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A study on how efficient measures for secondary district heating system performance can be encouraged by motivational tariffs

Kristina Lygnerud[1,2*], Theo Nyberg[2], Anna Nilsson[2], Antoine Fabre[3], Pascal Stabat[3], Chloé Duchayne[4] and Valentin Gavan[4]

Abstract

Background District Heating (DH) is a technology that provides heating and domestic hot water to buildings and is an important technology for supporting the European energy transition. As such the heating systems increasingly resort to renewable heat sources and waste heat, it is even more important that they operate in the most efficient way possible. DH companies have access to the primary network of which they can impact system performance. To maximize the efficiency of the system, however, it is important that the system at the building level, known as the secondary system, is also efficient; otherwise, overall system efficiency is reduced. To increase system efficiency, return temperatures from the secondary system into the primary system have been targeted through motivational tariffs. There is limited information on how to establish a motivational tariff that motivates the customer to improve both the primary and secondary systems, which is a gap that this paper aims to fill.

Results In this paper, the impacts of retrofit actions in secondary systems are assessed through simulations. The identified relevant refurbishment measures to lower the return temperature to the primary system are variable flow pumps, low-temperature radiators, parallel heat exchangers, and a pass-through DHW system. Apart from simulated refurbishments, we also identify that the secondary system sometimes generates excess heat, which is valuable to recover, especially during peak load periods for the primary system. Hence, motivational tariffs targeting secondary system efficiency should also encompass an incentive for the customer to make use of waste heat in the secondary circuit to lower peak demand for the DH system.

Conclusions To date, the most commonly used parameters introduced to customers are linked to the flow of water through the customer's asset and the bonus malus principle. The results from simulations show that DH companies can introduce additional parameters to support customers in guiding their secondary system to perform more efficiently. Increased overall system efficiency has a positive impact on both costs and emissions.

Keywords District heating, Secondary system, Retrofit actions, Motivational tariff, Price model

*Correspondence:
Kristina Lygnerud
kristina.lygnerud@energy.lth.se
Full list of author information is available at the end of the article

Background

District heating

District heating (DH) is a technology that provides buildings that are connected to a distribution network with space heating (SH) and domestic hot water (DHW). The heat is either generated in a production unit (it can be a plant for combined heat and power or a plant for heat generation only) or obtained from an industrial process or the urban infrastructure, and the heat carrier is water. Depending on the heat supply, its impact on the environment varies. DH allows the use of local and renewable energy sources, and as a consequence, this technology was identified as being important for the European energy transition laid out in the *EU Strategy for Heating and Cooling* published by the European Commission in 2016 [1]. The importance of making use of existing, sustainable energy solutions is increasing given the current climate crisis [2] and the geopolitical situation in Europe. The first commercial DH systems went into operation in the 1880s in the US [3]. Over time, the technology has progressed from using steam-based systems to the most modern technologies, which use low-temperature heat sources with a supply temperature below 70 °C [4]. Modern DH technology makes use of locally available heat sources that vary in terms of size (power), accessibility and temperature. The variation across these resources means that it has become increasingly important that the demand and supply accurately match. Indeed, assets need to be fully functional and operated to meet demand, using the most cost-efficient heat supply available and without faults in the system. Apart from cost savings, increased system efficiency allows for the use of fossil fuels to be reduced.

Secondary system impacts primary system performance

Reduced return temperature is a central parameter for decreasing heat losses, increasing the efficiency of heat pumps and flue gas condensation, and obtaining higher electricity yields in CHPs and the more efficient use of heat distribution capacity in all parts of the primary system [5]. Commonly, heat is supplied to the customer at a customer-building interface, where the heat is transferred into the building system (referred to as the secondary system) via a substation. A flawless system might appear to be a standard solution, but research has shown that system errors are frequent, often at the substation [6] but also a result of inefficient customer behaviour. In [7], the authors show that only 26% of substations work correctly and that one-third of malfunctions stem from the secondary system. In [8], substation valves are shown to cause 24% of faults, while those percentages for the substation control system, other substation items, the secondary side distribution line, the domestic hot water system, space heating system, and other are 15%, 12%, 14%, 12%, the 8% and other 15%. A study of Swedish DH companies, based on self-assessments of faults in customer installations, identified that errors are frequent, with leakages (33%) and the heating system not functioning properly (31%) accounting for the largest percentage of issues [9]. To improve systems, it is important to work on the technology as well as on the demand side. The secondary system is often out of reach of district energy companies, and so, any malfunctions in these systems must be managed by the customer directly. Not all customers are aware that their system is not fully efficient (the faults are evidencing themselves neither in indoor comfort nor in the temperature of domestic hot water supply), which can lead to negative impacts on the distribution system of the DH company (the primary system): if the return temperature of the water is too high, then it reduces the efficiency of the primary system.

Energy as a service

There is a novel development in the DH sector to offer heat supply as a service. Sweden is a mature DH market, with more than 50% of the heat supplied to buildings coming from DH. In such a market, the need to improve existing systems is important for overall district energy efficiency and for making energy services that can generate a win–win scenario for both customers and energy companies [10]. It is common that such services necessitate collaboration between primary and secondary systems, which leads to a minimization of inefficiencies for the whole system. One new type of collaboration, which is increasingly discussed in Sweden, is the inclusion of customer-owned heat pumps as part of the heat supply in the DH system [11]. The collaboration between secondary and primary energy systems can necessitate both technical and behavioural changes. In the latter case, the customer needs to use the system in such a way that the primary system benefits by, for example, working with the customer to shave peak load heat demand or using the building itself as a heat storage unit. It is often easier to modify a dysfunctional technology than to implement and operate adjustments at the customer level. The latter can, however, be achieved through certain business model features that are referred to as motivational tariffs.

Motivational tariffs

Motivational tariffs are one way in which customers' understanding of the secondary heating system, how well it operates and how it performs can be increased [12]. There are several ways in which to incorporate a motivational component into DH price models, the most common of which are listed in [8]. These tariff structures can be applied for an entire year or only during the heating season. Common motivational factors are as follows:

- Flow component tariffs (m^3/MWh) have the customer pay for the amount of water that has passed through the substation per consumed amount of heat, which is an indirect way to target low return temperatures, as increased flow leads to high return temperatures [13].
- Bonus-malus tariffs, which include percentage variations in the heating price, or one of its components, according to the offset between a measured key parameter (return temperature, cooling performance through the substation, and water volume per supplied heat) and a reference value [8]. In short, customers with return temperatures below a reference value receive a bonus, while those with return temperatures above the reference value pay a fee [13]. The value used for this calculation is often an average over the entire billing period: for one month and up to one year [8]. The value can be specified by the utility or be the average value of all customer installations. A bonus-malus structure can also be designed to be revenue neutral for the DH company [13].
- Discounts for using return-line heat: customers are offered a premium for drawing heat from the return line. Indirectly, this further reduces the return temperature of the water returning to the heat production unit. The aim is to encourage customers to install low-temperature systems, such as underfloor heating, combined with instant domestic hot water preparation.
- Incentives for customers to become prosumers: feed-in tariffs are aimed at waste-heat suppliers to encourage them to supply the system with heat [8].

Out of these four models, the flow component and bonus-malus are the most widely used in mature DH markets, such as Denmark and Sweden, to incentivize lower return temperatures, and thus, most of the literature on motivational tariffs focuses on the experiences of these two countries.

Insights on motivational tariffs from mature DH markets

In a mature market, technology is well established, and the offer to the customer is set. In such a context, system efficiency is crucial to remain a competitive heating alternative. Hence, it is not surprising that when reviewing the literature on motivational tariffs, most of the information comes from mature DH markets like Sweden and Denmark. It should be noted that these markets differ in terms of setup. In Sweden, the market has been deregulated since 1996 and holds a mixture of municipal, private and public–private organizations. In Denmark, the market is regulated. In 2013, approximately half of Swedish DH companies assessed had either a flow or a bonus-malus component to incentivize customers [14]. A motivational component is more common in the price models of larger DH companies. A study from 2017 [15], based on a price model survey of large Swedish DH companies, identified that the most common price model components for Swedish DH companies are a fixed component, a component reflecting the size of the installation (power), an energy demand component, and a flow demand component (present in approximately 50% of the price models surveyed). Another study of Swedish DH companies found that one-third of the Swedish DH price models with a flow demand component also include a bonus-malus structure, where customers' heat exchanger efficiency is compared with the average efficiency in the system and customers are incentivized to improve the efficiency of their heat exchangers wherever possible [13].

In [13], a large variety of flow component designs that may be applied to customers with contracted loads above a certain amount, a return temperature above a certain value, or a temperature difference below a certain value are identified. The flow component may also be applied only during certain times of the year, typically during the heating season, and to different customer segments. For a DH consumption profile of a typical Swedish multifamily house, the average flow demand component is small and accounts for approximately 2% of the total heat cost [16]; even so, flow can be an efficient way to talk to customers and to increase customer awareness about the importance of an efficient substation [5].

In Denmark, several DH companies have introduced motivational tariffs to incentivize their customers to reduce their return temperatures [17]. The tariffs are normally customized according to the specific characteristics of the DH systems and the heat consumers connect to the network. In [12], the involvement of five Danish DH companies in initiatives targeting critical heat customers was studied; they all had a motivational tariff in place to motivate customers to make improvements, and these were based on either flow, return temperature, or cooling performance.

In [18], a motivational tariff from Middelfart Fjernvarme, a DH company, was used. With the tariff, the DH company gives the heat consumer a discount of 1% for each 1 °C reduction (to a maximum of 20% in total) in their return temperature compared to the reference DH's annual average return temperature. The DH company finances the discount from the savings made from reducing the supply and return temperatures. The same applies to the DH grid in Viborg, where a bonus-malus motivational tariff was introduced in 2002 and the supply and return temperatures have decreased stepwise since then [19]. This motivational tariff led to extra costs for the DH company of 270,000 euro/year, but when taking the approximately 10% reduction in heat loss into account, it has generated cost savings of approximately 400,000 euro/year. The performance of the tariff has been further improved by delivering information to customers with the highest return temperatures and giving them advice on how to improve their heating systems to save money. Viborg DH realized that there must be an individual goal for the return temperature for each customer to properly motivate them. In the case of the Viborg grid, the calculation of the individual goal for the return temperature was enabled by the fact that the energy metres could collect data on both supply and return temperature (Ibid).

A motivational tariff may also be used between the DH supplier and distributor, as in the case of the Roedovre DH grid, which is supplied by heat from Vestegnens Kraftvarmeselskab I/S (VEKS) [20]. Roedovre DH pays additional fees to VEKS if the return temperatures at the substations connecting Roedovre DH and VEKS are too high or if the daily load variations are too large. In contrast, VEKS pays a premium if the same parameters are below a certain level. Both charges are based on hourly mean values, weighted by daily consumption, and paid on an annual basis (ibid).

Challenges with motivational price models

Some of the challenges are linked to customers' perception of what a 'good' DH price model looks like. In a focus group study with Swedish DH customers [21], a good DH price model from the customer perspective was described as easy to understand and fair, recognizing the need to build a close relationship with the energy company and accounting for conflicting interests.

Understandable to customers: One of the major challenges with a motivational tariff is that the structure can be difficult for the customer to understand [12, 13, 21]. In [16], it was suggested that the flow demand component in Swedish DH price models was the least transparent part, unlike the energy demand component. As a result of the lack of heat tariff transparency, customers are not aware of how much extra they pay because of poorly operated or malfunctioning systems [12]. For large customers, there might be a lack of internal communication between the person handling the bill, the person responsible for the heating system, and the building owner, leading to the cost of heating ending up as just a number in the financial report, without any measures taken to lower it. One way in which to reduce the risk of this situation happening is to present the motivational tariff separately on the bill and to have a more understandable tariff in general to ensure that customers can see the economic consequence of a system that functions poorly. It has been suggested by [15] that the design of future price models needs to be increasingly transparent, particularly the component that makes up the major share of the cost, which, in Sweden, is the energy demand component; this is also where any motivational effort should be directed. The experiences with the flow demand components of Swedish DH companies also show that with sufficient, easy-to-understand information on why there is a fee based on the flow and how to correct faults, customers are more inclined to act on the price signals from motivational tariffs and undertake improvements [13]. Without this information, customers regard the flow component as an additional ununderstandable cost that they do not want to pay. A study of ten Swedish DH grids [14] found that even if there had been an effect on return temperatures after the introduction of a motivational tariff (noticeable after 1–2 years and a significant improvement after 6–7 years), the relationship between the information given to heat customers and changes in return temperatures is easier to understand than is the motivational tariff per se.

Perceived fairness to customers: To manage the perception of fairness, DH companies usually introduce motivational tariffs with extensive information campaigns to reduce the risks of loud complaints from customers that are charged a malus under a bonus-malus structure [8]. When introducing a motivational tariff, it is also important to carefully select the most suitable key parameter. For example, customers may find a motivational tariff with a flow component unfair since supply temperatures vary from customer to customer due to heat losses in the grid [12]. This problem is reduced when the tariff is put on the return temperature since the supply temperature does not significantly influence this parameter. A few DH companies in Sweden that have a flow component have also introduced a correction factor to reduce the risk of some customer groups, such as those connected further away from the heating plant that supplies the heat, thus placing them at a disadvantage [21]. As the supply temperature varies more during the summer than during other seasons, when heat demand is low, the flow demand component could be applied only during the heating season, when the variations are lower and the conditions for good cooling performance are beneficial.

Customer relationship: In [21], the authors point to the fact that customers do not understand the flow component, indicating that it is not enough to introduce a flow component to incentivize customers to make improvements to their heating systems. In recent studies, the focus has been on increasing service orientation among Swedish DH companies, e.g., service agreements, invitations to yearly customer meetings, and analyses of customer data to detect faults [13]. The most important factor in increasing customers' willingness to lower their return temperatures is a close relationship with the DH company. Smaller DH companies that were interviewed conducted annual visits to their customers to spread information and establish close customer relations, while larger companies did not have the time and resources to establish such relationships. As a result, smaller DH companies found it easier to convince their customers to improve their installations to reduce return temperatures and to incentivize their customers through a collective responsibility to keep heating prices down than did large DH companies (ibid).

Conflicting interests: A close relationship between the DH company and its customers can facilitate the management of conflicting interests. In [8], the authors identify two important aspects to consider, namely, conflict between actors, particularly between the building owner and the DH company, about who should undertake and finance heating system improvements. In [13], some Swedish DH companies use a flow component as a last resort, only if no other measures have worked to persuade the customer to address the fault(s) causing high return temperatures. There is an inherent conflict of interest (who should pay) between the owner and the actual user of the heating system. Conflicts of interest are also highlighted by [11], particularly the conflict between the heat customer, pushing for high thermal comfort at a low cost, and the DH company, wishing to reduce DH supply temperatures. Between the two actors is the plumber, often performing any changes or upgrades to the heating systems, adhering to customers' interests by delivering a service at a low investment cost, but that may also over-dimension the systems to ensure the thermal comfort of the heat customer. It is suggested by [12] that the plumber is just as important as the customer in any initiative to lower return temperatures.

Summing up

Conventional DH price models are designed to cover the cost of fixed assets (network and production units) and operational costs (heat production, distribution, and maintenance). The models tend to have one part that is fixed and one that is variable, linked to the volume of heat consumed. Some companies have alternative variables linked to the volume of water passing through the customer's system or to the installed size (power). Price models are designed to cover the costs of the primary network (marginal cost principle). The first thing to do before installing a motivational tariff is to correct known errors in the installation. Thereafter, to minimize the impact on the primary system of a secondary system that is underperforming, motivational tariffs can be applied. For efficiency, these tariffs need to be customized to the characteristics of the DH network and its customers [18]. There is limited research on which motivational tariffs are most efficient, possibly explained by the fact that efficiency depends on the characteristics of the primary system. Another explanation is that in some systems, one action is applied, whereas in other systems, several actions are applied simultaneously, making it challenging to generalize as to which scheme represents an efficient motivational pricing scheme. As seen in the above literature review, flow components and bonus malus are the two actions for secondary system efficiency that appear most frequently in mature district energy markets, possibly explained by being actions that are understandable and tangible to customers compared to the capacity (also referred to as power) component, rather than being the most efficient actions through which to reduce return temperature. Indeed, in a study of Swedish DH companies, [22] it is shown that motivational tariffs reducing the need for high capacity (e.g., energy conservation) generate higher savings than do tariffs reducing annual energy use. In another study [23] of the impact of a new price model of a Swedish DH company, it was concluded that it is efficient to have peak load choices/steering performed by the DH company, whereas the customer can make active choices on base load supply.

Research question

Existing motivational tariffs target actions that directly benefit the primary system, but there is limited information on how to establish a motivational tariff that motivates the customer to improve both the primary and secondary systems. This research gap leads to the research question addressed in this paper: *What measures should be incentivized to increase the performance of the secondary network?* In answering this question, we aim to provide new knowledge allowing DH companies to improve their application of motivational tariffs.

Methods

To understand what a motivational tariff for a secondary system can look like, a generic price model scheme, allowing for such motivation, is derived first, based on the existing price modelling practice in DH (as presented in Sect. "Background"). Thereafter, a simulation is established to understand what refurbishment activities are most efficient for improving substation performance.

Generic price model scheme

The most common ways in which to incentivize customers to improve the performance of their systems are well known, and we can conclude that DH companies want to create as large a difference as possible between supply and return temperatures. Further analysis on those measures that improve the secondary system the most has been performed to shed light on the related motivational components.

The point of departure is a conventional price model, established for a primary system encompassing a fixed and variable tariff, to which an incentive tariff variable is added. On the primary side of the DH system, it is standard to charge a fixed subscription fee for the installed capacity (power) required by the customer and a variable, volume-related fee linked to the volume of heat consumed. In some price models, it is also standard to charge for the volume of water that has been used by the customer in their secondary system. It is in the interests of DH companies to maximize the difference between the temperature of the heat supply and that of the return supply (referred to as 'delta t') and to get as much cost-efficient heat supply into the system as possible. It is also important to reduce peaks, which are costly in terms of generation, making peak load shaving relevant.

The price model can be expressed as follows:

$$\mathrm{TT} = \mathrm{FT} + \mathrm{VT} - \mathrm{IT} \quad (1)$$

where TT = Total Tariff (the price to be paid by the customer, €); FT = Fixed Tariff (two parts: a one-time cost paid when connected and a repeated cost for subscribing to a certain capacity, €). It is also possible to express it as F_connection + F_capacity. *F_connection* is linked to distance; the further the distance to the customer is, the costlier it is to connect the customer. *F_capacity* is linked to the size of the customer installation (power). VT = Variable tariff (a price paid monthly, €), which is linked to the volume of energy consumed by the customer in MWh, where the cost per MWh is expressed VT can also include the volume of water in cubic metres flowing through the substation: (T_m^3 = Unitary Price (€/m^3)* Quantity (m^3)).

IT = Incentive Tariff (the monetary gain that a customer obtains through improving the performance of the secondary circuit). IT is an incentive for reducing the return temperature (on the primary side) below the design value. We iterate several different scenarios, testing technical measures to improve secondary system performance, to arrive at an efficient IT design. We assume that in mature markets, when working to improve the performance of the secondary system, it is important to generate win–win scenarios s for both the DH company and customers. Hence, we refrain from including malus in the motivational tariff. We also assume that both DH companies and customers are economically rational and, hence, that costs for improving the secondary system will be covered by the increased system performance and there is no need to add any repayment of investment element in the motivational tariff.

Analysis of refurbishment alternatives for secondary systems

Studies of DH system modelling are widely present in the literature, focusing mainly on the primary network and not on the secondary side [24–26]. In this study, the entire system, including the secondary side, is modelled (see Annex 1). To do so, a dynamic thermohydraulic model is deployed. As [27] demonstrated, the Modelica language and the dymola environment are suitable for modelling a DHN. A descriptive scheme of the applied model is shown in Fig. 1.

A heat generation plant composed of a deep geothermal source and a gas boiler (in series configuration), typical of a 3rd-generation DHN in France, is modelled. This type of plant is sensitive to return temperatures in the primary system. The geothermal source temperature is often limited, and as the power provided by the source is proportional to the difference between supply and return temperatures, an efficient way in which to increase the geothermal power is to lower the return temperature. Typically, the supply temperature is set through a temperature reset control based on the outdoor temperature and minimum DHW temperature allowed (see Fig. 2). In the model, the temperature reset control has been calibrated following the secondary-side equipment settings.

Gas boilers are used when the outlet temperature of the geothermal plant is operating below the temperature set point. Gas boiler efficiency and geothermal heat exchanger (HEX) efficiency are considered constant.

In this study, the DHN supplies six buildings with heat. The buildings are located in France, each with an annual consumption of 170 kWh/m^2/year. Simulations

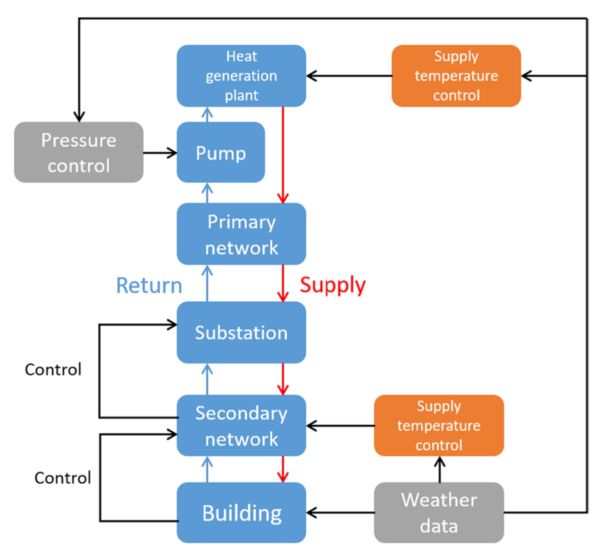

Fig. 1 Structure of the model from the building to the heat generation plant

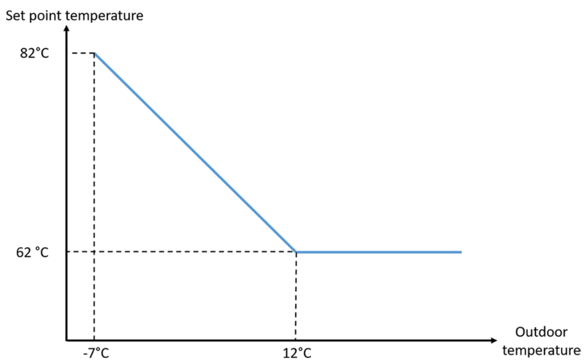

Fig. 2 Primary supply temperature reset control

are carried out for the month of January 2021 in the Paris area, for which the weather data are given in Fig. 3. From the January consumption, the winter season consumption is extrapolated based on the heating degree days (HDD) method. A total of 36 different configurations of secondary hydronic systems are studied to assess the energy gains of retrofit actions compared to a base (existing) case.

The substation architecture, namely, the heat exchanger, the pump and control technology (valves), the radiators for heating, and DHW preparation, have an impact on DHN performance.

Heat exchanger

Usually, a substation supplies SH and DHW through one or several heat exchangers (HEXs). According to [28], three different substation architectures are commonly employed, of which the parallel version (Fig. 4) is the most efficient. Nevertheless, although the architecture with a unique HEX was not studied in [28], its use is widespread in France. In this study, parallel and unique HEX substation architectures are both simulated.

Pump and control technology

The control system and pump technology on the secondary side must be considered jointly. The choice of control depends on the mass flow rate regime driven by the pump. Therefore, three different combinations can be used: a constant flow rate pump with a three-way valve (3 V), a variable flow rate pump with a three-way valve (V3V), and a variable flow rate pump with a two-way valve (V2V). In Fig. 5, the connection layouts of two- and three-way valves are shown.

Radiators

The system has been designed to work with high-temperature (HT) radiators, which are standard in existing buildings (with a temperature regime of supply 80 °C and return 60 °C), or low-temperature (LT) radiators used in retrofit and new buildings (with a temperature regime of supply 55 °C and return 45 °C).

Domestic hot water

For the DHW, three architectures are selected (see Fig. 6). The instantaneous architecture (a) supplies

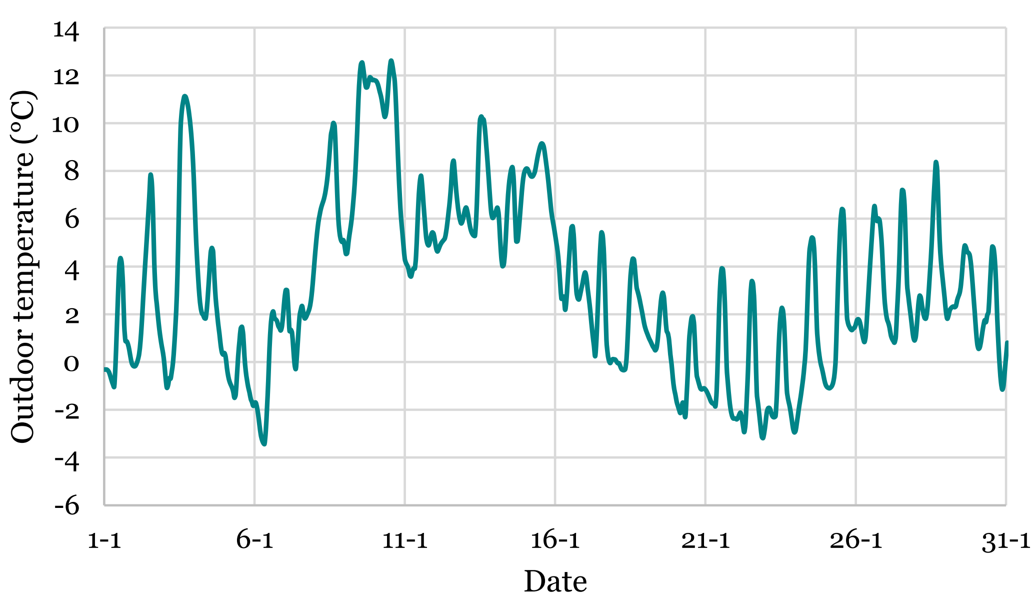

Fig. 3 Outdoor temperature evolution

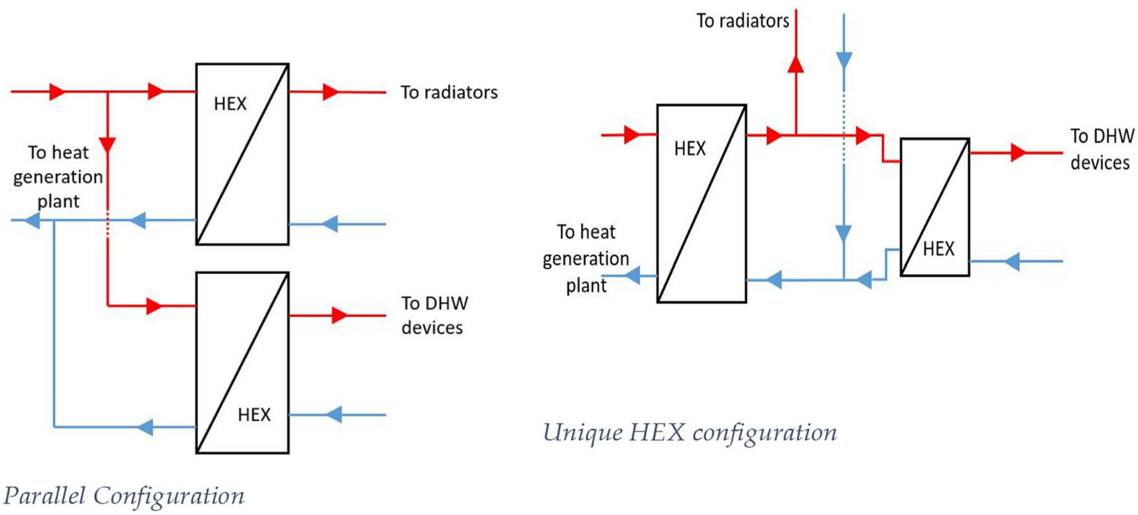

Fig. 4 Substation architectures

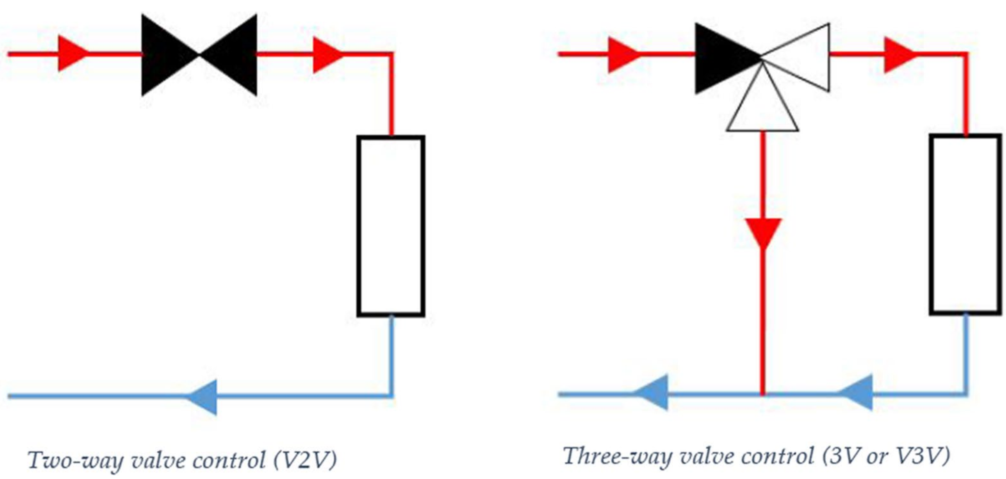

Fig. 5 Radiator control systems

the DHW secondary network directly from substation HEX without any storage. The second architecture introduces a hot water tank between the substation HEX and the DHW network (b). The third architecture is the bypass tank architecture (c), a compromise between the two previous solutions that can bypass either the tank or substation HEX; this third architecture is used only when it significantly lowers the return temperature of the primary system.

Results

First, the results from the simulations are provided, which are then applied to the generic price model for secondary systems.

Results from simulations

Two sets of simulations are performed (on a unique HEX architecture and on a parallel architecture). Below, the main results are presented, covering 18 simulations each.

Results from simulation 1: unique HEX

The first simulations are focused on the comparison of all the combinations for a unique HEX architecture. Figure 7 presents the evolution of the differences in primary system return temperatures.

According to these results, the control strategy using a variable mass flow rate pump and a V2V leads to a better

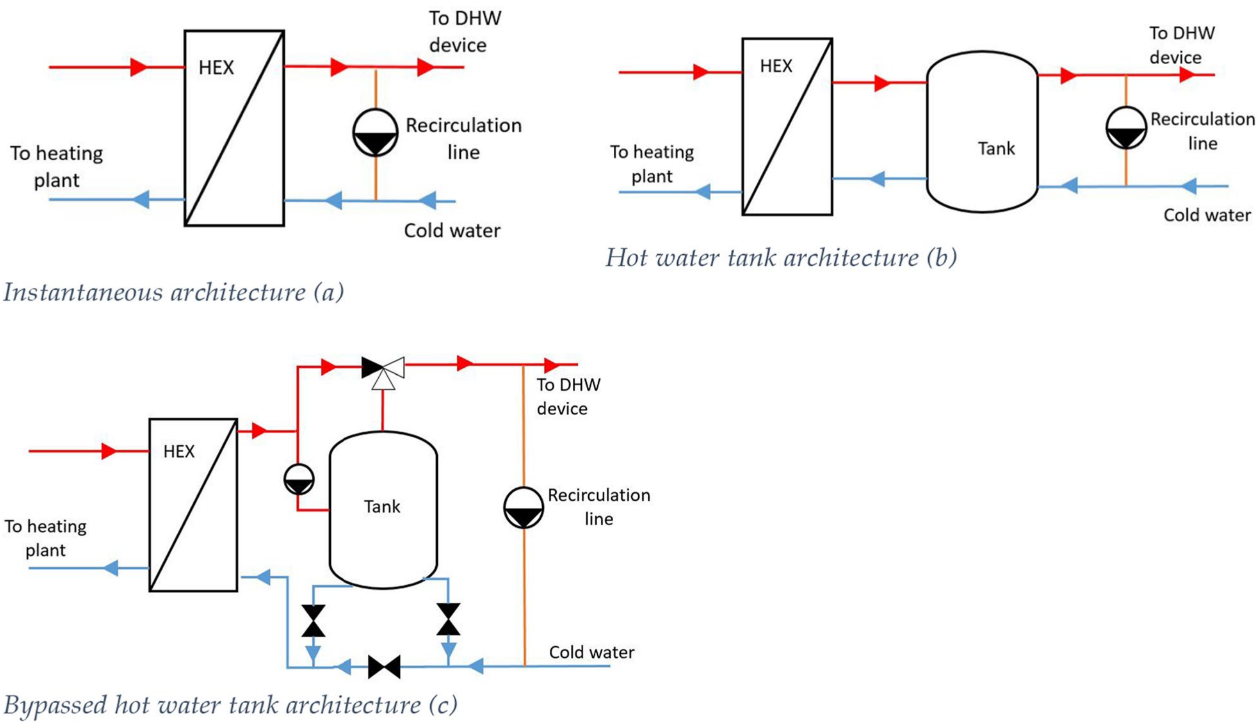

Fig. 6 DHW architectures

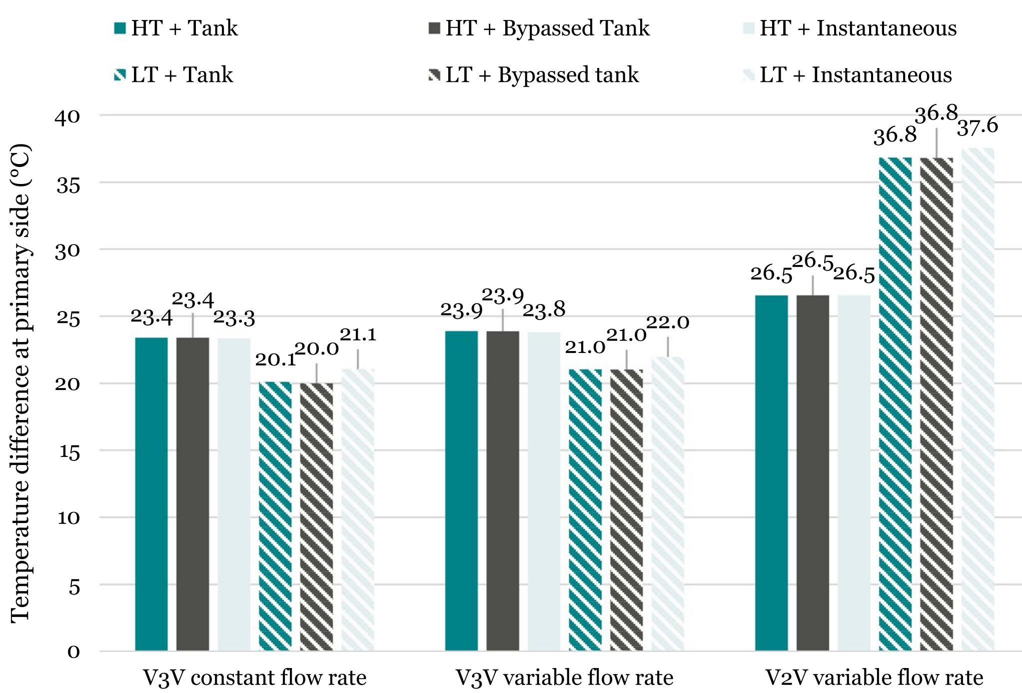

Fig. 7 Primary ΔT comparison for a unique HEX substation

ΔT value (i.e., better performance) compared to the other two control strategies, especially in the case with LT radiators. Indeed, the ΔT gain ranges from 3.1 to 14.2 °C, which is significant. With the V3V constant flow rate pump, when the operation is far from the design conditions, the flow rate passing through the radiators is lower than that delivered by the pump. Hence, most of the flow coming from the pump is bypassed by the three-way valve and mixed with the cooled flow coming out of the radiators. Consequently, the secondary-side return water heats up, thereby increasing the primary return temperature. In contrast, with the V2V and variable flow rate pump, no flow is bypassed, which implies that the secondary return temperature is equal to the temperature at the radiator outlet. Moreover, with a V3V and a variable flow rate pump, the bypass flow is decreased, and thus, the performances of the V3V and variable flow rate pump are better than are those for the V3V and constant flow rate pump but not as good as those for the V2V solution.

Regarding the results for the different DHW supply architectures, two cases must be considered depending on the type of radiator. For the cases with HT radiators, the DHW supply solutions have almost no impact, whereas with LT radiators, the instantaneous DHW supply creates a gain of 1 °C. Indeed, by using the instantaneous architecture, the hot water tank is no longer needed, and there is no need to compensate for heat losses. Hence, performance is improved. However, even if DHW performance is also improved, the flow rate used for space heating is more important for HT than for LT radiators; thus, the impact of DHW on the secondary return temperature is weaker.

LT radiators are interesting only where V2V is installed because, with the V2V and variable flow rate pump, the flow rate is continuously adjusted to the space heating demand, and the return temperature is lowered. In a V3V case, LT radiators can reduce the performance level compared to HT radiators. With a unique HEX substation, the supply temperature is 60 °C for LT radiators. The design of LT radiators is based on a lower ΔT between the inlet and outlet. Thus, when heating demand is lower than the design conditions, as the inlet temperature should be maintained at 60 °C for DHW, the flow rate in the radiators will be lower and the bypass flow rate will be higher.

Results from simulation 2: parallel HEX

The second simulation addresses the configurations of a parallel substation. Figure 8 presents the evolution of the primary temperature differences among the various cases.

The instantaneous DHW architecture is better than the bypassed tank architecture. Indeed, as previously stated, with the instantaneous solution, there is no need to maintain the temperature in the hot water tank. Nevertheless, the performance of the tank architecture is poor (temperature differential from 0.8 to 8 °C) compared to the performance of the other two solutions. In

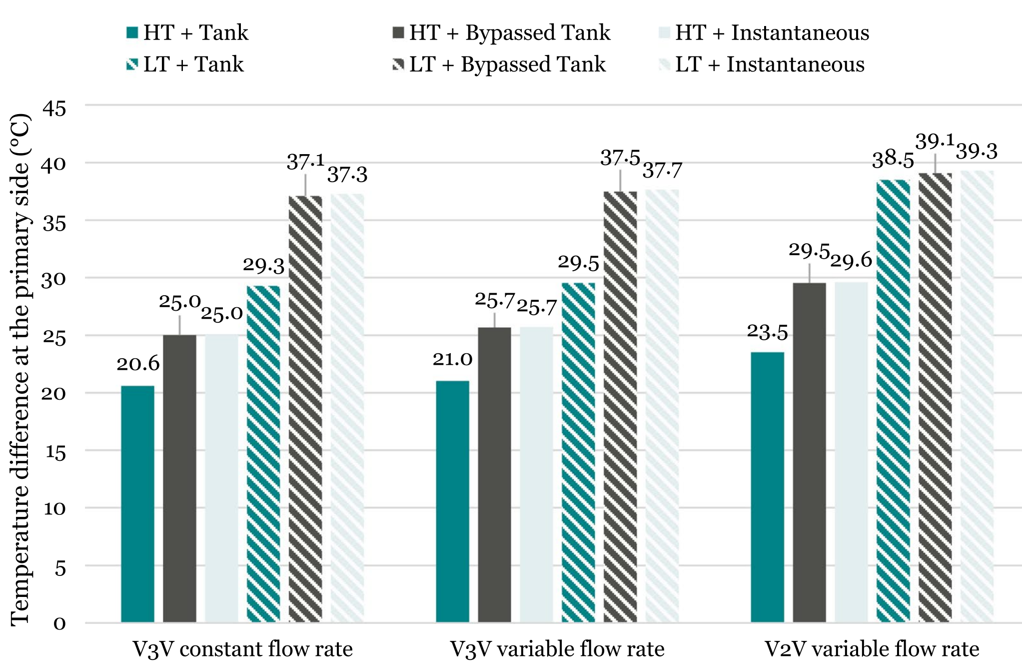

Fig. 8 Primary ΔT comparison for the parallel substation

this configuration, the flow at the inlet of the secondary side of the HEX comes directly and exclusively from the hot water tank (T = 60 °C), in contrast to the two other configurations. In these cases, the secondary flow at the HEX inlet can come not only from the hot water tank but also from the cold-water network and the recirculation line, thereby allowing for a reduction in return temperature.

The use of LT radiators enables an increase in ΔT at the primary side, implying a smaller return temperature at the secondary side than with an HT radiator. With the parallel architecture, the secondary supply temperatures of the DHW and SH are managed separately. As a result, to provide space heating, the secondary supply temperature can be lower than 60 °C.

Price model

In Fig. 9, the cases that have a positive impact on ΔT are plotted; eight were excluded because they result in a negative change in ΔT (e.g., no system improvement). The x-axis maps ΔT, and the y-axis is the cost of undertaking the action associated with the case. There is one case, the reference case, that does neither comes at any cost nor provides any change in ΔT, to which all other alternatives are compared. This reference case is characterized by an installation that is common in France: HT radiators, three valves with a constant flow, a heat exchanger, and a DHW tank without any bypass configuration.

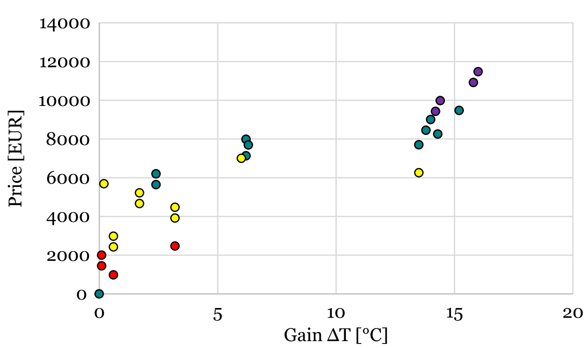

Fig. 9 A plot of the 28 cases showing ΔT and the cost of undertaking the action (in euros). Red dot = 1 action, yellow dot = 2 simultaneous actions, green dot = 3 simultaneous actions, and purple dot = 4 simultaneous actions

A summary of the best and worst cases in terms of ΔT is presented in the text below, as well as in Table 1.

Reviewing the cases where one action is undertaken, we can conclude that the best effect is that of ensuring efficient water flow with two valves and a variable flow rate; the worst effect is that of installing only LT radiators, as doing so yields a negative ΔT (leading to increased gas consumption).

In the cases where two actions are undertaken, the best effect is that of combining efficient flow (two valves and a variable flow rate) with LT radiators; the worst effect is that of installing LT radiators and a DHW bypass.

Reviewing the cases where three actions are undertaken, we find that the best effect is that of combining efficient flow (two valves and a variable flow rate) with LT radiators and parallel heat exchangers; the worst effect is that of installing LT radiators, distributing the hot water using a bypass, and making the flow variable while still resorting to three valves.

Where four actions are undertaken, the best effect is that of combining efficient flow (two valves and a variable flow rate), LT radiators, parallel heat exchangers, and instant domestic hot water preparation that requires no tank; the worst effect is that of installing LT radiators, parallel heat exchangers, a variable flow with three valves, thus transforming water distribution into a bypass system.

The following abbreviations are used in the table:

- LT: Low-temperature radiator
- V2V: 2 Valves and a variable flow rate
- V3V: 3 Valves and a variable flow rate
- Bypass: Make domestic hot water by means of a bypass, not a tank
- Instant: Instant preparation of domestic hot water

Table 1 Possible improvements to the secondary system

1 Action	1 Action	2 Actions	2 Actions	3 Actions	3 Actions	4 Actions	4 Actions
Best	Worse	Best	Worse	Best	Worse	Best	Worse
Technical changes							
V2V	LT	LT + V2V	LT + Bypass	LT + Parallel + V2V	LT + V3V + Bypass	LT + Parallel + V2V + Instants	LT + Parallel + V3V + Bypass
ΔT improvement							
3.2	− 3.2	13.5	− 3.2	15.2	− 2.3	16	14.2
Gas saving MWh							
15.5	− 138.1	53.4	− 157.5	56.5	− 229.6	58.3	53.4

- Parallel: Parallel heat exchangers

To conclude, if only one action is taken, then it should be to improve the flow by installing two valves and a variable flow. If two actions are taken, then LT radiators are efficient, in combination with an improved flow using two valves and a variable flow, but not with any other combination. A third action should be to consider parallel heat exchangers, in addition to the above two actions. When all other items have been upgraded, work on domestic hot water tanks appears relevant, even though the impact of upgrading tanks leads only to limited gains. The largest gains are those from adjusting the flow (two valves and a variable flow) in combination with LT radiators.

Payback

Assessing payback times, the cost of taking these action(s) and the related monetary savings are compared to saving a certain quantity of gas. The price of gas varies, and thus, we have taken the average price of natural gas in the French market (PEG) since 2012 as 20 euro/MWh (due to the geopolitical events of 2022, there was a peak at 130 euro/MWh in March 2022) [30].

The currently high natural gas prices lead to significantly lower payback times for the actions, ranging from 0.9–1.3 years, whereas gas prices at the lower levels that had been common until recently result in payback times of approximately 6–9 years (see Fig. 10). Assuming that the reduced costs are fully transferred to the customer and assuming that the customer has a payback time requirement of less than 10 years, all combinations of actions could be considered good investment opportunities. If the payback time requirement is shorter than 10 years, it might be necessary to resort to the ability of DH companies to wait for profit (referred to as patience capital).

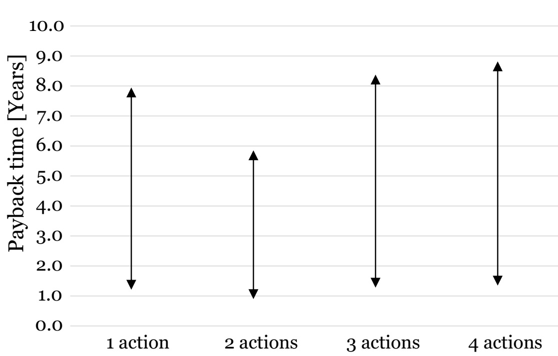

Fig. 10 Payback times for the best combination of actions for low (20 euro/MWh) and high (130 euro/MWh) gas prices. Actions are 2V (for one action), 2V + LT (for two actions), 2V + LT + parallel (for three actions) and 2V + LT + parallel + instant (for four actions)

It is beneficial for customers to increase the efficiency of their building if there is an economic gain from each efficiency measure.

Price model-secondary system motivational component

In terms of the price model outlined in Sect. "Methods", the IT element should target the flow through the secondary system (already captured in many motivational tariffs):

$$TT = FT + VT - IT \tag{1}$$

where IT is the incentive tariff (the monetary gain that a customer enjoys from improving secondary system performance), which is linked to an incentive for reducing the return temperature on the primary side to below that on the design value. An IT is based on an average temperature reduction (°C) in the substation, monthly values, with a certain bonus in €/°C and expressed as I_T°. The simulations identify that the relevant refurbishment measures to lower the return temperature to the primary system are variable flow valves, LT radiators, parallel heat exchangers, and a pass-through DHW system.

Apart from the simulated refurbishments, we also identify that the secondary system sometimes generates excess heat, which is valuable to recover, especially during peak load periods for the primary system. Depending on the building type, waste heat can come from industrial processes or from ventilation systems (residential building). Hence, IT should also encompass an incentive for the customer to make use of waste heat in the secondary circuit to lower peak demand for the district energy system (Unitary Price of Waste Heat (euro/MWh)* Quantity of Waste Heat (MWh of waste heat supply) expressed as I_W °C).

Accounting for the above modification, the price model addressing primary and secondary system incentives reads as follows:

$$TT = (F_{connection} + F_{capacity}) + \left(T_{MWh} + T_{m^3}\right) - \left(I_{T^0} + I_{Wasteheat}\right) \tag{2}$$

Discussion

We identify in the simulations that certain measures and combinations can improve the efficiency of the secondary system. The return temperature in the primary system is lowered, and costs are saved. From the literature, we see that motivational tariffs are rarely implemented without challenges; for example, the flow component, which is commonly deployed in mature DH markets, is difficult for customers to understand. Including additional measures in the motivational tariff necessitates substantial knowledge transfer in terms of secondary system configuration from DH companies to customers, which must include the following:

- information about the performance of the substation
- information about the efficiency improvements and costs of possible solutions to remedy any malfunctions
- an incentive to undertake the investments linked to refurbishing the substations

The improved efficiency of the secondary system, to benefit the performance of the primary system, means that building owners need to be interested in building a relationship with the energy company that allows it to shift its usual boundary conditions. In a conventional DH business model, heat is supplied to the building, and the secondary system is left in the hands of the building owner. With a tariff that motivates the customer to undertake improvements in the secondary system, which can be costly, a close win–win relationship with the energy company is needed. This situation means that the customer relationship must move closer to one that involves an energy performance contract (EPC), where both sides undertake investments for a joint win. EPCs reflect the development of energy as a service, which indicates that a price model with motivational elements towards the secondary system will shift the business logic of the energy company away from providing a product and towards providing a service and from standardized and arm's length customer relationships towards more tailor-made solutions that allow customers to make relevant investments in their substations and engage in an ongoing dialogue. It is important to ensure that the gains in the primary system from a well-functioning secondary system are higher than the costs of improving the secondary system.

In the mature heat market of Sweden, it is increasingly common for building owners to install a heat pump, thereby limiting the use of DH to very cold days. This situation is detrimental to the DH business case. Studies have shown that including the heat pump as a DH technology can be an efficient way to mitigate the risk of losing heat demand. In such a context, it can be strategic for the DH company to invest in the heat pump itself or jointly with the building owner, as doing so allows access to both the heat pump and the secondary system, which gives the DH provider the operational visibility of the secondary system. This example is provided to show that the increased efficiency of secondary systems can come at the cost of renovation and that such costs can be of strategic interest to DH companies, who may decide to absorb them, either wholly or partially.

Conclusions

Returning to the question of this research (*What measures should be incentivized to increase the performance of the secondary network?)* we conclude that upgrades in flows (from stable to variable), radiators (from high to low temperature), the use of heat exchangers (from unique to parallel) and DHW preparation (from tanks to bypass) should be encouraged. In addition, measures to recover any waste heat generated in the secondary system should be undertaken.

Currently, the most frequently applied motivational factors are linked to the flow of water through the customer's substation and the notion of bonus/malus systems encouraging the customer to improve their installation (without any guidance of what to improve). Our results show that there are additional relevant factors to discuss with customers. The configuration of the DH system and of the customer installations will impact which factors are most relevant to consider, even though, in most cases, a dialogue addressing aspects in addition to flow and bonus/malus appears to be relevant. A main conclusion from this work is therefore that DH companies should actively engage in incentivizing customers to ensure efficiently working secondary systems. If DH companies limit their efforts to the efficiency of the primary system (which is comfortable because it is within their own control), then they will miss out on important, alternative efficiency gains.

In this study, the focus is on understanding if there are additional components that can be added to current motivational tariffs. No simulation is made on the outcome of current price models, including the motivational components discussed herein. Such an analysis would, however, be relevant for future research.

Abbreviations

CHP	Combined heat and power
IT	Incentive tariff
DH	District heating
LT	Low temperature
DHN	District heating network
PEG	Point d'Echange de Gaz
DHW	Domestic hot water
SH	Space heating
EPC	Energy performance contract
TT	Total tariff
FT	Fixed tariff
V3V or 3 V	Three-way valve
HDD	Heating degree days
V2V	Two-way valve
HEX	Heat EXchanger
VEKS	Vestegnens Kraftvarmeselskab
HT	High temperature
VT	Variable tariff

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Author contributions
KL led the writing process, designed the structure of the paper and participated in the business model analysis. PS, AF, and CD performed the simulations of the retrofit impacts. VG provided validation from the energy company perspective on the results. TN and KL performed the business model analysis. AN performed a literature review on motivational tariffs.

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Author details
[1]Lund University, Energy Sciences, John Ericssons Väg 3, 223 63 Lund, Sweden. [2]IVL, Swedish Environmental Research Institute, Vallhallavägen 81, 114 27 Stockholm, Sweden. [3]CES- Centre for Energy Efficiency of Systems, MINES Paris, PSL Research University, 60 boulevard St Michel, 75006 Paris, France. [4]Lab CRIGEN, ENGIE R&I, 4 rue Joséphine Baker, 93240 Stains, France.

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