the return temperature from the substation, the more advantageous for the DC system. Another objective is therefore for the price model to be beneficial to customers with return temperatures higher than those specified in the design guidelines. Lastly, for ease of communication to and comprehension by the customers, an objective for the price model is to be fairly simple.

II. THE DISTRICT COOLING SYSTEM

This study is conducted on the district cooling system in Gothenburg, Sweden. The DC system was commissioned in the early 1990's and has since expanded to handle increased cooling loads in new buildings, in and around the city centre. The installed capacity is currently 80 MW with 40 km of piping. More information about the DC system can be found in [40].

Substations and collected data

In 2021 there was a total of 181 Substations in the DC system, a number which increases each year. For the price model assessment of this study, 26 substations have been selected for an in-depth analysis. For these substations, hourly data were collected from the energy meter on the primary side of the substation from May 1st to October 1st of 2018 to 2020, see Table I. The buildings are all commercial with different business types, mainly offices, retail space and restaurants and have been selected based on previous collaborations (see [40] for more information).

Based on data from Table I, the Primary delta-T has been calculated according to:

TABLE I
DATA COLLECTED TO EVALUATE THE PRICE MODELS.

Symbol	Name	Unit
Q_{DC}	District cooling energy	MWh
$\dot{Q}_{DC}$	District cooling power	MWh/h
$\dot{V}_{DC}$	District cooling volumetric flow rate	m³/h
$t_{DC,s}$	Primary supply temperature	°C
$t_{DC,r}$	Primary return temperature	°C

$$\Delta t_{DC} = t_{DC,r} - t_{DC,s} \quad (1)$$

III. ASSESSMENT OF EXISTING PRICE MODEL

The existing price model (PM) of Gothenburg district cooling system, here called "reference price model", is composed of the three components energy, power, and flow. The energy price has three seasons: winter (January, February, March, December) spring/fall (April, October, November), and summer (May through September). The price level of the power component is determined based on the substation's hourly maximum power as measured the past 12 months. The power component price consists of two parts: a fixed base price per year and a variable price per kW and year. The flow component charges for the flow rate based on cubic meters used per month [34].

In Fig. 1 the average shares of the reference price model's components energy, power and flow are

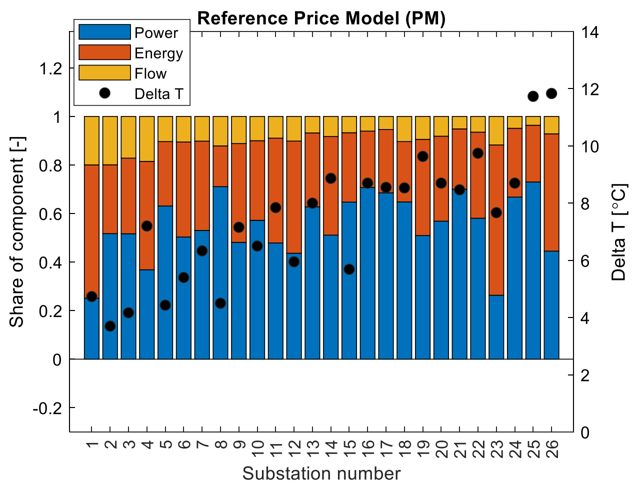

Fig. 1: Relation between price components of the reference price model (left y-axis) and PI primary delta-T (right y-axis) for each substation analyzed. The data are average values based on total costs from April thorugh September of 2018 to 2020 for 26 substations.

presented for the 26 investigated substations along with the performance indicator Primary delta-T. The flow component incentivizes the building owners to improve the performance of their substations but according to Fig. 1, the flow component's share is the lowest for each substation compared to the energy and power components, depending on the energy need and the substation's performance.

Exchange rate used: 1 SEK = 0.1 €.

To be able to evaluate the price model with respect to the substation performance, "proper" function or performance needs to be defined. This can be done with the aid of substation performance indicators (PIs) evaluated based on historical operational data. Such PIs, along with a substation performance assessment method, have been proposed by Jangsten et al. [41]. PIs suitable to assess the performance of the substations for price model evaluation have been identified as the following:

- Primary delta-T for peak cooling loads, Δt_{DC} [°C], see (1).
- Overflow [%]: share of flow with low delta-T compared to high delta-T.
- Combined PI: Overflow/Δt_{DC} [%/°C].

In Fig. 1 the PI primary delta-T can be seen. Substations with a higher share of the flow component generally also have lower delta-Ts.

To enable a comparison between the substations' cost and performance, the cost has been normalized based on the total energy delivered to the substation:

$$\frac{Total\ cost\ (Energy + Flow)\ [€]}{Q_{DC}\ [MWh]} \tag{2}$$

The normalization has been done using only the cost components energy and flow. This is because the relationship between the power cost and the power level is non-linear. Moreover, the substations have different maximum power demands regardless of their performance. A normalization according to (2) therefore enables a comparison of the substations' performance without the power component obscuring the cost-performance relationship.

In Fig. 2 the relationship between two PIs (Primary delta-T and Combined PI) and the normalized cost can be seen for the reference price model. In the upper graph the

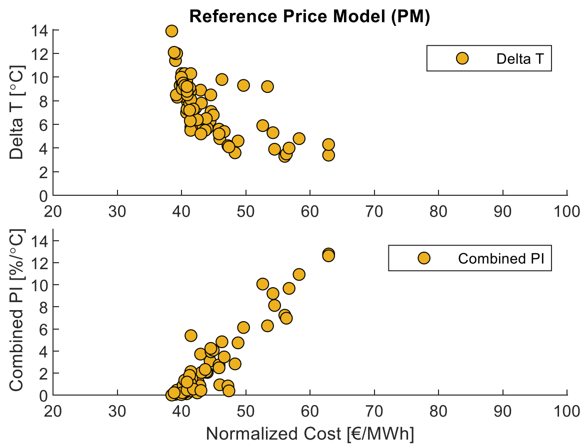

Fig. 2: Performance indicators Primay delta-T and Combined PI vs. normalized cost for the reference price model.

delta-T is decreasing for an increased cost, although there is a wide range of delta-Ts for a normalized cost around €40/MWh. In the lower graph of Fig. 2, the Combined PI is increasing for an increased normalized cost. This indicates the existing price model does provide some incentives for poorly performing substations since the cost increases with an increasingly poor performance as described by combining the PIs Overflow and Primary delta-T.

IV. Design of New Price Models

Based on the above literature review, new price models were developed and evaluated for the 26 selected buildings. The price model components identified to incentivize the DC customers to improve their return temperatures are an energy weighted delta-T component and an energy weighted primary return temperature component. The delta-T and return temperature components are energy weighted to account for the size of the substation. The weighting is done based on hourly data for each substation, see Table I.

$$E\Delta t_{DC} = \dot{Q}_{DC} \cdot \Delta t_{DC} \tag{3}$$

$$Et_{DC,r} = \dot{Q}_{DC} \cdot t_{DC,r} \tag{4}$$

where $\dot{Q}_{DC}$ is the substation's hourly energy use [MWh/h], Δt_{DC} [°C] is the instantaneous primary delta-T calculated according to (1) and $t_{DC,r}$ [°C] is the instantaneous primary temperature, measured once per hour.

The delta-T and return temperature price components are arranged to be revenue neutral for the DC company for substations with a performance equal to that of the DC system's design criteria. The difference between the hourly $E\Delta t_{DC}$ or $Et_{DC,r}$ and the energy-weighted system design Δt_{DC} or $t_{DC,r}$ are summed and multiplied with the price level (PL):

$$\textstyle\sum_i^n (\dot{Q}_{DC} \cdot \Delta t_{DC,\ sys\ design} - E\Delta t_{DC}) \cdot PL_{\Delta t} \tag{5}$$

$$\textstyle\sum_i^n (\dot{Q}_{DC} \cdot t_{DC,r\ sys\ design} - Et_{DC,r}) \cdot PL_{tDC,r} \tag{6}$$

where n is the total number of hours of the dataset, $PL_{\Delta t}$ is the price level for the delta-T component and $PL_{tDC,r}$ is the price level for the primary return temperature component in €/(°C·MWh). If the number is positive, the customer pays a fee and if the number is negative a bonus will be paid to the customer. The price levels of the temperature components were selected by matching the total cost generated by the flow component. The price levels applied were consequently the following:

- $PL_{\Delta t}$= €3.4 /(°C·MWh)
- $PL_{tDC,r}$= €3.6 /(°C·MWh)

The delta-T and the return temperature components are in essence targeting the same substation inefficiency problem. However, an aspect favouring a return temperature component as opposed to a delta-T component is if the primary supply temperature rises above 6 °C, to for example 8 °C. For such hours the customers may be unable to maintain a high delta-T of 10 °C. Moreover, the primary supply temperature varies throughout the DC network. Substations close to the DC plant typically receive lower temperatures than substations farther out in the network. Consequently, a return temperature component could be fairer in practice. However, in practice the return temperature is only co-calibrated relative the supply temperature and not with respect to the absolute temperature. For that reason, an implementation of the return temperature component may have to be preceded by conducting a calibration of the temperature sensors with respect to the absolute temperature. If the DC company was to undertake such a calibration assignment, its justification needs to be provided by a supporting evaluation of a price model including the return temperature component.

Price models A: replacing the flow component with a delta-T or a return temperature component

Price models A were created by keeping the reference price model's energy and power components unchanged and replacing the flow component with a delta-T or a return temperature component. These components were designed based on the DC system design temperatures which are 10 °C for delta-T and 16 °C for the return temperature. The normalization of the cost per delivered MWh energy for comparison purposes is for price models A done according to the following:

$$\frac{Total\ cost(Energy + Delta\ T\ or\ Return\ T)\ [€]}{Q_{DC}\ [MWh]} \tag{7}$$

Price models B: adding a delta-T or a return temperature component to the reference price model

For price models B, all three components (energy, power, and flow) of the reference price model were kept, and the energy-weighted delta-T or return temperature components of price models A were added. Price models B therefore consists of four components where two of the components, flow and delta-T or return temperature, both provide incentives for proper substation performance.

The normalization of the cost per delivered MWh energy is for price models B the following:

$$\frac{Total\ cost\ (Energy + Flow + Delta\ T\ or\ Return\ T)\ \ [€]}{Q_{DC}\ [MWh]} \tag{8}$$

An overview of the altered components of the new price models are provided in Table II:

TABLE II
OVERVIEW OF NEW PRICE MODELS.

Price model	Flow component	Delta-T component	Return-T component
1A		✓	
2A			✓
1B	✓	✓	
2B	✓		✓

V. RESULTS AND DISCUSSION

In this section the results of the evaluated price models are presented and compared with the reference price model. The shares of the components of the four new price models with respect to the total cost of the reference price model can be seen in Fig. 3, along with each substations' PI delta-T. In all four graphs the shares of the components power, energy, and flow (for PMs B) are the same.

Four of the substations have negative shares for the delta-T or return temperature components. Since these components are designed to be revenue neutral for substations with temperatures equal to the design temperatures (10 °C for delta-T and 16 °C for the return temperature), the negative shares show these substations exceed the design criteria. For these substations the total cost decreases compared to the reference price model.

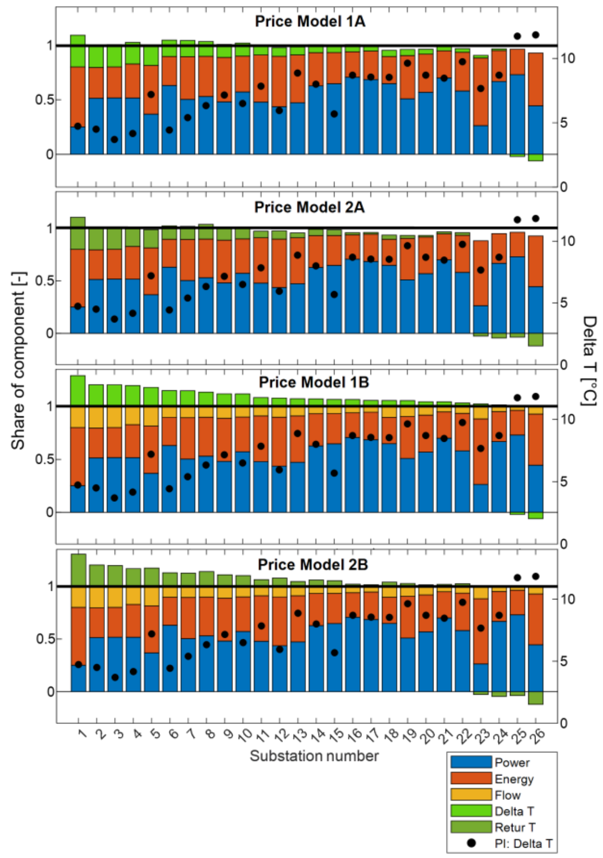

Fig. 3: Shares of price model components for the four new price models along with PI delta-T.

For price models B, the delta-T and return temperature components are added to the reference price model, whereby the incentives for the DC customers to maintain well-functioning substations increase overall. However, the total cost per customer only increases if the substation is performing worse than the design criteria and as can be seen in Fig. 3 for PM 1B, the total cost in fact decreases for substations number 25 and 26. These two substations also have the highest delta-Ts corresponding to 11.8 and 11.7 °C which indicate that price models B reward well-performing substations. For PM 2B, substations no. 23 and 24 also have negative return temperature components in addition to no. 25 and 26. Conversely, the delta-Ts for these substations are lower than the design delta-T, 7.7 and 8.7 °C respectively. A potential reason is the supply temperature has increased above 6 °C during the high cooling load hours for which the PI delta-T is calculated (75-100% of max cooling power). This means the return temperature can be ≥16 °C without the delta-T being ≥10 °C. Moreover, some customers have high delta-Ts or return temperatures for low cooling loads but not for high cooling loads. From a DC system point of view, it is most crucial to achieve high delta-Ts during high cooling load periods. Such substations will therefore be disproportionately favoured from the DC system's point of view whereby it may be beneficial to only apply the temperature component during peak load hours.

TABLE III
SUMMED TOTAL COST PER PRICE MODEL FOR
26 SUBSTATIONS, MAY-SEPTEMBER.

Price Model	Total Cost [€]	Difference
Reference	€ 388 000	NA
1A	€ 384 000	- 1.0 %
2A	€ 377 000	- 2.9 %
1B	€ 427 000	+ 10.0 %
2B	€ 420 000	+ 8.3 %

The total costs generated by the reference and the new price models for the period May through September for the investigated 26 substations are shown in Table III. The total cost for the substations is equivalent to the total revenue for the DC company, but for consistency the word "total cost" is used. Price models A have a lower total cost than the reference price model, and price models B have a higher total cost. Price models A result in a lower cost compared to the reference PM because the temperature component will generate a zero cost or a bonus for hours when the substation's temperature is equal to or greater than the design temperature. Contrarily, the reference PM will generate a cost for such hours since the flow component charges for every cubic meter used.

Price models B result in a higher total cost compared to the reference PM since they have four price components instead of three, along with most of the substations failing to achieve design temperatures. However, a sensitivity analysis can be done to find the price level of the temperature components so that the total cost for all substations would match the cost from the reference price model. For individual customers, such a price level will nevertheless increase the total cost for some and decrease the total cost for others.

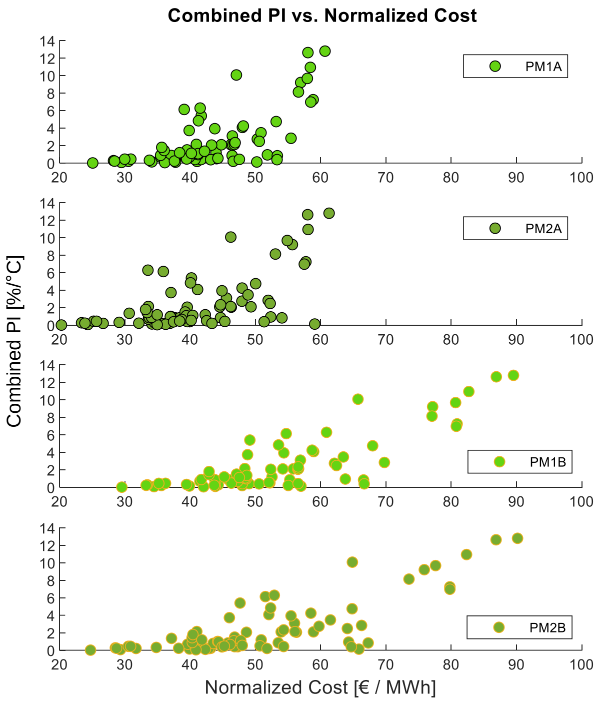

Fig. 4: Performance indicator Combined PI vs. normalized cost for the four new price models.

PMs 1A and 1B with a delta-T component, resulted in higher costs compared to PMs 2A and 2B with a return temperature component. This is due to the fluctuating supply temperature and as previously mentioned, a delta-T of 10 °C is more difficult to achieve compared to a return temperature of 16 °C. Therefore, a price model with a return temperature component instead of a delta-T component may be perceived as fairer from a customer perspective.

In Fig. 5, the relationship between PI delta-T and the normalized cost is presented for the four new price models. For substations with high delta-Ts, price models A resulted in a lower normalized cost compared to the reference PM in Fig. 2. Since price models B have one more price component than the reference PM, the normalized

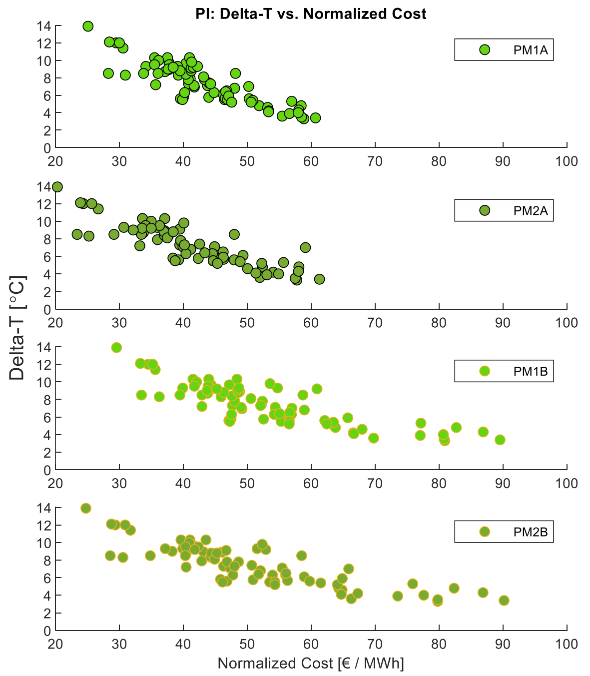

Fig. 5: Performance indicator delta-T vs. normalized cost for the four new price models.

cost increases considerably for substations with low delta-Ts. This demonstrates the new price models provide stronger incentives for improving low delta-Ts as well as substations with high delta-Ts are rewarded with a lower normalized cost.

In Fig. 4 the relation between the performance indicator Combined PI and the normalized cost is shown for the four new price models. Although the normalized cost is low for substations with a low Combined PI (<2.0 $°C^{-1}$) the range varies from about €20/MWh to €65/MWh. This indicates substations with a low Combined PI can either have a low or a high normalized cost. Nevertheless, for price models B, substations with a high Combined PI >8.0 $°C^{-1}$ also have the highest normalized costs of >€70/MWh, compared to price models A, which provide stronger economic incentives for improvements of such substations.

VI. Conclusion

In this paper, four new district cooling price models were designed and evaluated with the aim to provide incentives for efficient substation operation. The existing price model included the price components power, energy and flow and the new price models comprised a combination of the existing price model's components as well as either a delta-T or a return temperature component. The delta-T or return temperature components were designed as revenue neutral with respect to the district cooling system's design temperatures. It was shown the existing price model already provided some incentives for well-performing substations. Nevertheless, the new price models generated a lower total cost for efficient and well-performing substations, thereby providing stronger economic incentives for the customers to achieve higher delta-Ts and return temperatures. However, this assumes the customers autonomously will improve poorly performing substations affronted with large cost increases. Increased costs generate increased revenues for the utility company. An opportunity for the utility company is thereby to offer support to customers in need of improving their substations, which in the long-term will favour both the customer and the utility company.

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