BEST PRACTICES TO LOWER DISTRICT HEATING SUPPLY TEMPERATURES

ADDRESSING CRITICAL HEAT CUSTOMERS

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Preface

This Master's Thesis with the title completed by Jeppe Krogh Skjølstrup, student at Aalborg University, at Sustainable Energy Planning & Management.

The thesis investigates the problem of DH companies having operating temperatures above what is suggested by scientific literature, among others from the research center 4DH. Research request technological change, and the DH companies try their best. The is often rooted in few critical heat customers that hinders the reduction of supply temperatures. The thesis dives into the everyday life of DH companies that successfully converted an area to lower operating temperatures by addressing the critical heat customers. The thesis identifies the economic value of heat customer initiatives, and knowledge and actor-network related barriers that exist among heat customers, plumbers and DH companies and hampers technological change. Recommendations are provided on how to overcome these barriers.

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Dansk Resume

Dette speciale spørger hvor og hvordan kritiske varmekunder bør adresseres for at kunne sænke fremløbstemperaturen i et distributionsnet. Der arbejdes ud fra forestillingen om at der findes tre typer kritiske varmekunder:

- Varmekunder med dårlig drift
- Varmekunder der ikke kan opnå komfort ved lavere fremløbstemperaturer
- Varmekunder der risikerer Legionella i brugsvandet, når fremløbstemperaturen sænkes

Til at besvare hvor kritiske kunder bør adresseres er der opstillet 6 teoretiske fjernvarmesystemer. Undersøgelsen antager at den selskabsøkonomiske gevinst ved en kritisk kundeindsats er afgørende for hvor indsatsen målrettes. Undersøgelsen tager udgangspunkt i et distributionsnet, der opererer med forhøjede temperaturer, fordi for mange varmekunder har dårlig drift.

Til at besvare hvordan kritiske kunder bør adresseres anvendes 5 case-studier. Disse er valgt på baggrund af fjernvarmeselskabernes medvirken i at forbedre de kritiske kunder for at sænke fremløbstemperaturen. Der er her tale om Høje Taastrup fjernvarme, AffaldVarme Aarhus, HOFOR, Viborg fjernvarme og Albertslund forsyning. De to førstnævnte er historiske cases, hvor gennemførelsen er sket ved medvirken i et EUDP-projekt. HOFOR gennemførte Vesterbro Lavtemperatur med kommunens hjælp og er ligeledes en historisk case. Viborg fjernvarme og Albertslund forsyning er to fjernvarmeselskaber, som er i gang med en omstilling af deres kritiske kunder. Alle cases er belyst gennem interviews af repræsentanter for fjernvarmeselskaberne og dokumenter vedrørende projekterne. De historiske cases er primært belyst igennem tilgængelige dokumenter, idet interviewpersonerne ikke var involveret i projektet. Udfordringen med at forbedre kritiske varmekunder er teoretisk anskuet som en teknologisk forhandlingsproces, hvor viden og etablering af et aktør-netværk er afgørende for at gennemføre udviklingen med succes.

Undersøgelsen af de 6 teoretiske fjernvarmesystemer når frem til at kritiske varmekundeinitiativer skal prioriteres i distributionsnet, hvor

- Den variable fjernvarmepris er høj
- Der er flere produktionsenheder, hvor produktionsenheder der drager fordel af lavere temperaturer kan erstatte dyrere produktionsenheder, der ikke drager nytte heraf
- Der er en høj andel af varmepumpeproduktion, fordi denne teknologi drager særlig fordel
- Produktionsenheder har effektivitetsforbedringer og enten har relativt dyrt brændsel, høje brændselsafgifter, høje drift og vedligeholdelsesomkostninger eller kan erstatte dyrere produktionsenheder.

Et system udelukkende bestående af træflisfyret kedel var det system, som gav den markant laveste værdi af en kritisk kundeindsats, fordi de variable omkostninger var lave og der ikke var andre produktionsenheder at erstatte.

Værdien af produktionssystemerne var antaget overførbare til fjernvarmekunderne. Derigennem kunne det konkluderes at tilbagebetalingstiden generelt er bedre for store varmekunder fremfor små. Det samme gælder for energirenovering fremfor forbedret bygningsvarmesystemsdesign, hvis kunden alligevel stod foran en renovering. Det giver anledning til at prioriterer indsatser, hvor der er store kunder med er forestående renoveringsbehov.

Undersøgelsen af de 5 fjernvarmeselskaber fandt at i grove træk ved kunderne ikke at de er kritiske, kender ikke omkostninger forbundet ved det og mangler viden til at kunne gøre noget ved det. Fjernvarmeselskaber havde omvendt den nødvendige viden til at kunne identificere kritiske varmekunder på baggrund af analyser af kundedata. De havde også viden til at kunne finde og løse de specifikke problemer hos kunde, men det vil kræve, at man besøgte kunden, hvilket var en barriere, der afholdt nogle af de historiske cases fra at gøre mere ved kritiske kunder.

Varmekunders videnbarrierer bør imidlertid ikke udelukkende imødegås ved kundebesøg og fejlfinding. De undersøgt cases indikerer at man kan komme langt med at sætte nogle bedre strukturer op. Anbefalingerne er:

- Få en forståelig motivationstarif.
- Give kunderne mulighed for at konkurrere med hinanden.
- Sikre at kunderne får opsøgende, uvildig og gratis rådgivning.
- Der bør arbejdes i retning af mere ensartede varmesystemer hos kunderne for at gøre arbejdet lettere for både VVS'ere og fjernvarmemedarbejdere.
- Dertil vil det formentlig være brugbart for mange kunder at kunne se de foreslåede forbedringer i form af demonstrationer.

Der er imidlertid også interessemæssige udfordringer mellem fjernvarmeselskab, VVS'er og varmekunde. Varmekunder vil have varmekomfort, for få omkostninger og lidt arbejde. VVS'erne tolker i bredt omfang kundens behov som en service, der er så billig som muligt, til trods for at en lidt dyrere service kunne give bedre drift og bedre økonomi for varmekunden i det lange løb. Følgende tiltag ville bidrage til ensretning af interesser:

- Installation af en mængde- og returtemperaturbegrænser hos kritiske kunder. Den fratager den termiske komfort, hvis varmesystemet er underdimensioneret eller dårligt driftet, hvilket bl.a. vil skabe efterspørgsel på bedre VVS service.
- Den kritiske varmekunde tilbydes finansiel støtte. En målrettet støtte kan skubbe kunden til at tage hånd om problemet med det samme. Til trods for arbejdet, der er forbundet med det.
- Vedholdende dialog kan være nødvendig for at sikre at varmekunden over tid bliver opmærksom på fordelene ved at forbedre sig. Det kan være særligt nødvendigt hvis der kræves større ændringer af varmekunden.
- Varmecentral leasing og udbud for VVS'ere vil både sikre at varmekunden skal gøre mindre for at sikre at varmesystemet fungerer, fordi service er en del af aftalen. Leasing har været populært blandt varmekunderne, og derfor er der mulighed for at installationen af dem sker igennem VVS udbud. Dermed kan fjernvarmeselskabet kvalitetssikre økonomi og krav til design og installation.

Erfaringer fra casene peger endvidere på at interesser først endeligt bliver ensartet, når der opnås opbakning til en plan, hvor mål, gevinster og tekniske tiltag er klart defineret. I den forbindelse tyder meget på at også kommuner og produktudviklingsvirksomheder kan være interessante at få engagerede i en kritisk kundeindsats.

Det foreslås desuden at de mulige tiltag prioriteres forskelligt afhængigt af hvilken type kritiske kunde, man som fjernvarmeselskab vil forbedre.

Abstract

This thesis investigated where and how critical heat customers should be addressed to lower district heating supply temperatures. It finds that critical heat customer initiatives should be prioritized where the local heat supply systems have a high variable heat prices, large production share covered by heat pumps, multiple heat production units, and low temperature benefitting technologies where fuel, taxes, operation and maintenance costs are high. It finds the best payback period for large heat customers that are about to renovate and choose an energy renovation supplied by a HP system. The worst payback period is found for small heat customers choosing a heating system design solution, and who is situated in a distribution grid supplied by a flue-gas condensing wood chip boiler. Generally, the business case is great across the different types of heat supply systems, but to harvest benefits and make critical heat customers invest, knowledge and actor network initiatives are needed. Three critical heat customer strategies to lower DH supply temperatures exist:

1. Address poor performing customers in distribution grids of hydronic bottlenecks
2. Address customers that cannot obtain thermal comfort at lower supply temperatures
3. Address customers that cannot ensure legionella safe domestic hot water

The findings indicate that the first strategy requires the least to execute. Actor-alignment may be achieved by the installation of a flow limiter because it allows the plumber to deliver a better service, because customers will request it. The second strategy may be more extensive because it requires the critical customer to energy renovate or increase the heating power of heat emitters. It requires persistent dialogue and outreaching, impartial and free consultancy to convince heat customers that it is worth the effort, and to provide them with knowledge and comfort to invest in improvements. Municipalities may be an obvious partner due to its' expertise in participation process and the legitimacy they can add to the strategy. The third strategy may involve the implementation of more radical new technologies for large heat customers to ensure legionella safe DHW. Consequently, this strategy also requires persistent dialogue, and to a larger extent a demonstration that new techniques are adequate for the critical heat customer. Partnering with product developers may also enhance results from such strategy, due to their expertise in making the radical new technique work as intended.

Clarification of concept

Heat customer:
A heat customer is defined by a substation. The substation separates the DH system from the heat customers building heating system. One or more buildings can be attached to one substation. Typically, small heat customer has one substation per building, whereas larger heat customer may have several buildings and apartments connected.

List of Abbreviations

AVA:	AffaldVarme Aarhus
DH	District heating
DHW:	Domestic Hot Water
HOFOR:	Hovedstadens Forsyning
HP:	Heat pump
LTDH:	Low Temperature District Heating
SH:	Space Heating

Reading guide

This thesis is structured in 9 chapters.

Chapter 1 introduces the problem field of lowering district heating operating temperatures. The energy system benefits are described, but also the specific challenge concerning critical heat customers. It introduces the techniques that can be applied to improve critical customers and the political pressure to save energy. Finally, it poses a research question that this thesis will tackle.

Chapter 2 introduces the building heating system that provides the reader with an understanding of how a customer become critical from a technical perspective. It also introduces the 5 cases of DH companies that successfully were involved in improving critical customers to lower supply temperatures. These cases are used to answer parts of the research question. Lastly, 6 heat supply systems are introduced which will be used to answer another part of the research question.

Chapter 3 presents the theoretical framework which is applied for the investigation of the heat supply system and cases. Profit is presented as the evaluation criteria for heat supply systems, and the theory to estimate production profit of lower supply temperature are presented. Secondly, technological change theory is presented that is used to understand the cases of DH companies that improved critical heat customers. Knowledge and actor-network are argued to be crucial for technological change and is presented as the analytical framework.

Chapter 4 describes the overall methodology, including the methods applied to acquire and handle data.

Chapter 5 constitutes the first part analysis, where heat supply systems are evaluated based on their value of from a critical heat customer initiative. It analyses production efficiency and the resulting changes in production share. It finds the economic value for each system and compares it to the investment cost at the critical heat customers.

Chapter 6 constitutes the second part analysis, where the cases of DH companies are analyzed on the role of knowledge. It investigates how critical heat customers are identified and how they manage to make their heat customers become knowing of the benefits. It analyses how adequate solutions to improve customers are developed.

Chapter 7 is the last analysis, where the interest of heat customer, plumbers and DH company is found. It analyses the tools that DH companies have at hand and have applied to align interest. Finally, it investigates how the alignment of interest became stabilized in the different cases.

Chapter 8 discusses the findings of each analysis and ranks the initiative according to three types of critical heat customer strategies. It discusses the choice of methods and theories and its impact on the findings.

Chapter 9 concludes where and how DH companies should address critical heat customers. It also suggests an alternative research angle on the implementation of critical heat customers

TABLE OF CONTENTS

1 INTRODUCTION

Currently the world faces a great threat of anthropogenic climate change that can only be avoided when comprehensive changes takes places in the use of fossil fuels. Therefore, a transition process towards a 100 % renewable energy system is targeted, making Denmark a CO_2-neutral society (DMEUC 2018). Such a transition includes the integration of the more fluctuating renewable energy sources, into an energy production that must fulfill the energy demands of the industrial-, transportation-, heat- and electricity sector. For a cost-efficient transition, large energy savings are needed. (Mathiesen et al. 2015)

1.1 OVERALL ENERGY SYSTEM CHALLENGE

Whereas fossil fuels, such as oil and coal, can be stored and used when needed, e.g. wind turbines and photovoltaics only generate energy when wind and sun is available, respectively. Consequently, it becomes a challenge to match the energy production with the real time energy demand. A *smart energy system* has been proposed as a cost-effective approach to integrate more renewable energy production. The objective of a smart energy system is to integrate the industrial-, transportation-, heat- and electricity sector, which provides more storage opportunities. Lund (2018) concludes that all countries transitioning into a 100 % renewable energy system need to find a way of storing electrical overload and concludes that cost-efficiency is achieved by utilizing the existing gas and district heating infrastructure as storage systems through the conversion of electricity into gas and heat. Integrating the heating and electricity sector must according to (Mathiesen et al. 2015) take place through the implementation of heat pumps (HP) that exploits excess heat sources. However, HPs are highly temperature dependent as the technology become more efficient the smaller the temperature difference is between the heat source and the heat produced (Energinet and DEA 2016). As a result, too high district heating (DH) operating temperatures hampers the implementation of HPs and essentially increases the cost and primary energy use of transitioning into a 100% renewable energy system.

1.2 BENEFITS OF LOW TEMPERATURE DISTRICT HEATING

In Denmark, District heating (DH) delivers 64% of Denmark's total heat demand (DF 2017), making DH the most applied heating method. The total production amounts 37.7 TWh. Currently, the sector integration between electricity and heat is very limited, electricity-consumption for heat production units only constitute 1 % of the total fuel consumption in Denmark (DEA 2018a).

Lower DH temperatures not only enables HP implementation, but generally bring a more efficient DH system. Lund et al. (2018) state that when operating a district heating system at low forward- and return temperatures, the heat supply system benefits from increased production efficiency of solar thermal plants, condensing heat production units, and HPs. Other benefits to lower district heating temperatures counts lower distribution heat losses. Lund et al. (2017b) predicts, from a socio-economic perspective, that Denmark in 2050 will have most benefits achieved when supply temperatures are reduced at 55°C, assuming return temperature at 25°C. Such a temperature-set is defined low-temperature district heating (LTDH), where DH supply temperatures are reduced to the minimum temperature level at which domestic hot water (DHW) can be produced without the risk of legionella growth. Whether a DH supply temperature at 55°C ensure legionella safe DHW depend on the context. Today some DH companies consider legionella safe DH supply to be at least 60 - 65°C which accounts for temperatures losses in one or two heat exchangers. (Skov 2019; Honeré

2019) Conversely, the implementation of new DHW technology ensures legionella safe DHW at supply temperatures close to 50°C (DEA 2014a).

Further reduction of forward temperatures would require the installation of heat production units at each heat customer to increase the domestic hot water (DHW) temperature to avoid legionella growth. Such a system is defined ultra-low temperature district heating (ULTDH) and have the benefits of even lower distribution losses, due to the smaller temperature difference. According to Lund et al. (2017b) LTDH is the preferable target, because investments costs of small local DHW production units are too high. Only in very specific contexts, ULTDH might be preferable.

The desired LTDH concepts is far from the current operating temperatures of Danish DH companies, which can be identified in Figure 1.

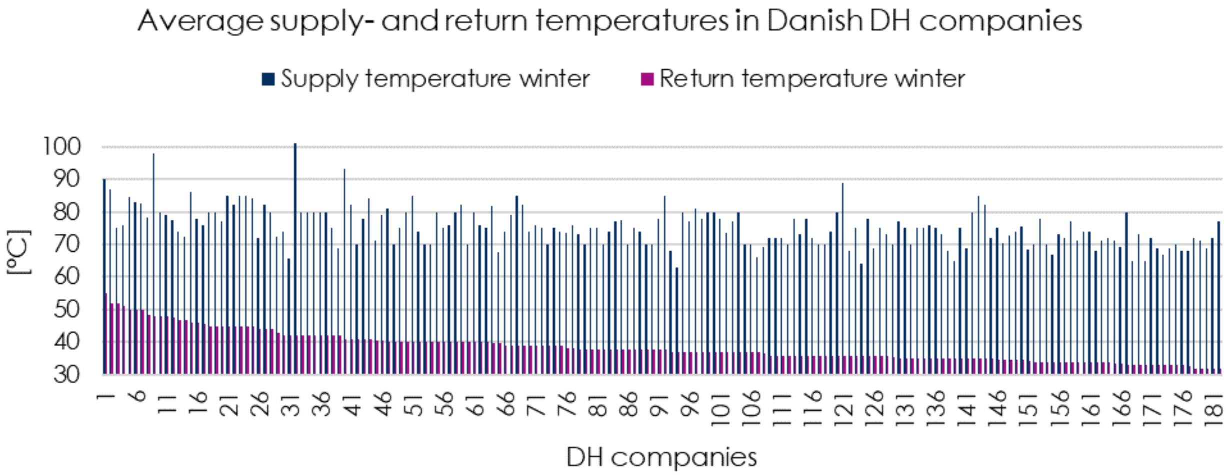


FIGURE 1: SUPPLY AND RETURN TEMPERATURES IN DANISH DH COMPANIES. BASED ON DATA FROM DANSK FJFERNVARME (DF 2018)

Supply- and return temperatures differ significantly from one DH company to another, but on average Danish DH companies have forward temperatures at 75°C and return temperatures at 39°C during the heating season. Summer season temperatures were on average 70/40°C (DF 2018). A few DH companies has supply temperatures above 90°C. As a result of the operating temperatures and the general condition of the DH network, grid losses amount to 7.5 TWh, equal to 23 % of the total produced heat (DF 2018).

1.3 TARGETING CRITICAL HEAT CUSTOMERS

So why do DH companies operate at higher temperatures, when lower temperatures are proven to be more cost-efficient? Reducing DH operating temperatures implies that less thermal energy can be transferred in the supply chain of production, distribution and consumption, due to the smaller temperature difference. It means that lower DH temperatures threatens the purpose of DH – to deliver enough heat to the heat customer, which from a DH company's point of view is unacceptable. Technically, some heat customer most be improved to allow DH temperatures to be lowered, these are the critical heat customers.

In this thesis, a critical heat customer is defined based on the interviewed DH companies; Viborg, Høje Taastrup, HOFOR, AVA and Albertslund, and informal communication with grid operators, energy consultants and customer-support employees at HOFOR. The definition is:

"A critical heating customer is a customer that helps prevent a reduction of the operating temperatures in a distribution grid."

Meaning that the extent to which the customer is critical depends on the purpose for which the district heating company wishes to reduce its operating temperatures. To operationalize the definition, three different preconditions for supply temperature reductions are imagined, which forms three types of critical heat customers:

1. **Poor performing customers:**
   A DH company faces hydronic bottlenecks, which forces the DH company to operate with supply temperatures above what is expected to be necessary to accommodate the heating demand at the customers. In this case, the customers with the highest return temperatures become the critical customer as those with the highest return temperatures, because they through a poor performance indirectly cause a demand for high DH temperatures.

2. **Customers with thermal comfort issues:**
   A DH company faces no hydronic bottlenecks and intends lowering DH supply temperatures in the heating season, but are restricted in doing so, because some customers cannot obtain thermal comfort at lower DH supply temperatures. In this case, the critical heat customer are buildings that have an under-dimensioned heating system for the desired supply temperature reduction, which typically will be poorly insulated buildings.

3. **Customers at risk of legionella infection:**
   A DH company faces no hydronic bottlenecks and intends lowering DH supply temperatures in the summer season, but are restricted from doing so, because some customers risk a legionella infection of their DHW system. In this case critical heat customers are buildings equipped with a DHW system which cannot guarantee legionella free domestic hot water production at the targeted new supply temperature. The risk of legionella depends on the internal DHW circulation system, DHW system design principle and legionella disinfection method.

1.4 THE MEANS TO ACHIEVE LOWER DH OPERATING TEMPERATURES EXISTS

Current research has already contributed a lot to the field on how to improve critical heat customers and has highlighted the long-term benefit of doing so (Lund et al. 2017b). The techniques to lower DH supply temperatures are in this section specified for each type of critical heat customers as described in the previous section.

MEASURES TO ENSURE BETTER PERFORMANCE

Critical customers with poor energy performance require thorough adjustment of the building heat control system, and/or a replacement of one or more technical components.

Månsson et al. (2019) conducted a survey where Swedish DH companies reported which typical faults they detected, when they visited heat customers. They reported that a substantial number of faults were related to the customers' internal heating system (31 %), and leakages (33%). Less frequent, but still a significant number of faults were related to control valves, the actuator inside the valves, and heat exchangers. Errors at heat customers were caused by poor design and lack of maintenance where malfunctioning components has not been replaced.

Most of the problems concerning the main heat exchanger are caused by leakages. Actuators are often broken and needs to be replaced. Control valves are often over-dimensioned, why the need to be replaced with smaller ones. Internal building heating system faults are mostly caused by broken thermostatic radiator valves, poorly hydraulically balanced SH systems, and too high set-point temperatures for radiators, which can be solved by balancing the system and replacing single components. (Månsson et. al 2019)

An energy management tool offers the heat customer to operate the building heating system. It may also offer consultancy on improvements of the heating installations, which help the heat customer in detecting faults and improving the control of the system. Various energy management tools exist. Examples are Forsynometer, LeanHEAT, ECOpilot and ESCO. If faults of the building heating systems are corrected, energy savings in the range of 10 %-15% might be achieved (Trüschel 2005). A Sweedish report finds that in some cases energy savings of above 15 % can be achieved by balancing the heating system in an apartment block. Balancing the energy system and thereby ensuring better operation come at a relatively low costs and at payback periods below 6 years (Trüschel 2005; Østergaard 2018).

MEASURES TO SOLVE THERMAL COMFORT ISSUES

For buildings struggling to obtain a necessary level of thermal comfort at lower DH supply temperatures, a renovation can solve the problem and drive energy savings. Wang et al. (2015) proved it theoretically by modelling the energy consumption of a typical multi-family house before and after different energy savings measures. The house represents the archetypical building from the period 1950-1975 in Sweden. They conclude on the different types of energy renovations: A ventilation system renovation provides large energy savings and are easily implemented. External wall renovation provides the largest energy savings but may cause disturbance for the occupant and may not be cost-efficient. Improvement of roof, windows, and airtightness, all provide significant energy savings in the range of 18.2-22.9%. Combining all measures would derive energy savings at 55.3%, reducing heat consumption of the modelled building type from 144.9 to 64.7 kWh/m2 per year. Additionally, they find it possible to supply the building at temperatures below 50°C.

Similar results were found in a study that investigated the effect of three different renovation strategies on the supply temperature into two building blocks from the early 19's. The study concluded that that an intermediate building retrofit strategy that upgrades window, ventilation, basement and roof to BR10 standards will enable lower energy consumption in the range of 30-50% and enable supply temperatures below 70°C throughout the entire year. (Harrestrup and Svendsen 2015)

Østergaard and Svendsen (2016b) did a theoretical investigation on temperature requirements for space heating systems in single-family houses which had undertaken only the most feasible energy renovations. It revealed that buildings that have undergone reasonable energy renovation should make LTDH supply (40-65°C) possible, see Table 1, in most existing building with return temperatures 20°C lower than the supply temperature.

TABLE 1: THEORETICAL SUPPLY TEMPERATURES DEPENDING FOR BUILDING UNDERGPME REASONABLE ENERGY RENOVATION. THE TABLE ONLY CONCERNS 6 ARCHETYPES OF SINGLE-FAMILY HOUSES (ØSTERGAARD AND SVENDSEN 2016B)

Construction period	1851-1930	1931-1950	1951-1960	1961-1972	1973-1978	1979-1998
Max. supply temperature required [C°]	56	62	64	60	52	54

Studies that aim at bringing the energy system of Denmark into a 100% renewable energy system, stress the importance of energy saving measures, and state 40% savings to be socio-economically beneficial (Mathiesen et al. 2015). Another study finds 50% heat savings in the case of Frederikshavn to be the best solution in the long-term (Sperling and Möller 2012). While 33% heat savings is believed to provide a positive return on the investment on a national scale for both society and the private investor, according to Wittchen et al. (2017).

An alternative strategy to building renovation is to increase the heating power, it has been proven both theoretically and demonstrated that five single-family houses from the 1930's could be supplied with 55/30°C after replacing the smallest and most critical radiators and radiator valves. (Østergaard and Svendsen 2016a; Østergaard and Svendsen 2018).

MEASURES TO ENSURE LEGIONELLA-SAFE DOMESTIC HOT WATER

The risk of legionella generally depends on temperatures and water volumes, because legionella growth may occur in stagnant water below 50°C. Consequently, today it is recommended to ensure 50°C at the tapping point and 55°C for DHW storages (DS 2009). The techniques to ensure legionella safe DHW is about increasing the thermal length of the heat exchanger to reduce temperature transfer losses (Averfalk and Werner 2017). A supplementing strategy is to make DHW design, which produce DHW as close to the point of consumption as possible, such a concept has been named; flat stations. The technique reduces water volumes to a minimum, which minimizes the risk of stagnant water and thereby the growth of legionella. Another method allows DH temperatures to be lowered, while boosting the DHW through the installation of a heat pump. The last technique to be mentioned is chemical treatment, where small doses of chlorine is added to the DHW to remove all bacteria. All these methods ensure that legionella safe DHW. All techniques allow DHW production to be produced at temperature below the current level without the risk of legionella, applying new DHW techniques may even lead to energy savings close to 50% (Yang et al. 2016). The lower limit to DH supply temperatures become as a result of implementing these techniques, the DHW comfort temperature 40-45°C (DS 2009), plus the temperature transfer loss in the heat exchanger.

SUMMARY OF MEASURES

It can be concluded that tools and knowledge to help the various critical heat do exist and is available. The literature study showed that energy renovation and increasing the heating power works to improve critical heat customers that cannot obtain thermal comfort. Energy management tools that ensure supervision, adjustment and replacement of single components in the building heating system can address heat customers with performance issues. Legionella-safe DHW production, when supply temperatures are reduced, can be ensured by changing DHW system design. An overview of all measures is provided in Table 2. The measures are categorized according to a critical heat customer type for best match, but energy renovation and increased heating emitting surface may also help critical heat customer with performance issues. Therefore, the table should not be interpreted too rigid.

TABLE 2: TECHNIQUES TO IMPROVE CRTITICAL HEAT CUSTOMERS

Critical heat customer	Performance issue	Thermal comfort issues	Legionella issues
Measures	✓ Energy management tool with: - Supervision - Adjustments - Replacement of components	✓ Energy renovation ✓ Increased heating emitting surface	✓ Chemical treatment ✓ DHW temperature boost ✓ Flat stations ✓ Larger heat exchange surface

1.5 THE POLITICAL PRESSURE INTENSIFIES ON RELUCTANT DH COMPANIES

Despite the measures are available to improve the critical heat customer, DH companies are reluctant towards being engaged at heat customer level.

Brange et. al (2017) investigated how Swedish DH companies reacted when they realized that they lacked hydronic capacity. They found that DH companies typically mitigated the lack of hydronic capacity through increased supply temperatures, increased pump or grid capacity. Less frequently they applied measures at heat customer-level, where the operation and thus the cooling of the substation was improved, or preliminary reduced the heat demands through demand side management strategies. Despite, heat customer initiatives being potentially more cost-efficient. (Brange et. al 2017)

Measures taken at heat customer level is associated with challenges relating to the ownership structure, as DH companies typically do not operate the substation, nor do they own or know the internal heating installation of the heat customer. They also doubt the robustness of improvements as occupant behavior could dissolve improvements. Finally, they also fear that such measures would be time consuming. But when they evaluate different hydronic capacity measures, they emphasize that for any measure the most important thing is the cost-efficiency of a measure (Brange et al. 2018).

The DH companies` reluctancy towards being engaged at the heat customer level contrasts the tendencies on the political level. In 2018 EU passed on two new directives aiming at achieving enough energy savings to meet the goal of 27% less energy consumption by 2030 compared to the projected consumption. According to EU, buildings are responsible of approximately 40% of the overall energy consumption (European commission 2016), which is why energy savings are a crucial necessity to meet the goal of 90 % CO^2 reductions by 2050.

The directive on *Energy performance of buildings*, brings initiatives that entitles member states to make strategies for renovating the existing building mass. These strategies should identify cost-efficient methods for deep retrofits and push for more intelligent buildings. The strategy should be supported by mechanisms where building owners can access financial support to investment in improvements and energy consultancy to choose the adequate solutions. Thereby reducing the experienced risk of building owners associated with investments in energy savings. Moreover, the directive state that heating installation above 70 kW should be supervised and evaluated, or the heat customer should be advised on which changes that are needed to improve the operation of the heating installation. (EU 2018a)

The directive of *Energy efficiency* supplement by demanding on measurements on heat and DHW consumption of all buildings and apartments, if it can be done at reasonable costs. Measurements should be by remote reading and be accessible to the heat consumer. Thereby, the initiatives bring energy consumption awareness to the building owner, increase the DH companies' level of information on the operation of heating installation, and allow buildings to be operated more intelligent. (EU 2018b)

The new directives are yet to be implemented in the member states and underpins therefore the highly pertinent situation on finding ways to implement energy savings through heat customer initiatives. DH companies are already responsible of carrying out energy saving measures through the energy saving scheme (DEA 2018b), and they do have experiences with handling data from heat customers, production and distribution measurements. The new directives seem to even strengthen the role and responsibility of DH companies, why they will also be obligated to do better. DH companies should consider how they can use and play into the directives' requirements on

- More consumption measurements
- More consultancy and financial support to heat customers
- Providing renovation strategies of the building mass
- Yearly savings at 1.5 % of total energy production (until 2021) and 0.8% savings in energy consumption from 2021 and onwards

Such obligations may be seen in a future low-temperature district heating perspective, because reducing DH operating temperatures bring energy savings and these are dependent upon initiatives at the building level. For the DH companies to contribute to the increasing energy saving requirements, they need an effective way of engaging with heat costumers and it seems reasonable to assume that costumer-oriented initiatives must focus on the most critical heat consumers. And as the introduction has revealed, it is not about developing technologies to improve the building heating system, because they already do exist.

Rather, there is now a need for research that investigates best-practices of how critical heat customer can be addressed to lower the supply temperature. Best-practice should take a starting point in DH companies that have successfully lowered DH temperatures and serves the purpose of enabling other practitioners in the field to learn how they can plan and execute a technological transition of their critical heat customers. Consequently, a research question is posed in the following section.

1.6 Research question

With the purpose of identifying best-practice methods for addressing critical heat customer the following research question has been posed:

Where and how should DH companies address critical heat customers to lower DH supply temperatures in existing district heating distribution grid?

To answer in which area critical heat customer should be addressed, the supportive question below has been formulated. The question will be answered through the modelling of archetypical heat supply systems.

- What type of heat supply system would benefit the most from critical customer initiatives in concern to profit? In addition, what is the payback period of investment of the critical customer initiatives in the given heat supply system?

To answer how critical heat customer should be addressed two supportive questions are posed below. These questions will be answered based on the case-studies of five DH companies that currently or in the past, addressed critical heat customers to lower DH supply temperatures.

- How can it be known who the critical heat customers are? In the process of convincing critical heat customers to improve, what knowledge barriers between heat customers and DH companies may be faced, and how could they be addressed?

- How have the interests of key social actors been aligned to allow critical heat customer improvements?

The research design which is applied to answer the research question contains a mix of methods. First, a quantitative approach is applied to identify areas where DH companies should initiate critical heat customer initiatives. It is done through the modelling of different heat supply system that quantifies the economic value of a critical heat customer initiative. The quantitative approach focusing on profit is chosen because DH companies emphasize profit in the decision-making process, as stated by Brange et al. (2018). To answer how DH companies could plan and implement a critical heat customer initiative, and to exemplify some of the barriers encountered in the process, a qualitative approach is selected. It involves the multiple case-study of five DH companies. The approach is suitable to answer the research question, because all DH companies either currently or in the past addressed critical heat customers. The method provides in-depth knowledge about best-practices through a total of 7 conducted interviews and through the desc research of each DH company's plans for addressing critical heat customers.

1.7 Delimitations

There are certain delimitations to the investigation of the research question. The question of where critical heat customers should address will only be answered by investigating the business economy of it. Justification for the choice is found in section 3.1. Moreover, the economy is only investigated for distribution grids with hydronic bottlenecks, targeting poor performing customers. The profitability of reducing supply temperatures in the summer period was disregarded. It may have been a more profitable critical heat customer strategy, but due to time constraints, the choice was made to exclude it. In the investigation of how critical heat customers should be addressed, it has been chosen to focus on DH companies, plumbers and heat customers. DH companies are chosen for their presumed interest in lowering supply temperatures. Plumbers are chosen because, they may often be the guy in between a critical heat customer and a DH company. Heat customer are chosen because they are subject to change. It infers that it becomes an investigation on the local level, where actors from the international, national and regional level are disregarded. It is reasonable to look at the local level, because some DH companies have already succeeded under the current regulatory framework to reduce DH supply temperatures. Consequently, it should be possible for other DH companies by utilizing the tools they have at hand.

2 BACKGROUND

This chapter introduces first the various parts of a building heating system and how lowering supply temperatures affects it. It provides the technical understand of the three critical heat customer definitions. The chapter also introduces the investigated cases of DH companies that have experiences from addressing critical heat customers. It shortly describes the conducted critical heat customer initiatives and summarize on the difference between the cases. These cases are the foundation for Chapter 6 and 7. Lastly, the investigated heat supply systems are introduced, which refers to the analysis of Chapter 5.

2.1 THE BUILDING HEATING SYSTEM

In this section, reader is provided with the technical understanding of why some customers become critical, when supply temperatures are reduced. The space heating system helps understand, why some customers get thermal comfort issues. The description of the domestic hot water system helps understanding why some customer will risk a legionella infection. The description of the combined operation of the two systems helps understand why some customers will perform poorly.

SPACE HEATING SYSTEM

The space heating (SH) system supplies the heaters installed in each room. The SH system typically set the lower boundary of supply temperatures during the heating season in older existing buildings. Supply temperatures of the DH system increase as the outdoor temperatures drops, to compensate for the larger building heat losses. Alternatively, larger flow rates in the SH system is needed to accommodate the increased heat loss, which could potentially result in higher return temperatures.

One major influencing factor on the necessary supply temperatures, and thus the accompanying return temperatures, would be the type- and the size of the heater. Generally, two types of heaters exist; radiators and floor heating, where floor heating systems, requires substantially lower supply temperatures, because of a larger heating surface. This section will however focus on radiator, as it is the most common heater found in the existing building stock.

Radiators may vary in size, from room to room, as a result of varying heat losses, dimensioning methods, but also due to dimensioning faults and choices of occupants. Under-dimensioned radiators require more heat than an over-dimensioned radiator, because the heat transferring surface is smaller. Design temperature requirements for radiators is shown in Table 3. The temperature requirements for the radiator systems through time, should be treated carefully as they are merely indications. Especially for radiator systems built before 1961, where other radiator supplier standards and no guidelines for dimensioning standards existed. (Østergaard and Svendsen 2016b) The table indicate that it may be more difficult to lower DH supply temperatures the older the building is. On the other, the older the building is the more likely it is that it has undergone some sort of energy renovation, which reduce temperature requirements as described in section 1.4.

TABLE 3: DIMENSIONING STANDARDS OF RADIATORS IN RELATION TO CONSTRUCTION YEAR OF THE BUILDING. THE TEMPETURES ARE REQUIRED FOR RADIATORS TO HEAT A BUILDING AT OUTDOOR TEMPEARUTRES AT -12°C (ØSTERGAARD AND SVENDSEN 2016B)

Construction period:	1851-1960	1961-1972	1973-1978	1979-1998
Design DH temperature of heaters (Supply temperature/return temperature)	90/70°C	80/60°C	80/40°C	70/40°C

Problems associated with the space heating system may not only be due to the radiators. Malfunctioning radiator valves and a poorly adjusted SH system may create hydronic imbalance, where some radiators cannot function due to the lack of pressure. The problem is fortified for large heat customers compared to small heat customers as such a customer will have more radiators attached to the SH system. (Trüschel 2002)

DOMESTIC HOT WATER SYSTEM

During summer, when the heating demand is minimal or non-existent, the DHW system set the lower boundary of DH supply temperatures. DHW system require temperatures of no less than 50°C at tapping point to be legionella safe (DS 2009). The DHW is most commonly heated directly by a spiral heat exchanger in a DHW tank, or with an instantaneous heat exchanger both connected directly to the DH system. The greatest risk of legionella is in DHW tanks, which is over dimensioned, because the it entails stagnant water. Especially for large heat customers, the DHW system may come with a circulation system, as visualized on the right-hand picture on Figure 2. Such circulation system entails heat losses and cause water temperatures to drop. Insufficient flow fortifies the problem (DEA 2014b). Consequently, higher temperatures are required for large customers with circulation systems to avoid legionella growth.

FIGURE 2: TO THE LEFT: DHW SYSTEM DESIGNED WITH INSTANTANEOUS HEAT EXCHANGER. TO THE RIGHT: DHW SYSTEM DESIGNED WITH STORAGE

OVERALL PERFORMANCE - HEAT CONTROL SYSTEM

The supply temperature to the SH systems is decided based on a temperature compensation curve, which accounts for the building heat losses at different outdoor temperatures. To regulate the supply temperature of the SH systems, valves increase or decrease the water flow from the DH systems through the main heat exchanger as shown in Figure 3.

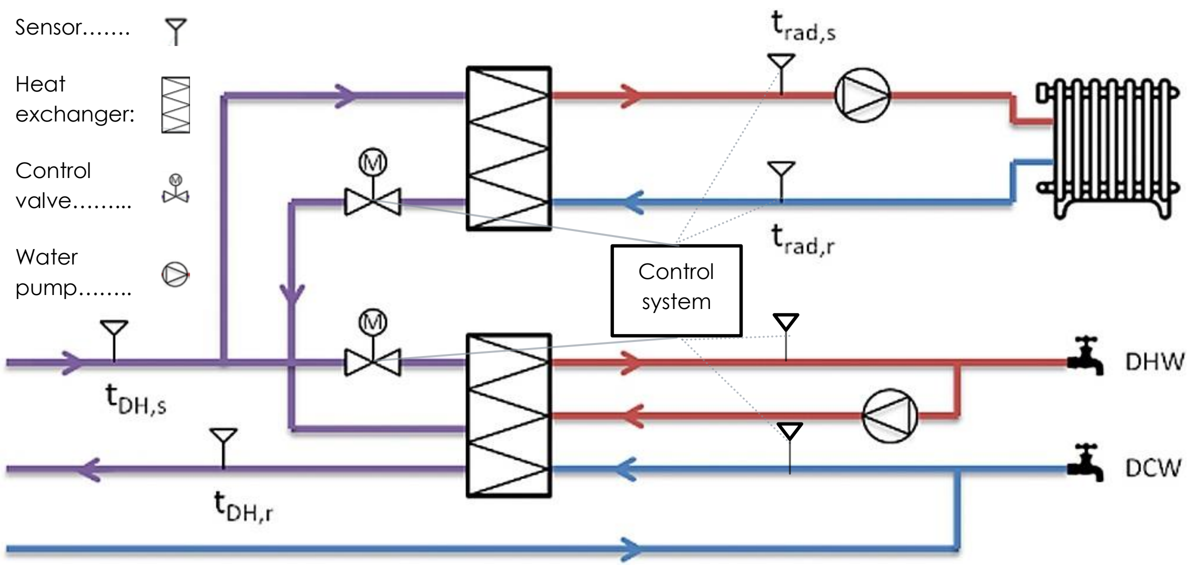


FIGURE 3: A POTENTIAL BUILDING HEATING SYSTEM SET-UP, MODIFIED AND BORROWED FROM JANGSTEN ET AL. (2017)

Water pumps in the SH system increase the pressure and ensure a differential pressure that enables enough water flow to accommodate the heating demand at the given supply temperature. If the differential pressure is too low, the SH system will not be able to supply enough heat to meet the heating demand at the given supply temperature, therefore the supply temperature must be increased. If the supply temperature of the SH system is increased to a point where it is equal to, or higher than the supply temperature of the DH system the control valve would open constantly, and large amounts of water will flow through the heat exchanger. This results in high return temperatures, and an increase in energy consumption. Thereby, the hydronic status of the SH system directly affects the DH operating temperatures. (Trüschel 2002) Figure 3 provides an overview on a DHW system and SH system connected to the DH system, together with some of the components that are crucial to the operation of the system. The visualized components include pumps, heat exchangers, valves, sensors, pipes, and control system. When just one of the components are malfunctioning due to wear and tear or wrong adjustments, the entire building heating system will respond with higher return temperatures and/or higher energy consumption than what it has been designed for. Since the overall performance is the combined performance of the DHW- and SH system, large heat customers are likely to be more poor performing than small heat customers, because they are technically more challenged with both the DHW and SH system.

SUMMARY

It can be concluded that from a technical perspective, large heat customers are more vulnerable to experience thermal comfort issues, because risk of hydronic imbalance are greater when more radiators and radiators valves become malfunctioning. Moreover, older buildings may also be more vulnerable due to higher temperature requirements if they have not been energy renovated. Large heat customers are also more likely to be at risk of legionella infections, because they typically have a circulation system installed, which requires higher supply temperatures, due to distribution losses. Consequently, large heat customers are also more likely to be a critical heat customer from a technical point of view.

2.2 CASE DESCRIPTION

This section introduces the five cases of DH companies and how they currently or in the past were involved in a critical heat customer initiative. The DH companies are Viborg, Albertslund, Høje Taastrup, AffaldVarme (AVA), and HOFOR. The cases will be used to answer how critical heat customers should be addressed to lower DH supply temperatures.

VIBORG DH COMPANY

Today Viborg DH company buy most of the heat from a combined-cycle gas turbine, but Viborg DH company plan to have their own heat production by highly temperature dependent air-to-water heat pumps, why lowering DH temperatures through heat customer initiatives have become a key strategy. Viborg DH company delivers approximately 300,000 MWh which makes it a medium sized DH company. On average the heat loss is at 20 %. The DH system is today organized with two key actors; Energi Viborg, who produces the heat and Viborg DH company which is the distribution company. The production company is owned and driven by the municipality and the distribution company is owned by the heat customers. Plans are to merge the two separate organizations.
Recently, Viborg DH company decided to lower the DH temperatures in their grid to increase the heat production efficiency of the future heat pumps. Through an analysis of their distribution they found that it could be divided into two zones. A cold and warm zone. The formation of a cold zone would enable that the maximum supply temperature could be reduced by 10°C, because heat

customers in the zone were in a better condition than in the warm zone. However, return temperatures of the customer must be lowered to ensure enough hydronic capacity (NIRAS 2018). Furthermore, the DH company plan to lower DH supply temperatures towards 50°C between the summer and heating period by addressing all critical heat customers that cannot guarantee legionella-safe DHW at these supply temperatures. It is presumably achieved by replacing the DHW heat exchanger with the highest return temperatures. Thereby, enabling supply temperature reduction in both summer and in the winter period at approximately 10°C on average. For 90 large heat customers, a different technique is needed due to a DHW circulation system. Here they consider techniques such as chemical treatment methods for legionella or temperature elevation by a booster HP. They estimate a time horizon of 10 years to be appropriate for the transition of their heat customers (NIRAS 2018). Figure 5: Envisioned heat supply system temperatures. Operating temperatures are ranked according to the flow rate in the DH grid. Borrowed from (NIRAS 2018) Figure 5 shows the targeted DH supply and return temperatures in each zone and in the transmission grid that supplies the zones. The new zone division and the critical heat customers are seen on Figure 4. The execution of the plan is ongoing. According to the definition of critical heat customers, Viborg DH company are mainly working with critical heat customers that are at risk of legionella disinfection, but combines it with also poor performing customers, see definition section 1.3.

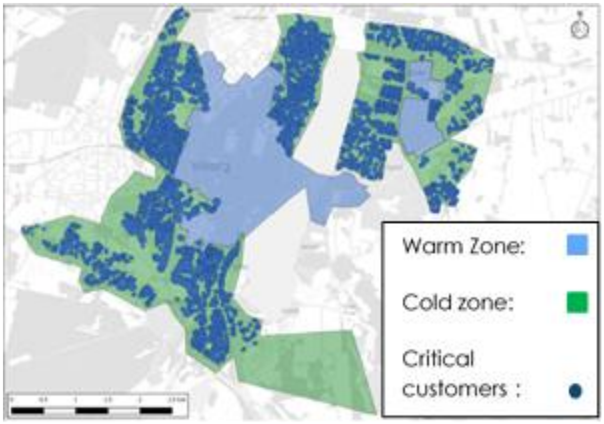


FIGURE 4: VISUAL PRESENTATION OF CRITICAL CUSTOMER INITIATIVE IN VIBORG. BORROWED FROM (NIRAS 2018)

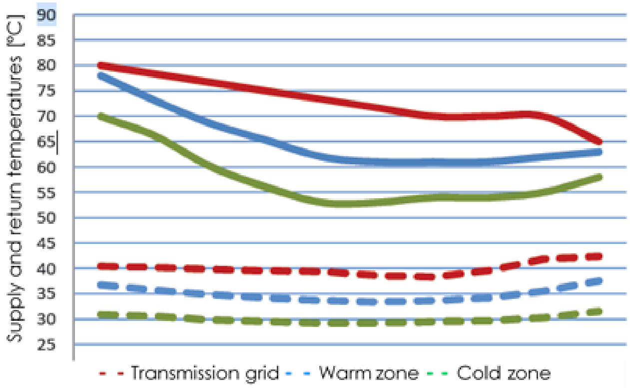


FIGURE 5: ENVISIONED HEAT SUPPLY SYSTEM TEMPERATURES. OPERATING TEMPERATURES ARE RANKED ACCORDING TO THE FLOW RATE IN THE DH GRID. BORROWED FROM (NIRAS 2018)

COPENHAGEN (HOFOR)

In Copenhagen, HOFOR is DH company that both produce and distribute heat. The largest share of heat is produced by large CHP plants. These are fueled mainly by wood pellets, but there are also significant production shares fired by coal and waste. The DH company is a private limited company owned by Copenhagen Municipality. They meter 34,120 heat customers that consumes a total of approximately 5 TWh. It makes them a large DH company.HOFOR has DH temperatures ranging between 65°C-95°C, but was in 2013 able to supply Inner Vesterbro with temperatures at approximately 75°C. It was enabled by installation of new substations combined with energy renovation initiatives promoted by the municipality through urban retrofit funding. In total 225 mostly large heat customers were converted, see Figure 6. (BTK-KK 2005; Skov 2019).

FIGURE 6: LEFT: LARGE BUILDING SUBJECT TO RENOVATION. RIGH: THE AREA OF THE 225 HEAT CUSTOMERS (BTK-KK 2005)

ALBERTSLUND DH COMPANY

Albertslund DH company is situated in Greater Copenhagen and buys heat from the transmission operator in the area. For peak and back-ups, the DH company has a natural gas fired boiler. The average heat loss is 20 %. The DH company is a rather small one.

The municipality owns and administrate the relatively small DH company and has put forward a strategy and goal for reaching DH temperatures at 60°C in the entire utility area of 7500 customers, see Figure 7. To reach the temperature parts of their strategy is intended at lowering return temperatures through replacement of old substations. The main challenger however is to address critical heat customers with thermal comfort issues. They promote energy renovation as their main technique to improve the customers but do also assist customers that want a less capital-intensive solutions, which is improved radiator heating power. The plan is ongoing and will presumably be realized by 2025. (AF 2016)

FIGURE 7: MAP OF THE UTILITY AREA. ALL TYPES OF CUSTOMERS ARE PREPARED FOR LOWER DH TEMPEARUTURES (LYHNE 2016).

HØJE TAASTRUP DH COMPANY

Høje Taastrup is also situated in DH area of Greater Copenhagen. They have three heat pumps and plan to have two more. Approximately 5% of the heat production is today covered by heat pumps.A solar collector produces approximately 1%. The rest is covered by a transmission grid.

The DH company is consumer-owned and is a rather small DH company with 18 people employed. Høje Taastrup has no goal or strategy on how to lower supply temperatures. Instead they target lower return temperatures, which currently is 45°C, but should be 41°C by 2025.

Høje Taastrup DH company is investigated due to their participation in a Research & Development project, in which an area, see Figure 8, of 75 customers were improved to lower DH supply temperatures. The initiatives were targeted the DHW systems, where new instantaneous heat exchanger with a larger thermal length was installed to lower ensure legionella-safe DHW at lower DH supply temperatures. It allowed that the return temperature from the neighboring grid could be used for supply. The project was completed in 2014 and achieved supply temperatures at 55°C. Compared to the main grid, it was a supply temperature reduction at 25°C (DEA 2014d). Results from the project was achieved over a period of 2 years.

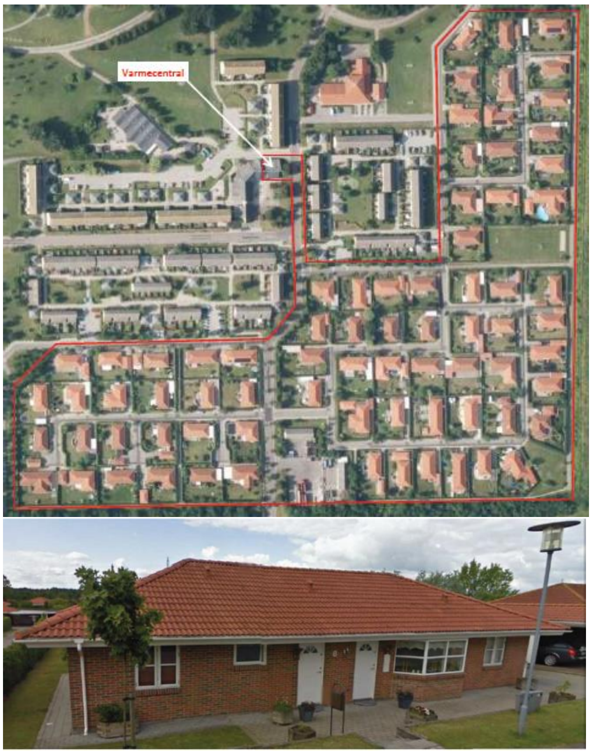


FIGURE 8: SINGLE-FAMILY HOUSE WHICH HAD THE DHW SYSTEM REPLACED WITH A UNIT WITH LONGER THERMAL LENGTH (DEA 2014D)

AffaldVarme Aarhus

Heat production of the DH company; AffaldVarme Aarhus (AVA) is primarily based on large steam CHP plants. The main fuel input is wood pellets, but waste and straw also constitute significant shares. These units are equipped with flue-gas condensation. The yearly heat production amounts approximately 2.5 TWh. The DH company is municipality driven and represents a large DH company.

In Arhus, they promise only DH temperatures at 60°C, but in practice they operate at up towards 110°C in some part of their distribution areas. They do also have designated low temperature areas where local boost of DHW is needed. However, this thesis will refer to the cases of Lystrup and Tilst.

In Lystrup 40 critical heat customers were addressed to guarantee legionella-safe DHW at lower DH supply temperatures, see above picture on Figure 9. New DHW tank or an instantaneous heat exchanger with larger thermal length than the former was installed and adjusted at the customers. It allowed DH supply temperatures to be lowered from 55°C to 52°C on average (DEA 2014c). In the project of Tilst, energy renovation, replacement of valves, radiators and substation was promoted to lower DH supply temperatures. The area was small consisting of 8 small heat customers from 1970s, see bottom picture of Figure 9. In a combination with other initiatives, they achieved a supply temperature reduction at approximately 10°C (~75-65°C), despite only one customer was convinced to conduct an energy renovation. It was found that radiators were over-dimensioned and that alternative heat sources contributed with extra heating power (DEA 2014e). Results from both projects were achieved over a period of 2 years.

FIGURE 9: ON TOP: TERRACED HOUSE WHICH HAD DHW SYSTE IMPROVED IN LYSTRUP. BOTTOM: SINGLE-FAMILY HOUSE FROM 70S WHERE SEVERAL SH SYSTEM IMPROVEMENTS WERE PROMOTED (DEA 2014E; DEA 2014C).

Summary of cases

The cases of DH companies are selected based on their experience from addressing critical heat customers to lower DH temperatures. Critical customer initiatives in Viborg and Albertslund are ongoing and provide insights in the process. HOFOR, AVA and Høje Taastrup are DH companies that in the past addressed critical heat customers, which presumably provides a different perspective on how critical heat customers should be addressed. Moreover, the DH companies vary in sizes and ownership. Experiences are from both large and small heat customers, which may also bring different perspectives. The combination of cases covers experiences from the three critical heat customer types listed in section 1.3; poor performing, thermal comfort issues, and risk of legionella infection.

2.3 Investigated heat supply systems

Six different production- and distribution systems have been designed to investigate where critical heat customers should be addressed. The systems are designed, to reflect the variety of district heating systems found in Denmark. Each system is provided with a more thoroughly justification of why it has been chosen for investigation.

An overview of the investigated heat supply systems is seen in Table 4. Each system is marked to the left. It shows which production unit is in each system, which fuel/input the unit consumes and what the modelled production share is. It should be noted that transmission grids are modelled with an undefined fuel, because it can be all possible kinds of fuels.

TABLE 4: INVESTIGATED HEAT SUPPLY SYSTEMS

	Production units	Fuel/input	Heat production share
Temperature independent system	Transmission grid	Undefined	100%
Solar collector system	Solar collector	-	21%
	Transmission grid	Undefined	80%
HP system	Heat pump	Electricity	60%
	Transmission grid	Undefined	40%
Condensing system (Natural gas)	Natural gas motor	Natural gas	97%
	Natural gas boiler	Natural gas	3%
Condensing boiler system (Wood)	Wood chip boiler	Wood chips	100%
CHP incineration system	Incineration plant	Waste	25%
	Wood pellet steam CHP	Wood pellets	63%
	Transmission grid	Undefined	12%

All heat supply systems have been designed with a hot water storage at 100 MWh, which reflects that all heat supply systems have been modelled to supply the same heat demand. Likewise, all DH companies have been modelled with the same heat losses in the distribution system, which is the average heat losses of DH companies in Denmark (DF 2018). The characteristics of the grid is seen in Table 5.

TABLE 5: CHARACTERISTICS OF THE DISTRIBUTION GRID OF ALL HEAT SUPPLY SYSTEMS

Delivered heat from plant	33,000	MWh
Grid loss	23	%
Heat demand consumer	25410	MWh
DHW share of heat demand	20	%
Supply temperature, heating season	75	°C
Return temperature, heating season	39	°C

TEMPERATURE INDEPENDENT SYSTEM

Some DH companies don't have their own heat production units and other DH companies have heat production units that are temperature independent. All these DH companies are represented through the temperatures independent system. In the system, it is assumed that heat from transmission grids can be bought at 368 DKK/MWh, based on DF (2018).

SOLAR COLLECTOR SYSTEM

Approximately 570 DH companies exists (Danish Utility Regulator 2018), 9% of these have solar collector in the system (Added Values, Dansk Gasteknisk Center and Grøn Energi 2017). Usually, solar collectors come in combination of gas motor and gas boiler. To avoid overlap with the condensing system (natural gas), solar collectors are modelled with a transmission grid instead. The dimensioning of solar collectors and storage is based on recommendation from Energinet and DEA (2016). The solar collector covers 21 % of the heat production. It is equal to 11,250 m^2 based on formula described in section 3.1, and the solar radiation profile; DRY zone 3 (EnergyPRO 2013). A transmission grid covers the leftover heat demand with the same characteristics as the other transmission grids.

HP SYSTEM

Heat pumps are represented by less than 65 units out of 1883. Heat pumps are therefore currently not a typical system design, but regulations on electricity taxations have changed lately, making a heat pump system a system of the future. This heat pump system has a heat pump is dimension to cover 60 % of the production. Such heat production share is according to DEA and Grøn Energi (2017) reasonable.The HP has a heat capacity at 2.5 MW_{heat}. The HP is modelled as a ground water HP with heat source temperatures at 9 °C and a Lorentz efficiency at 50 % which result in COPs as of Table 6 Taxes and tariff include the new electricity tax (Government 2018), DSO and TSO tariffs (DEA and Grøn Energi 2017). The rest of the heat production share is covered by a transmission grid with the same characteristics as the other transmission grids.

TABLE 6: SIZE EFFICIENCY AND VARIABLE COST OF THE HP

	HP	Unit
Capacity	2.5	MW_{heat}
Heat efficiency	3.2	COP
Electricity tax and Tariffs	342	$DKK/MWh_{electricity}$
O&M	24	DKK/MWh_{heat}

CONDENSING SYSTEM (NATURAL GAS) – DECENTRAL CHPS

This system is designed with natural gas boiler and a gas motor, which is a DH heat supply system that represents 16% of all DH systems found in Denmark (Added Values, Dansk Gasteknisk Center and Grøn Energi 2017). The technical specifications are based on Jetsmark Energiværk (2019). Whereas taxes, fuel and O&M costs are based on PWC (2018), DEA (2018a) and Energinet and DEA (2016), respectively. Both natural gas motors and boilers are modelled with heat recovery of flue-gas, it is described in further detail in section 3.1.

TABLE 7: NATURAL GAS MOTOR AND BOILER SPECIFICATIONS

	Gas Motor	**Gas Boiler**	**Unit**
Capacity	10 /7.5	9.5	MW_{heat}/MW_{el}
$Efficiency_{heat/el}$	54 /41	95/-	%
Fuel costs incl. tax	2,295	4,80	DKK/Nm3
Fuel tax (prod.)	2.59	-	DKK/Nm3
O&M	50	5	DKK MWh

CONDENSING BOILER SYSTEM (WOOD)

This heat supply system is modeled with a woodchip boiler which covers the entire production. According to Added Values, Dansk Gasteknisk Center and Grøn Energi (2017) DH companies with wood chip boilers as main production unit represents 9% of all DH companies. The system specification of efficiency, O&M (Energinet and DEA 2016), fuel costs, and taxes (DEA 2018c) are seen in Table 8. The wood chip boiler is modelled with heat recovery of flue gas, which is described in further details in section 3.1.

TABLE 8: TECHNICAL SPECIFICATION OF WOOD CHIP BOILER

	Wood chip boiler	**Unit**
Capacity	9.5	MW_{heat}
Efficiency Heat	95	%
Wood chip costs	42.3	DKK/GJ
O&M	10	DKK/MWh
NOX taxes	0.5	DKK/MWh

CHP INCINERATION SYSTEM – LARGE STEAM CHP PLANTS

Steam CHP plants and incineration plants are typical for large and medium sized DH companies. Heat production from incineration plants cover 24% of the total heat demand in Denmark (EA Energianalyse 2016). This system is designed with an incineration plant covering base load at 25 %, CHPs covering 60% and a transmission grid that covers the rest. It is assumed that both incineration and steam plants have heat recovery of flue-gas. The production benefits of lower DH temperatures are described in more detail in section 3.1.

Operation costs, fuel and transport costs of the wood pellet fired CHP is based on Energinet and DEA (2016) and (2018c). Operation, taxes and fuel cost is based upon Danish Waste Association, DI and Danish Energy (2016). The numbers are shown in Table 9.

TABLE 9: TECHNICAL SPECIFICATIONS OF INCINERATION PLANTS AND STEAM CHP PLANT

Production unit	Incineration plant	Wood pellet CHP plant	Unit
O&M	~310	~ 7	DKK/MWh input
Taxes on fuel	~80	None	DKK/MWh
Fuel cost	~-148	~245	DKK/MWh
Transport cost	Waste producer pays	8	DKK/MWh input
Efficiency$_{el}$	15%	28.6%	%
Efficiency$_{heat}$	80%	68.0%	%

SUMMARY OF HEAT SUPPLY SYSTEMS

In this section all heat supply systems 6 different heat supply system was established. All heat supply systems were designed with similar heat demands and heat losses and a thermal storage at 100 MWh. It was concluded that all heat supply systems represent a large share of systems that can be found in the real world. However, all combustion units have been equipped with a condenser to recover heat from the flue-gas. No statistics were found to explain how many plants that have such system installed. Consequently, they representative of the systems are uncertain. Next chapter will provide the theoretical understanding for how each technology of the heat supply systems is affected by lower DH operating temperatures. It will also provide the theoretical approach for the cases presented in section 2.2.

3 THEORETICAL FRAMEWORK

The theoretical framework is divided into two sections. First part presents profit as the key evaluation parameter. It describes equations that are used to calculate the correlation between DH operating temperatures on the efficiency of production technologies and distribution of heat. These equations are used in the modelling of the heat supply systems described in 2.3, which will be used to answer where critical heat customers should be addressed. Secondly, a theory of technological change is presented, which guides the analysis of how the DH company transitions critical heat customers.

3.1 TEMPERATURE DEPENDENCY OF THE HEAT SUPPLY SYSTEMS

As discussed in the introduction, profit is one of the determining factors, when DH companies choose between different techniques to address hydronic bottlenecks. According to Hvelplund (2011) profit is not only important for the specific area of hydronic bottlenecks. It is rather a general tendency that actors in the energy sector, such as DH companies, puts great emphasize on profit. Profit influences which technological development DH companies aim for and which they don't. The heat supply production technologies and the heat distribution losses are both important factors, when determining the profit of a heat customer initiative. Below follows a description of equations that have been used to theoretically estimate production and heat distribution efficiency gains of lower DH supply temperatures.

PRODUCTION EFFICIENCY

Production efficiency are determining for the fuel consumptions and thereby the cost at which heat can be produced. The more efficient production, the less input energy is needed. The efficiency of a conversion depends on various things, but temperature levels are an important parameter to many conversion units. The impact of supply and return temperature reductions on the heat production will be explained, focusing on the production units of the modelled heat supply units, presented in section 2.3.

Heat recovery of flue gas

A plant with a flue-gas heat recovery system attached to DH return temperatures, increases its efficiency when DH return temperatures are lowered, because more heat can be recovered from the flue-gas. The increase of efficiency depends on the combustion process and the composition of the fuel. Wood chips and waste have a high moisture content that cannot be used in the combustion process but in the flue-gas heat recovery process. Figure 10 shows the additional heat potential per MWh, correlated with the return temperature. CHP plants produce more flue-gas per MWh heat, because of a simultaneous electricity production. As a result, these plants have a relatively larger benefit from heat recovery of flue-gas than boilers operated with a similar fuel. Natural gas does not contain water, but water is produced in the combustion process (Song et al. 2004).

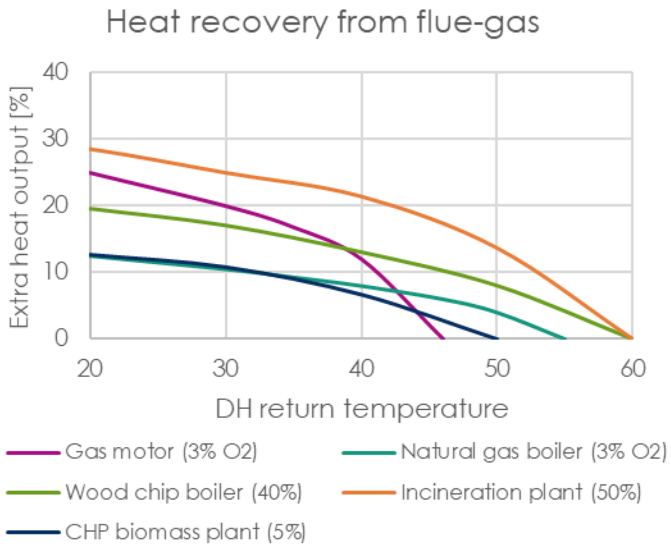


FIGURE 10: THE FIGURE SHOWS THE EXTRA HEAT OUTPUT RESULTING FROM LOWERED DH RETURN TEMPERATURE. THE PROCENTAGE WITHIN THE BRACKETS INFORMS ABOUT THE MOISTURE CONTENT OF THE FUEL.

The efficiency profile of the production units that recovers flue-gas, described in section 2.3, are visualized in Figure 10. The efficiency profiles are based on work from Paaske (2015) and Added Values, Dansk Gasteknisk Center and Grøn Energi (2017).

Steam CHP plants

Back-pressure CHP plants also benefits from reduced supply temperatures. It enables a larger electricity production. The Carnot cycle can be used to calculate the electricity output from a steam CHP plant. η in formula [1] is the electric power output from the steam turbine. T_{high} is the temperature in the steam turbine, which is assumed to be 500°C (Cengel, and Boles 2005) It is evident from the formula that the higher temperature difference between combustion and supply temperature, the larger electric output.

$$\eta = 1 - \frac{T_{low}}{T_{high}} \qquad [1]$$

Solar Collectors

For solar collectors, the efficiency increases when the temperature difference between the ambient air and the fluid is minimized. Therefore, both supply and return temperature matters. Formula [2] is found in EnergyPRO (2013), and it enables the heat production efficiency of solar collector Y [W] to be calculated. It requires the input of the total collector surface; A [m^2], as well as the solar radiation for each hour; I_s [W/m^2], and a maximum efficiency n_0, which is assumed to be 81.7%. The maximum efficiency can only be achieved in the case where ambient temperatures t_a [°C] are equal to the mean temperature between supply and return t_m[°C]. When ambient temperatures are lower, there is an efficiency loss determined from the first and second-order coefficient a_1 and a_2 [W/(m^2 °C], which are assumed to be 2.205 and 0.013, respectively (EnergyPRO 2013).

$$Y = A \cdot (I_s \cdot n_o - a_1 \cdot (t_m - t_a) - a_2 \cdot (t_m - t_a)^2) \qquad [2]$$

Heat pumps

A heat pump also benefits from reduced supply and return temperatures because the temperature difference between the heat source and the heat output becomes smaller. To describe how supply and return temperatures affect heat pump a Lorentz cycle is applied, see formula [3] (DEA and Grøn Energi 2017). The coefficient of performance (COP) is calculated applying a system efficiency η at 0.5. T_{high} is logarithmic mean temperature in the condenser, whereas the T_{low} is the logarithmic mean temperature in the evaporator. Both T_{high} and T_{low} are calculated from equation [4]. T_{low} are calculated from input data on heat source temperature in and out of the evaporator, where the heat source cooling is assumed to be 5°C. T_{high} is calculated from DH temperatures in and out of the condenser.

$$COP = \eta \cdot \frac{T_{high}}{T_{high} - T_{low}} \qquad [3]$$

$$T_{high} \; or \; T_{low} = \eta \cdot \frac{T_{in} - T_{out}}{Ln(T_{in}) - LN(T_{out})} \qquad [4]$$

Distribution

Once the conversion of heat has taken place, it is transported to the heat customer. At this stage, we are at the distribution level. The distribution level consists of pipes in varying sizes depending on the heat load at the specific pipe branch. As mentioned in section 1.2, the distribution of heat takes up on average of 23 % of the gross heat production. Hence, improving the efficiency of heat distribution constitute a large potential for energy savings. The potential heat savings can be calculated from the formula [5] found in Østergaard and Andersen (2016):

$$Grid\ loss = U_{value} \cdot ((T_s - T_g) + (T_r - T_g)) \cdot 2 \cdot L \qquad [5]$$

The heat loss in the grid do depend on the supply and return temperatures which vary from hour to hour. In the model, the ground temperature T_g is assumed to be 8 °C and the U-value [MW/m °C] 0.0000003 (Østergaard and Andersen 2016). The grid length; L is assumed to be 16,500 m.

In distribution grids with no leaks, heat losses depend on the insulation of the pipe, the size of the pipe, the length of the pipe, and lastly the temperature difference between the outside of the pipe and the inside of the pipe. Considering that pipes potentially have a lifetime above 40 years, the only controllable variable to heat losses are the DH operating temperatures. The more the temperature can be reduced the lower heat losses, due to a smaller temperature difference. Return temperatures depend on the heating system of each single heat customer as described in section 2.1. Consequently, supply temperatures are not easily lowered. Lowering supply temperatures will reduce the hydronic capacity, which is given by the difference between supply and return temperatures combined with the heat consumption. Thus, to avoid replacing pipes in the distribution grid improved customer operation or reduced consumption of the heat customers is required.

SUMMARY ON TEMPERATURE DEPENDENCY

The technologies of the heat supply systems presented in section 2.3 do all benefit from lower DH return temperatures except the transmission grid. The natural gas boiler and motors do not benefit from lower DH supply temperatures. Table 10 presents an overview of technologies and their temperature dependency based on the theoretical exposition.

TABLE 10: EFFICIENCY GAINS FOR EACH HEAT SYPPLY SYSTEM TECHNOLOGY INCLUDING DISTRIBUTION OF HEAT.

Efficiency gains	DH return temperature lowered	DH supply temperature lowered
Transmission grid	-	-
Solar collector	✓	✓
Heat pump	✓	✓
Natural gas motor	✓	-
Natural gas boiler	✓	-
Wood chip boiler	✓	-
Incineration plant	✓	✓
Wood pellet steam CHP	✓	✓
Distribution of heat	✓	✓

3.2 TECHNOLOGICAL CHANGE – IMPROVING CUSTOMERS' HEATING SYSTEM

The implementation of lower DH operating temperatures may be described simply as the need of a few technological upgrades as described in section 1.4. However, to answer how DH temperatures can be lowered, it will be insufficient only to look at technical aspects. This section provides a theoretical framework stating that social and technical aspects must be thought together to create a technological change. It draws upon theory of technological change (Müller 2011), theory of working knowledge (Davenport and Prusak 1998) and actor-network theory (McLoughlin 1999).

The implementation of critical heat customer initiatives is seen as a technological change. Müller (2011) propose that technological change depend on both social and technical aspects. Disregarding the holistic picture of a technological change may very well lead to an unsuccessful implementation of a technology. Some see technology as only the technique itself, but in the theory of technological change, implementation of technology is very context depended. The technique needs to fit into the existing knowledge of the user and fit to the organizational set-up. If it does not, other techniques that can produce the same product will be implemented.

Technology may therefore be understood as having four components; product, technique, knowledge and organization, where changing one component requires, the other components to adapt. A short definition of the components is provided below:

- *Product* is the output of the technology, which in this thesis is interpreted as lower DH operating temperatures.
- *Technique* is the device producing the product, which could be insulation of the building envelope, replacement of the substation or chemical treatments of the domestic hot water.
- *Knowledge* is the skills and intuition it takes to apply the technique.
- *Organization* is how the work to improve critical heat customers is managed and coordinated.

It has been found useful to carry out a couple of modifications of the theory, as the theory has been developed in a slightly different setting of non-energy related transformation processes in developing countries (Müller 2011).

Rather than investigating all components, it has been chosen to exclude the components of product and technique from the analysis. Hence, all the necessary techniques exist, see section 1.4, why these should not be the focal point of an investigation. Moreover, the product of technological change is indirectly represented in the selection of cases for this thesis because all cases are chosen since they achieved or work towards the product of lower DH temperatures. The complicated aspect is that critical heat customers have the authority to make decision about their own building heating system, but DH companies want to influence it to lower DH operating temperatures. It opts-out for more attention towards organization and knowledge aspect of technological change. The application and adjustment of these two components are explained in the following.

THE GENERATION AND TRANSFER OF KNOWLEDGE

The knowledge component of technological change is found suitable as a theoretical frame to answer the second sub question. The question concerns the identification of critical heat customers, and the role of knowledge when DH companies try to convince critical heat customer to improve. The term of knowledge may according to Davenport and Prusak (1998) easily be misinterpreted as simply information and data. Data is not knowledge, because it is discrete measurements of the world that are unprocessed and without purpose. Information is neither knowledge, but one step closer. Information is processed data, which provides an interpretation of the data. Information is spread orally or through information channels such as e-mails or newspapers. However, information is not necessarily useful, and too much data may even hamper the ability to take decisions, because information can be contradictory. For information to become knowledge it needs to pass through four check points at the receiver; 1. *Comparison* with other information to see differences. 2. *Conversation* with peers, to share viewpoints, and see if other find the information valid. 3. *Consequences* for decisions and actions are assessed. 4. *Connect* the piece of information to the existing knowledge, to ensure that it fits in. The ability to pass through all check points are among other things dependent upon trust, culture and how it is shared. (Davenport and Prusak 1998)

Skills come from applying the knowledge to do something (Müller 2011). Flyvbjerg (2006) refers to skills as the first learning stage, which is more schematic and less fluid. *Intuition* is the knowledge that come along working with doing something for a longer period and offers fast application of knowledge.

This type of knowledge is hard to transfer, but may be transferred when two people spend time together in the same location (Müller 2011; Davenport and Prusak 2016)

DH company presumably possess both skills and an intuition onto how building heating systems can be improved in contrast to the critical heat customer. On the contrary, the critical heat customer is an expert in his or her own life and knows which solutions for building heating system improvements he or she finds suitable. As a result, how knowledge is transferred from DH company to heat customers becomes of interest.

For DH companies, knowledge is valuable, but the speed of knowledge is presumable essential as it allows work to be carried out more efficiently. A critical heat customer needs to be convinced on improving his heating system, in this process, it may be of more importance that information from the DH company transforms into knowledge of the heat customer.

AN ACTOR-NETWORK RATHER THAN AN ORGANIZATION

The organizational components refer to how the coordination and management of a critical heat customer-oriented initiative. Heat customers and the DH company can hardly be seen as one organization, because heat customer is not employed in the DH company. The independence of heat customers is upheld by law stating that they cannot be obligated to purchase heat (Danish Ministry of Energy, Utilities, and Climate 2019).

There is no doubt that DH companies wish to push the critical heat customers in the direction of better performance. Actor-Network Theory offers a perspective that accommodate the independence of heat customers and the interest of DH companies to push for change.

The theory states that both humans and nonhumans have agencies, these goes within the collective name of actants. The term: Actors, is in the theory used to specify human actants. Examples on actors are DH companies, critical heat customers, plumbers and municipalities. Non-human actants, on the other hand, could be regulation or specific techniques to improve the building heating system of critical heat customers. An actor-network is formed when several actants share the same interest (e.g. addressing the critical heat customers) and it is at this point the technological transition into improving the critical heat customers can take place. (McLoughlin 1999)

PROBLEMATIZATION AND ACTOR ALIGNMENT STRATEGIES OF THE KEY ACTOR

The initial phase of a technological development will always be characterized by actants with diverse interests. Consequently, for an actor-network to be formed it requires a process of *problematization.* In this process scenarios are constructed by demonstrating to other social actants that their interest is best served through membership in an actor-network. (McLoughlin 1999)

It is the role of the key social actor to lead the problematization process, which may be the DH company that possess regulatory tool which can support a problematization process. The success of the DH company in the promoting of an actor-network that addresses the critical heat customers depend on one thing. Actors need to accept that their agenda and interests will be downgraded on behalf of the common agenda of the network in order to be enrolled. It makes the DH company depended on actors' willingness to accept a simplification of their interests.

For the DH company, it is about using all its means to exert power over potential members to have them enrolled to improve critical heat customers. Power in that sense is both direct and indirect power. Applying direct power could be using regulations which actors need to adhere to. Indirect power is about communicating how the product of lower DH operating temperature serves the mutual interest of e.g. heat customers, plumbers or/and municipality. DH companies' implementation of regulation that further their interest must be studied. Moreover, the values and beliefs ascribed to techniques and value and beliefs of the critical heat customers must be studied to explore how actor-networks are brought together.

Obligatory passage point

An actor-network is never more stable than the implementation of a technique could easily destabilize the network. E.g. if a technique does not fit into the customers' heating system as intended, the network could be destabilized.

To avoid destabilization, it is necessary for the actor-network to establish a so-called *obligatory passage point*, which is something that ties both human and non-human elements together. Rydin (2012) suggests that within urban planning, a planning consent process is an obligatory passage point, because the entire purpose is to tie actants together. However, DH companies are not imposed to establish planning consent processes, why the obligatory passage point may look differently for the investigated cases.

Thereby, substituting the organizational components with actor-network, the investigation will focus more on the interest, motivation, and arguments convincing actors to align with the DH company and the building of an obligatory passage point where plumbers, critical heat customers, municipalities, building heating system techniques and other relevant actors and actants have been tied together.

To sum up the theoretical framework applied in this thesis, technological change theory is applied as the main theory. While the theory states that all components are relevant to technological change, I find for this thesis that the product is pregiven to be lower DH temperatures at the critical heat customer, and techniques to achieve it on building level already exist. The investigation should focus on knowledge and on how an actor network can be established.

3.3 Summary of theoretical framework

DH companies' motivation for a heat customer initiative is mostly associated with the profit gains, why economic savings of different heat supply systems must be studied to answer where a critical heat customer initiative can take place. How to address critical heat customer is presumably something that requires one to study knowledge generation and transfer and the establishment of actor-networks.

The knowledge analysis is about investigating if the skills exists to identify critical heat customers and to investigate how knowledge is transferred between DH companies and critical heat customers in the process of implementing adequate solutions.

The investigation of actor-network requires a study of the motivation and values of actors, the values ascribed to techniques, and of the power instrument that DH companies possess to align conflicting interests. Lastly, the analysis must identify which obligatory passage point that was created to keep actor and actants tied together.

Table 11 provides an overview on analysis elements that is used to answer the three sub questions posed in section 1.6.

TABLE 11: THEORETICAL LENSES ON THE SUPPORTIVE QUESTIONS

Sub question 1:	Profit • Economic savings in various heat supply systems from a critical heat customer initiative	
Sub question 2 and 3	Knowledge • Skills to identify critical heat customers • Knowledge exchange between critical heat customer and DH companies.	Actor-network • Actor motivation • Actor-alignment strategies: DH companies power instruments • Obligatory passage point

4 Method

This chapter explains the overall methodology applied to answer the research question. It starts by introducing overall research design and continues explaining the research approach. It ends up elaborating on the methods that were applied to gather and handle data. Each section provides a short discussion on the pros and cons related to the methods.

4.1 Theories of science and research design

The work of this thesis is structured from an understanding that critical heat customer initiatives partly result from approximated facts about the cost and benefits of such initiative, and partly from how cost and benefits are perceived. The perception is shaped in the underlying structures in the local context. Consequently, to generate knowledge to answer where and how critical heat customer should be addressed both quantitative and qualitative methods must be applied. Heat supply systems are modelled through technical characteristics of production units and heat losses. The purpose is to predict where critical heat customer initiative should be carried out. The model represents a simplified reality as It depends on assumptions and theories on the interaction between DH temperatures and efficiency, as described in section 3.1. The modelling result provides a path, which either is to address critical heat customers or avoid addressing them. However, deeper underlying structures concerning DH companies, plumbers and heat customers may infer that the path is not always taken. Consequently, they must be studied to identify what underlying structures that impact the perception of a critical heat customer initiative and how these structures have been changed by the DH companies. The viewpoints represent a theories of science position called critical realism (Bryman 2016).

The research design has been structured according to above-mentioned viewpoints, as seen in Table 12. The research is designed for a multiple case-study approach. The multiple cases are investigated using mixed methods which includes both the qualitative heat system modelling method and the qualitative interview methods. Value of customer initiatives are quantitatively evaluated by determining the profit of different heat supply systems. Barriers in addressing critical heat customers are qualitatively covered by investigating conflicts of interest, knowledge barriers. The outcome is strategies DH companies have applied to ensure that critical heat customer initiatives are in everyone's interest, and initiatives to generate and transfer knowledge that enables identification of critical heat customers and the development of adequate solutions.

TABLE 12: RESEARCH DESIGN TO ANSWER THE RESEARCH QUESTION

Research approach	**Multiple case-study**		
	Heat system analysis	Qualitative part	
Theoretical scope	Profit	Actor network	Knowledge
Data acquisition	Customer and grid data	Interviews Desc research	Interviews Desc research
Data handling	energyPRO	Thematic analysis	Thematic analysis
Analysis scope	Value of customer initiative	Influence/interest/collaboration approach	Transfer and generation of knowledge to identify and develop solutions for customers.
Outcome	Profit of different heat systems	Actor alignment strategies for critical customer initiatives	Knowledge generation and transfer approaches to critical heat customers

MIXED METHODS

When carrying out a piece of research, the results may be improved and gain trustworthiness once a triangulation of methods takes places. Triangulation is the appliance of both quantitative and qualitative methods, because each method has its strengths and weaknesses. Quantitative methods allow a broader range of data to be analyzed than for qualitative methods and thereby provides more information on the scale of a phenomenon. Contrary, qualitative methods provide more insights to the explanatory factors of a phenomenon. The quantitative investigation of various heat supply systems provides insights on the economic benefits from a critical heat customer-oriented initiative. Based on the hypothesis that profit is one of the main determining factors for DH companies to commit themselves into addressing critical heat customers, the quantitative heat system analysis allows the question: "where can critical heat customer potentially be addressed?" to be answered. The qualitative interviews supplement the investigation by revealing motives of those DH companies that did address critical heat customers, thereby testing the hypothesis that DH companies does it for profit. This interrogation of the results is the great advantage of mixed methods (Brannen 2012)

4.2 RESEARCH APPROACH

This section explains the reasoning behind choosing a multiple-case study approach. It outlines the problem of generalizability for case-studies and explains how a case-selection strategy reduces the problem. It should be noted that cases applied for the qualitative analysis are distinct from the quantitative analysis.

MULTIPLE CASE STUDY - THE QUALITATIVE PART

A multiple case-study approach has been used to investigate how DH companies can address critical heat customers. The research method is often applied in social sciences to describe and explain phenomena of human agency. When DH companies address critical heat customers the goal is to change their behavior in order to make them well-functioning heat customers. This require explanatory knowledge on how heat customers can be influenced. Consequently, a qualitative research approach is suitable for answering the research question. The general challenge within social science is generalization of results with the purpose of forming theories, this partly due to human agency being unpredictable. By consciously selecting cases for qualitative analysis, issues regarding generalizability can be addressed. (Flyvbjerg 2006).

In this thesis, a snowballing method (Bryman 2016) has been applied, where correspondence with professionals in field let to the selection of DH companies that successfully addressed critical heat customers to lower DH operating temperatures. It is a selection strategy where *extreme* cases are identified. The case-selection strategy is useful to point out what it takes to address critical heat customers, because all cases succeeded doing it. And when multiple case studies are investigated it proliferates the amount of obtained insights. Thereby, it improves the possibilities to learn something general from the case-studies by identifying factors that repeatedly occur in the cases.

In the end, the snowballing method provided the investigation with a handful of success-cases. As it turned out, the DH companies involved in these success cases were very different in size, ownership, heat production technologies, and type of heat customers, see section 2.2. These very different conditions had the consequence that the cases cannot only be defined as extreme cases, but also as maximum variation cases. According to Flyvbjerg (2006), it is very typical that after a closer investigation, cases lead to a new understanding of the cases.

For the purpose of generalizing, cases should preferably differ in only one dimension (Flyvbjerg 2006). The selected cases have DH companies that differ in size, ownership, heat production technologies and critical heat customer types. Due to the variety of changing dimensions, the thesis will be careful not to generalize, but only provide indications on the significance of the dimensions.

MULTIPLE CASE STUDY - THE QUANTITATIVE PART - HEAT SYSTEM MODELLING

A heat system modelling approach has been selected to answer where DH companies can address critical heat customers. Instead of trying to model the systems of Høje Taastrup, Viborg, HOFOR, AVA and Albertslund, 6 archetypical heat supply systems with very distinct technologies have been established following the maximum variation case selection strategy (Flyvbjerg 2006). The cases only differ in terms of heat production technologies and are modelled in terms of the business economic costs including fuel, tax and tariff costs, why a cross-case comparison is possible. It enables to conclude what significance the heat production technology has for the profit of a heat customer initiative. The investment costs for improving large and small heat customer, can finally be deducted from the profits. Thereby, it can be answered where critical heat customers should be addressed based on the heat supply technologies and the size of the heat customer.

4.3 DATA ACQUISITION METHODS

Both quantitative and qualitative data acquisition and handling methods have been applied due to the choice of a mixed method research approach. The sources of data are introduced and evaluated. The qualitative data acquisition is evaluated on saturation and the quantitative data is evaluated on its validity to estimate profit in heat supply systems.

HEAT CUSTOMER AND GRID DATA FROM INNER VESTERBRO.

Various types of quantitative data are used as input to model the heat systems to carry out the profit analysis. These data include technical data, described in Appendix, and economic data described in Section 2.3. External conditions of the heat supply systems include the following hourly data: spot market prices of 2018, ambient temperatures and global radiation from Danish Reference Year: 2001-2010 (EnergyPRO 2013). These are historic data, but the analysis tries to estimate a future value. It implies that validity of results generated from these data are reduced proportionally with a longer time-horizon.

Moreover, data has been acquired from the remote meters of the entire population of heat customers in Inner Vesterbro on the 28/03/2018. The data included average hourly: return- and supply temperatures, water flow consumption, and heat consumption. The same type of data, aggregated for all heat customers and including the heat distribution loss, was acquired through the remote reading of a heat exchanger into the same distribution grid. The critical heat customer group was found through a histogram analysis, where the heat costumers were grouped in three based on their return temperatures. The group with the highest return temperatures was assumed to be the critical heat customers.

According to Bryman (2016), one should be cautious generalizing from one sample population to another because the return temperatures of heat customers may be distributed differently from grid to grid due to differences in e.g. tariffs, heat customers' skill to operate their building heating system or e.g. the age of the building heating system. However, no better data source was accessible, why the results of the heat supply analysis only will be used to indicate where there potentially could be a profit from a heat customer initiative.

INTERVIEWS

In this thesis, cases that successfully addressed critical heat customers have been represented by primary data acquired through interviews of each DH company and has been supplemented by both secondary and primary data acquired through desc research, and interviews of other actors such as energy consultants and plumber's organization. When doing qualitative research, the reliability of data is addressed by continuous data collection until data saturation is met (Bryman 2016). Data saturation is defined by the point where data starts replicating itself and no new topics emerge. To determine whether data saturation was met in the present study, the interview data has been split according to topic. Data saturation regarding the role of the DH companies was met, on the contrary, data saturation regarding the role of plumbers cannot be guaranteed since only one interview was conducted. In two of the cases, the interviewee chose to invite an employee with a different role in the organization, thus forming a small focus group. It allowed for even more aspects to arise regarding the internal differences in DH companies. It means that the largest credibility can be given to conclusions regarding the role of DH companies in addressing critical heat customers.

The interviews have been trusted to provide insights on the critical heat customer, who could not be interviewed as the numbers and diversity of critical heat customer is too large to be able to reach data saturation. The choice to trust secondary-sources' insights on critical heat customers become a bias of the study.

An interview guide was prepared for the interviews, which initially was created based on theory of technological change, as described in section 3.2. A continuous adjustment of the interview guide took place, as more detailed insights on the research topic was achieved. Such an approach is typical for qualitative research and is called an iterative process. The fact that the interview guide was created with inspiration from theory of technological change reduced the risk of bias (Brinkmann and Kvale 2015; Bryman 2016) and ongoing adjustments ensured that the research became more precisely defined. On the other hand, the adjustments created poorer conditions for comparison across the cases (Bryman 2016). The interviews were executed with a semi-structured approach, ensuring that interviewees responded to aspects deemed important from their perspective with room for new aspects to appear. An overview of the interviews is provided by Table 13.

TABLE 13: OVERVIEW ON CONDUCTED INTERVIEWS FOR THIS THESIS

Interviewee	Company	Role
Astrid Birnbaum	Høje Taastrup DH company	Manager
Jeanette Thøgersen	AffaldVarme	Head of department: DH Operation
Henrik Brizarr	AffaldVarme	Energy consultant
Tom Diget	Viborg DH company	Manager of distribution
Peter Boysen	Energi Viborg	Engineer
Per Sönder	Energi Viborg	Engineer
Niels Hansen	Albertslund DH company	Consultant on energy & administration
Wisam El-khatib	Albertslund DH company	Project leader and energy consultant
Carsten Nielsen	HOFOR	Energy consultant
Birger Tannebæk Christiansen	Tekniq	Consultant

Informal communication with colleagues at HOFOR has also provided insights for the thesis:

- Morten Skov (Chief Engineer – customer section)
- Kristian Honeré (Project leader – EnergyLab Nordhavn),
- Kim Mygind (Project leader – grid section)

- Kim Kanstrup (project leader for low DH temperature activities)

4.4 DATA HANDLING FOR QUALITATIVE METHOD

The interview data has been handled using thematic analysis. The interviews have been summarized and important statements have been transcribed for further analysis. Summaries and statements across all interviews have been coded allowing both theory of technological change and new perspectives to arise from the data. The applied method gives a description of how critical heat customers have been handled by the DH company. It also enables the deduction of explanatory factors on why these DH companies have been successful in addressing critical heat customers. Due to the case selection strategy, these explanatory factors may form a theory of how critical heat customer should be addressed which in the end will support the recommendations of the thesis (Bryman 2016).

4.5 DATA HANDLING FOR QUANTITATIVE METHODS

This section introduces how the data has been handled in the quantitative analysis. It argues for the applicability of energyPRO as the modelling tool and describes how data measurements from Vesterbro Distribution grid has been handled, to create an input temperature profile for the heat supply systems.

MODELLING TOOL

EnergyPRO is an energy system modelling tool developed for the modelling of the heat systems of Danish DH companies. It is a simulation model which allows the user to construct the heat system. The construction of the system involves the choice of input parameters such as heat demand, heat loss, solar radiation, electricity prices, and production efficiencies. When the heat system is constructed, it can be operated in hourly steps throughout a year. The simulation approach follows an hourly prioritization of the cheapest heat production unit and continuously adds other production units or discharge the thermal storage until the hourly heat demand has been fulfilled (energyPRO 2013).

Other simulation tools exist, such as EnergyPLAN, which has been developed for national energy system analyses. As this thesis is concerned with a smaller geographical scale, energyPRO is preferred as it provides the opportunities for a more detailed heat system modelling compared to e.g. EnergyPLAN (Lund et al. 2017a).

EVALUATION OF HEAT SUPPLY SYSTEM ANALYSIS – DYNAMIC PAYBACK PERIOD

The final evaluation of the quantitative investigation is based on the payback period calculation. The method is applied to determine the number of years it takes to pay-back an investment in the critical customer initiative, if the total gained profit in the heat supply system is allocated to the critical heat customer.

When different investment alternatives are compared on their pay-back time, the investment with the shortest pay-back time is preferred. The method has been criticized for a couple of shortcomings. Income after the investment is paid-off is not considered in the evaluation and there is, according to investment theory, no criterion that can be used to conclude how short the pay-back must be before the investment can be considered feasible (Lund and Østergaard 2010). Anyhow, the dynamic payback method is suitable in this case because the purpose is not to identify whether an investment is feasible or not, but to compare the relative investment feasibility of different heat supply systems and heat customers to answer where critical heat customers should be addressed.

SUPPLY TEMPERATURE REDUCTION FROM A CRITICAL HEAT CUSTOMER INITIATIVE

6 different heat supply systems have been modelled and operated in the EnergyPRO tool to analyze the profit gained from addressing critical heat customers in the short-term perspective. The supply systems and the economic assumptions for each system is seen in section 2.3. This section will focus on the applied temperature profiles before and after a critical heat customer initiative. I could have assumed a DH temperature profile, but I chose to try to calculate it. The approach is present below for the purpose of transparency.

In the heat supply analysis, the critical heat customer is defined as a poor performing heat customer, see Introduction. The critical heat customer is in this definition defined as those customers with the highest return temperature and consequently therefore also high flow rates (m3/h per MW). In other words, the poorest performing building heating systems.

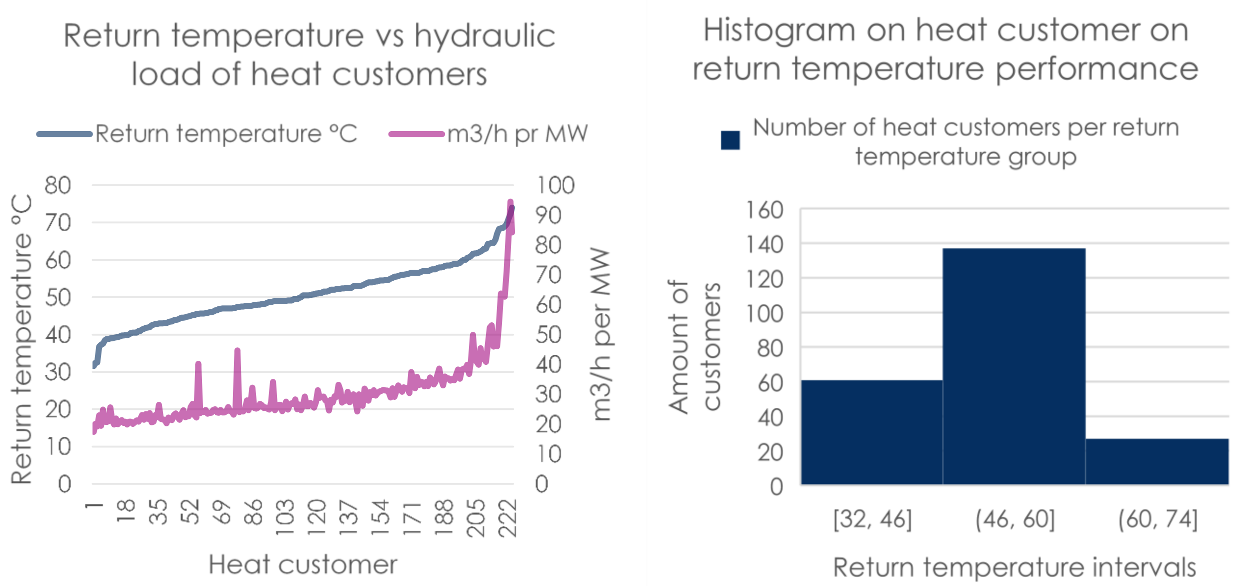


FIGURE 11: LEFT: RETURN TEMPERATURES AND FLOW RATES OF 225 HEAT CUSTOMERS IN THE DISTRIBUTION GRID OF INNER VESTERBRO ON THE 28/03/2018 RIGHT: HEAT CUSTOMERS GROUPED INTO THREE CATEGORIES; WELL-FUNCTIONING, NORMAL AND CRITICAL. (HOFOR 2018)

Figure 11 provides an example on the performance of the heat customers in the distribution grid of inner Vesterbro, where return temperature data from all the heat customers have been aligned from lowest to the highest. A histogram of heat customers and their return temperatures are seen on the right side of Figure 11, where the customer have been grouped into three; a group of well-functioning heat customers, with return temperature from 32-46°C, normal heat customers with return temperatures from 46-60°C, and critical heat customers with return temperatures above 60°C. Most of the customers have return temperatures between 46-60°C, while only a few customers have a return temperature above 60°C. However, these very few customers have a greater impact on the distribution grid as they have significantly higher flow rates and therefore should be addressed. The return temperatures are based on the daily average on the coldest day in 2018. It means that their yearly average return temperature is lower. Yearly average values are found in Table 14. The table presents the average performance of three categories; Critical, average and well-functioning. Both return temperatures and energy consumption has been scaled to reflect the average heat consumption of distribution grids in Denmark (DF 2018), preserving the flow share and energy consumption share of each customer group.

TABLE 14: YEARLY AVERAGE ENERGY CONSUMPTION SHARE, FLOW SHARE AND RETURN TEMPERATURES OF HEAT CUSTOMERS (HOFOR 2018)

Customer type	Well-functioning customers (WFC)	Average customers (AV)	Critical customers (CC)	Total
Energy consumption share	19%	66%	16%	100%
Flow share	15%	64%	21%	100%
Weighted average return temperature [°C]	29	36	46	37
Energy consumption [MWh]	5 412	16 948	3 151	25410

It is assumed that the investigated distribution grid utilizes the entire hydronic capacity the supply temperature reduction boundary is met at 60°C. It allows supply temperature reductions whenever the supply temperature is above 60°C, if the critical customers have their return temperatures and energy consumption reduced.

The potential supply temperature reduction can presumably be calculated through formula [6], which is inspired by the well-known formula: $\frac{h}{(\Delta T \cdot C \cdot \rho} = \mathrm{q}$ (Andersen 2012) where h [kW] is the heat demand, ΔT [°C] is the return temperature subtracted from supply temperature and C being 4.18 [kJ/kg°C] and the water density; ρ being 1000 [kg/m^3]. The result of the formula; q is the water flow rate [m^3/s].

In formula [6], each customer group, in abbreviation, as presented in Table 14, is represented by a water flow rate share, but because critical heat customers (CC) are improved, the heat consumption (h_{after}) [kW] is lowered, and the delta T (ΔT_{CC_after}) becomes larger which result in a lower water flow rate [m^3/s]. Consequently, the delta T can be reduced with x [°C] until both equations equal one another, because then the water flow rates are similar. Delta T is reduced by reducing the supply temperature, but when supply temperatures are reduced, return temperatures increase as seen on Figure 12.

$$\frac{h_{before}}{((\Delta T_{WFC}) \cdot WFC_{flow.share} + (\Delta T_{SSC}) \cdot SCC_{flow.share} + (\Delta T_{CC\_before} - x) \cdot CC_{flow.share}) \cdot C \cdot \rho} \quad [6]$$

$$= \frac{h_{after}}{((\Delta T_{WFC} - x) \cdot WFC_{flow.share} + (\Delta T_{SSC} - x) \cdot SCC_{flow.share} + (\Delta T_{CC\_after} - x) \cdot CC_{flow.share}) \cdot C \cdot \rho}$$

The final supply temperature reduction is therefore calculated from equation [7], where y denotes the supply temperature reduction [°C], and x denotes the delta T reduction [°C].

$$x = (T_s - y + T_r + y \cdot 0.23) \quad [7]$$

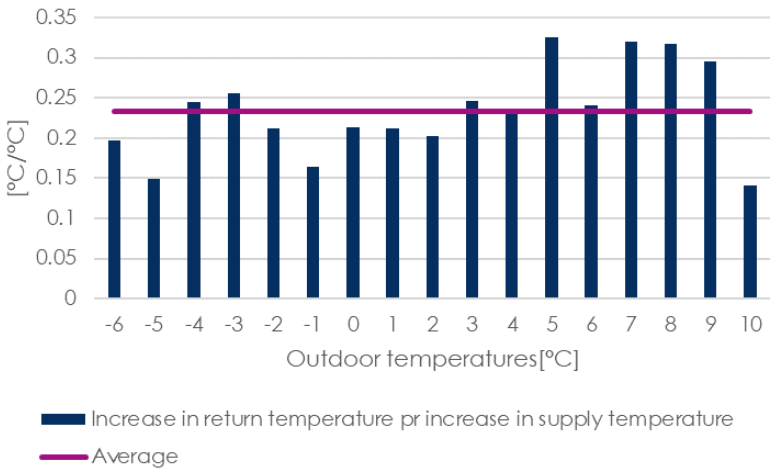


FIGURE 12: INCREASE IN RETURN TEMPERATURES, WHEN SUPPLY TEMPERATURES ARE REDUCED BASED ON DATA EXSTRACTION FROM VESTERBRO IN THE PERIOD OF 2014-2018 (HOFOR 2018).

HEAT SUPPLY SYSTEM SCENARIOS AND TEMPERATURE PROFILES

Thus, a before and after scenario can be established for a critical heat customer initiative

1. Reference scenario – no heat customer initiative
2. Critical customer initiative – all critical customers become well-functioning

For a critical customer initiative, it is assumed that the DH company successfully promotes a combination of improved performance, design and energy renovation of the critical customers, which bring return temperatures to the level of the well-functioning and reduces the energy consumption with 25 % of the critical customer group.

The temperature profiles become as visualized in Figure 13, when customers are not remedied and when critical heat customers are addressed. Note that in summer, the supply temperature cannot be reduced below 60°C, because legionella safe DHW must be ensured. These DH operating temperatures are used as input data for the heat supply systems in the subsequent chapter.

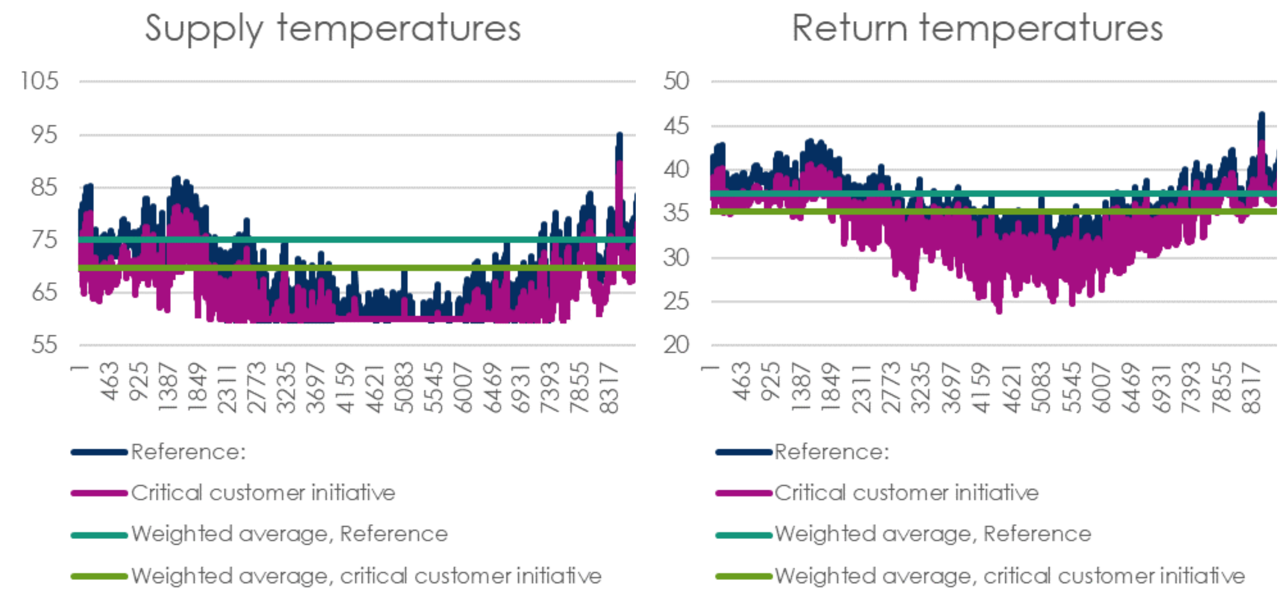


FIGURE 13: SUPPLY AND RETURN TEMPERATURES FOR THE REFERENCE SCENARIO AND THE CRITICAL CUSTOMER INITIAITVE SCENARIO

5 Profits from critical customer initiatives

This chapter will respond to the first sub question:

What type of heat supply system would benefit the most from critical customer initiatives in concern to profit? In addition, what is the payback period of investment of the critical customer initiatives in the given heat supply system?

Six different production- and distribution systems have been designed for the investigations as described in section 2.3. The heat supply systems are listed below

- Temperature independent system
- Solar collector system
- HP system
- Condensing system (Natural gas)
- Condensing boiler system (Wood)
- CHP incineration system

Each system is evaluated on their operation under the performance under the DH operating temperatures with and without a critical heat customer initiative, see Figure 13, section 4.5.

5.1 Production efficiency

This section presents the heat production efficiency gains, caused by lower DH temperatures paved by the improved critical heat customers.

Figure 14 visualizes the simulated heat production efficiency gains of the heat supply systems, which reveal some differences in efficiency gains as also presumed from theory, see section 3.1. The HP has the greatest benefit, which increased heat production efficiency at 17.8 percentage points. Contrary, the biomass CHP unit has only a marginally increase in the heat production efficiency compared to other combustion technologies such as incineration plants, natural gas motors and boilers. There are two reason to it. First, the biomass CHP is fired by wood pellets with a relatively low water content (5%), compared to e.g. waste where the water content may be 50%. It means that when return temperatures are lowered, the extra heat which can be extracted from the fuel is 45 percentage points lower in wood pellet than for waste.

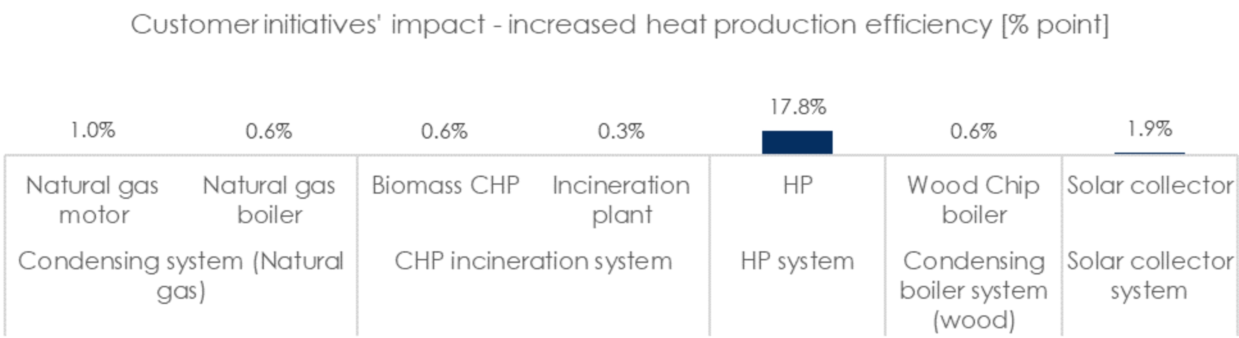


FIGURE 14: PRODUCTION GAINS FROM DH TEMPERATURE REDUCTION

The heat production efficiency gains in the Biomass CHP and incineration plant are only modest, because a larger share is converted to electricity instead of heat. The solar collector plant has the second highest production gain and produces 1.9 percentage points more than before the critical heat customer initiative.

5.2 PRODUCTION SHARE CHANGES

Production shares changes take place because some technologies have larger efficiency gains and consequently a larger reduction in the marginal cost of producing one MWh of heat than others. Moreover, some technologies increase their capacity, because more heat is recovered from the flue-gas. Figure 15 shows the production shares of each technology of every system based on the DH operating temperatures that can be achieved from; no, or a customer initiative. As projected, in all systems the temperature independent production unit; transmission grid, loses production shares, except for the system where it is the only production unit.

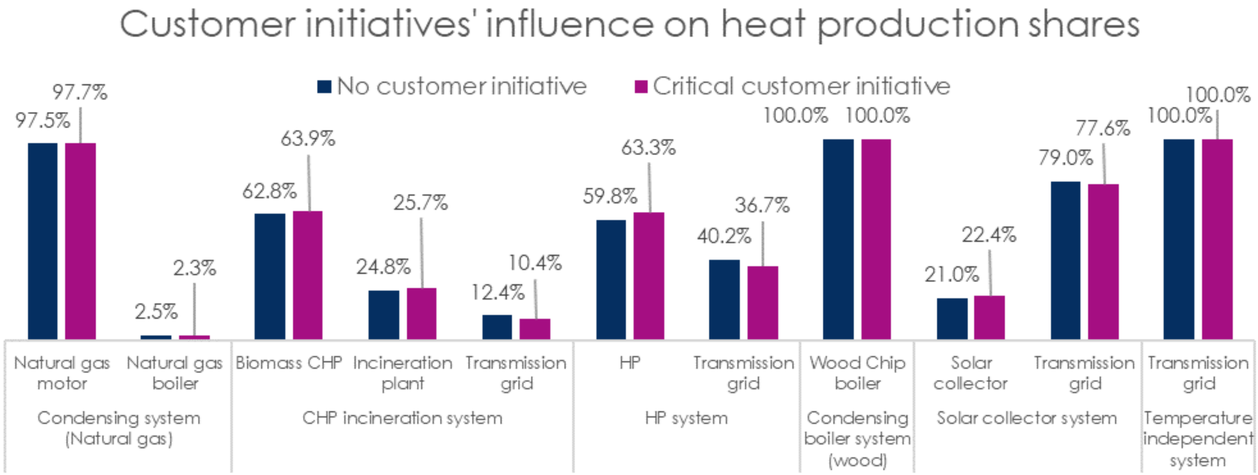


FIGURE 15: CHANGES IN PRODUCTION SHARES FOR EACH HEAT SUPPLY SYSTEM, DUE TO A CRITICAL HEAT CUSTOMER INITIATIVE.

Specific to the condensing system (natural gas), it should be noted that the gas motor has a very large production share, which contrast the general picture for decentralized natural gas DH systems, where the tendency has been towards fewer production hours of the gas motor (Grøn Energi 2016). There are two reasons why this analysis contrast that picture. In this analysis 2018 spot market prices have been applied which are rather high compared to the spot market price of the past years (NORD POOL 2019). Furthermore, the efficiency of the gas motor is considerably higher than most gas motors, because the modelled gas motor recovers heat from the flue-gas. Heat recovery from flue-gas is therefore a mean in reaching more production hours, as it has also been stated in Added Values, Dansk Gasteknisk Center and Grøn Energi (2017).

PRIMARY ENERGY CONSUMPTION

Not only production shares changes, but also the total heat production. Hence, all systems benefit from reduced distribution losses, because DH temperatures are lowered, and each customer initiative also lead to energy savings at the customer. The reductions are shown in Table 4Table 15. In absolute numbers, it implies that the gross heat demand is reduced from 33 GWh to 32 GWh, where the customers' heat demand goes from 25.5 GWh to 23.5 GWh. The distribution loss was in the reference situation with "no customer initiative", 23% of the gross heat demand, while being reduced to 22.5% of the gross heat demand.

TABLE 15: REDUCTIONS IN HEAT DEMAND AND LOSSES AS A CONSEQUENCE OF A HEAT CUSTOMER INITIATIVE

Heat savings	Delivered heat from plant	Distribution loss	Customer heat demand
Critical customer initiative	-4%	-6%	-4%

The combination of increased production efficiency and reduced heat losses result in a lower fuel/electricity consumption. The reduction in fuel/electricity consumption is shown in Figure 16, where it is evident that the condensing system (natural gas), the HP system, and the solar collector system experience the largest fuel savings, which was also the heat production units with the largest efficiency gains.

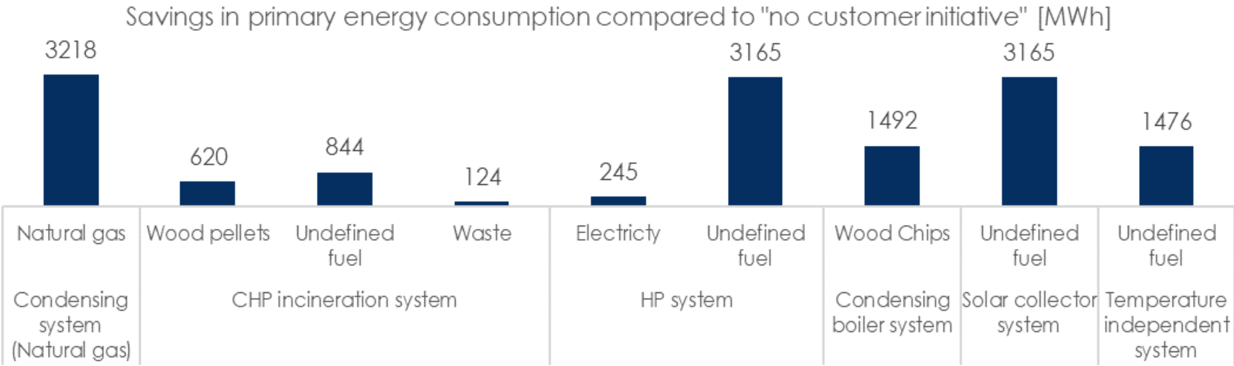


FIGURE 16: TOTAL PRIMARY ENERGY SAVINGS OF THE MODELLED DH SYSTEMS

The temperature independent system reduces the energy consumption with 1476 MWh, due to lower distribution losses and a lower energy consumption. It is assumed that the transmission grid receive heat from a heat production unit has with an efficiency at 100% and the fuel has not been defined. The condensing system (wood) have only slightly higher fuel savings than the temperature independent system. This is mainly because the condensing wood system has higher system efficiency, why the fuel savings related to energy savings are lower than for the temperature independent system.

The modelling choice of using return temperatures reductions to lower supply temperatures has had an impact on the result. The condensing boilers and gas motors, production benefit related to return temperatures. For systems with a majority heat production share of such units, it may be better not to lower DH supply temperatures. The balance between return temperature and supply temperature reductions are out of the scope in this thesis but could be interesting for further investigation.

What has not been shown, is the electricity production increase of the CHP incineration system. Next section will show the economic impact of the fuel savings and increase in electricity production of all the investigated heat supply systems.

5.3 Economic value of critical customer initiatives

The demonstrated benefits of critical customer initiatives presented in in sections 5.1-5.2 will in this section be provided with an economic value in addition to the environmental benefits.

The economic value of transitioning into lower DH temperatures is expressed in DKK/°C/MWh on Figure 17, and in DKK/MWh in Figure 18. The economic value differs from the various heat supply systems, because of changes in, efficiency, production shares and energy consumption. The value depends on the variable costs, such as operation and maintenance costs, taxes, fuel/input, which are described in section 2.3, and electricity sale.

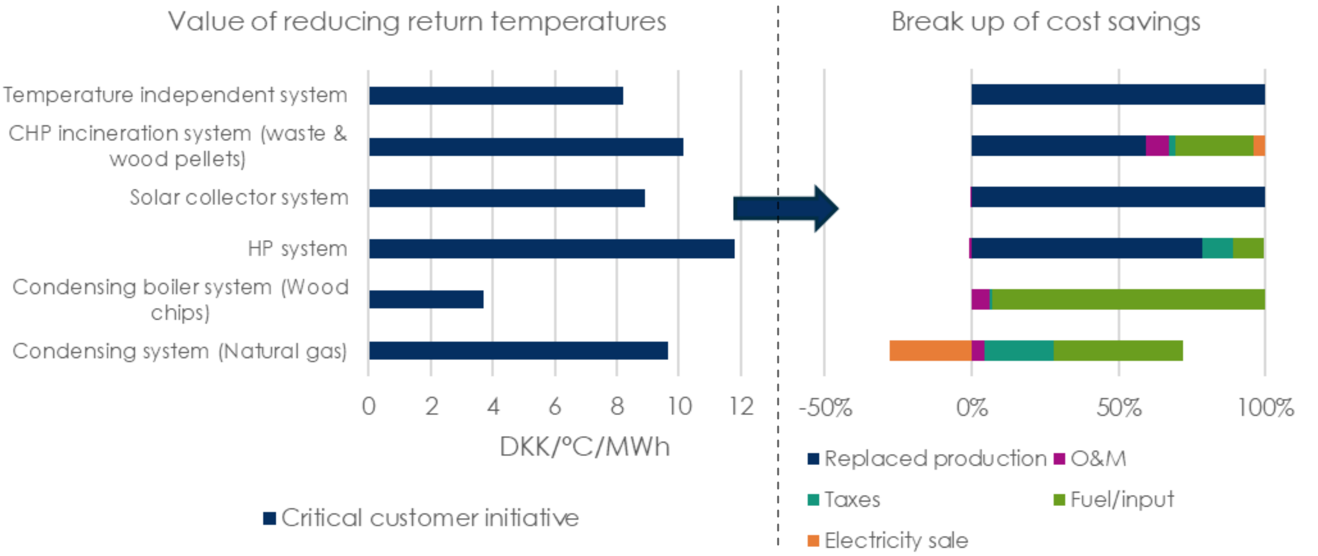


FIGURE 17: TO THE LEFT: ECONOMIC VALUE OF A HEAT CUSTOMER INITIATIVE FOR EACH HEAT SUPPLY SYSTEM. TO THE RIGHT: BREAK UP OF COST SAVINGS FOR EACH HEAT SUPPLY SYSTEM.

Not surprising the HP system benefits the most, as it was also the system with the highest efficiency gains and the largest fuel savings. A critical customer initiative can bring a value up to 12 DKK/°C/MWh at customer level. The economic value of the customer initiative is primarily caused by alternative production that is replaced by the heat pump and by energy savings. Figure 17 compared to Figure 18 reveal the general tendency that the higher the variable heat price, the larger value of a critical heat customer initiative.

In contrasts the condensing system (wood) has considerably production benefits, but a relatively low economic value from making a heat customer initiative. It is due to the absence of opportunities to replace other production units. It also influences that wood chips are cheap and not taxed, because it reduces the marginal benefit of saving energy. Hence, the high cost; "temperature independent system", see Figure 18 has a larger economic benefit from addressing critical heat customers, see Figure 17

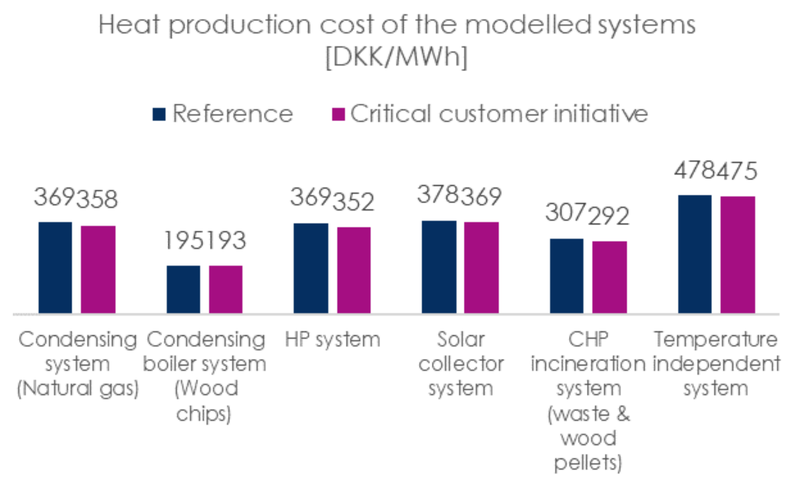


FIGURE 18: HEAT PRICES OF EACH HEAT SUPPLY SYSTEM

Figure 19 shows that savings from lower distribution heat losses is only a small share of the total savings from a critical customer initiative. Heat savings at customers and production savings have generally larger impact on the business case.

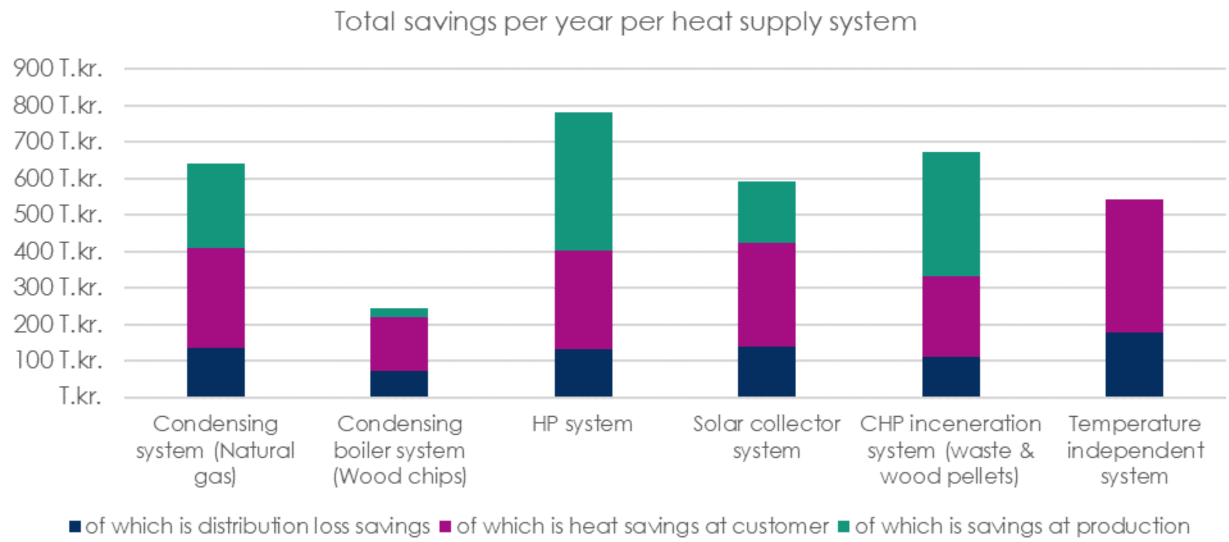


FIGURE 19: THE FIGURE SHOWS ECONOMIC SAVINGS OF HEAT SAVINGS PER HEAT SUPPLY SYSTEM DIVIDED INTO SAVINGS FROM INCREASED PRODUCTION EFFICIENCY, SAVINGS FROM LOWER ENERGY CONSUMPTION AT CUSTOMER LEVEL, AND SAVINGS FROM A LOWER DISTRIBUTION HEAT LOSS.

5.4 Description of payback period examples

In this section, the cost of improving the critical heat customers is estimated and compared to the economic value. It is assumed that the entire DH profit is allocated to the critical heat customers. The section evaluates the payback period from a critical heat customer initiative, considering two types of heat customers; small and large.

It is assumed that the heat supply systems analyzed in 5.1 - 5.3 could either be supplying 242 large heat customers or 1412 small heat customers. Moreover, in each hypothetical system, all heat customers are equal in size and the share of critical heat customers is 16 %, as described in section 4.5, Table 14, based on HOFOR (2018). It means that in a heat supply system of large heat customers, 38 would be critical. And when all heat customers are small, 222 would be critical, see Table 16. In the example it is assumed that critical heat customers are constructed in 1950s as it influences the cost of an energy renovation (Wittchen et al. 2017).

TABLE 16: HEAT CUSTOMER ASSUMPTION OF SIZES, CONSUMPTION AND CRITICAL HEAT CUSTOMER SHARE

Heat customer (Large: multi-family house)		**Heat customer (Small: single-family house)**	
Total number of customers	242	Total number of customers	1412
Critical heat customers	38	Critical heat customers	222
Construction year	1950's	Construction year	1950's
m2	1000	m2	140
kWh/m2	105	kWh/m2/year	129
Heat consumption [MWh/year]	105	Heat consumption [MWh/year]	18
Total heat demand incl. heat losses [MWh]	33,000	Total heat demand incl. heat losses [MWh]	33,000

As described in section 1.4, various solution exists to solve critical heat customers. In this example it is assumed that the small and large critical heat customers are improved by either:

1. Energy renovation
2. Improved heating system design

Assumptions for critical customer solutions

Improvements of the heating system design involves the replacement of pumps, radiator valves, radiators, heat exchanger and DHW system. The difference in customer size does according to Østergaard (2018) influence the cost of making a heat customer initiative. The frequency of faults does also impact. The assumed cost for small and large heat customers is shown in Table 17. The costs reflects that it is assumed that 30% of all radiators and radiator valves must be replaced (Østergaard 2018).

TABLE 17: TO THE LEFT: COST OF HEATING SYSTEM IMPROVEMENTS FOR LARGE HEAT CUSTOMERS. IN THE MIDDLE: COSTS OF HEATING SYSTEM IMPROVEMENTS FOR SMALL HEAT CUSTOMERS. THE DATA IS BASED ON ØSTERGAARD (2018) AND DISCUSSED AND ADJUSTED WITH ANDERSEN (2019).

Multi-family house	
Costs per customer	[DKK]
Pumps [DKK]	6000
Improved control	4000
Costs per customer	[DKK/MWh]
Radiator valve	114
Radiator	645
Heat exchanger	70
DHW system	200
Total costs per customer	120,000 DKK

Single-family house	
Costs per customer	[DKK]
Pumps [DKK]	2500
Improved control	1600
Costs per customer	[DKK/MWh]
Radiator valve	81
Radiator	630
Heat exchanger	300
DHW system	225
Total costs per customer	27,000 DKK

Energy renovation is the second solution to solve the problem of poor performance at the critical customers. Costs of an energy renovation is based on Wittchen et al. (2017) and considers only costs related to energy efficiency improvements. It is evident from the Table 18 that energy renovation is significantly more expensive for small heat customers in DKK/m^2.

TABLE 18: COSTS OF ENERGY RENOVATION (WITTCHEN ET AL. 2017)

Cost of energy efficiency improvements	Multi-family house	Single-family house
DKK/m2	86	201
Per customer [DKK]	86,000	28,140

5.5 Payback period results

In this section, the economic value of improving critical heat customer is combined with the costs of it. The payback period calculation applies a discount rate of 3.5%, under the assumption that the DH company offers financial aid to customers that has poor access to capital.

The results are presented in four graphs in Figure 20. Each graph represents either a large and small heat customer, who is combined with either an energy renovation or a heat system *design* solution.

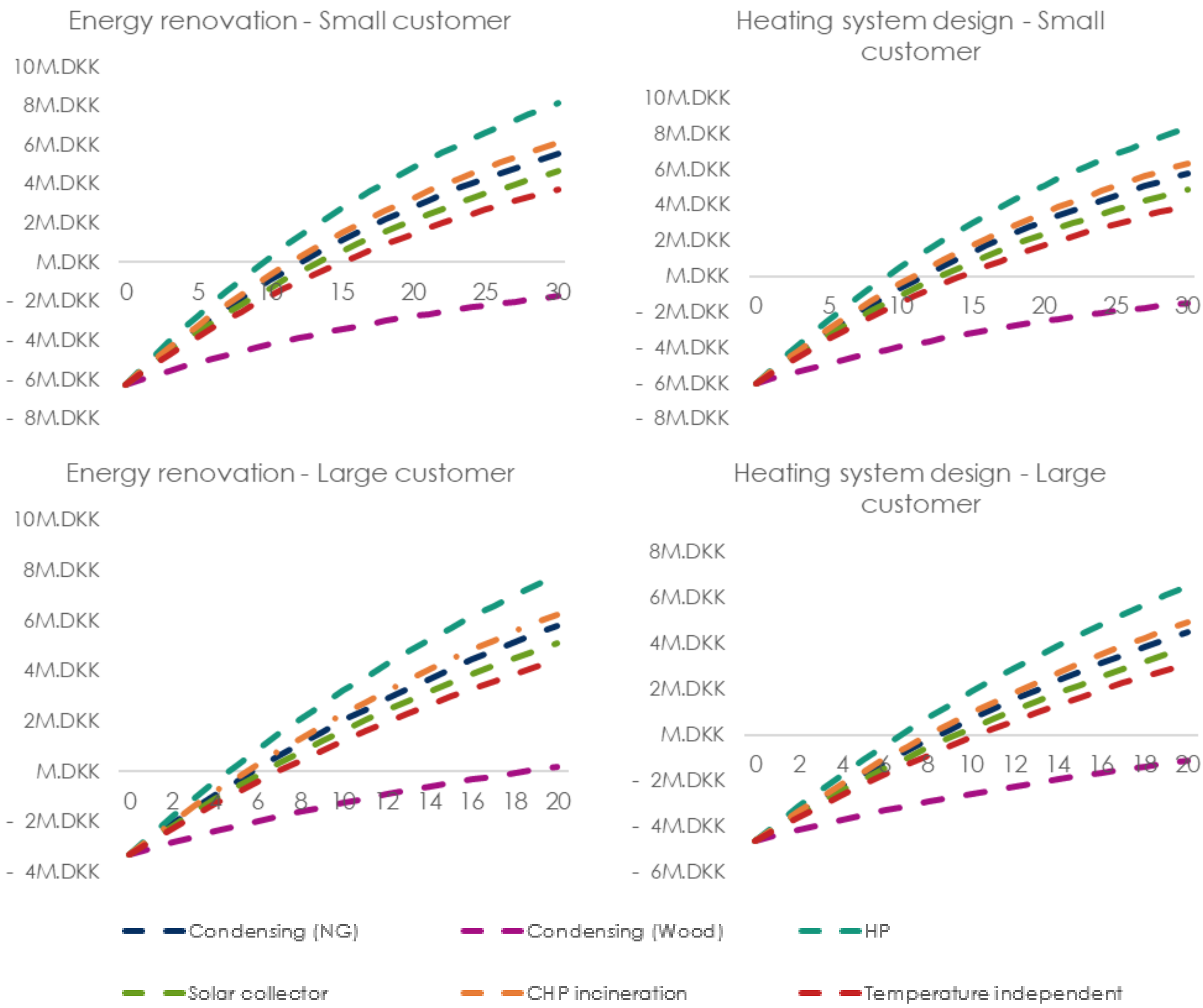


FIGURE 20: THE FIGURE SHOWS PAYBACK PERIOD OF IMPROVING ALL CRITICAL HEAT CUSTOMERS WITH A HEATING SYSTEM DESIGN SOLUTION COMPARED TO ENERGY RENOVATION SOLUTION. LIKEWISE, SMALL AND LARGE HEAT CUSTOMERS ARE COMPARED. THE DOTTED LINES INDICATES WHICH HEAT SUPPLY SYSTEM THE HEAT CUSTOMERS IS SITUATED IN. THE COST IS SEEN ON Y-AXIS IN M.DKK, AND THE PAYBACK PERIOD IN YEARS IS SEEN ON THE X-AXIS

It can be concluded that a critical heat customer initiative pays off in most settings. The best business case is found in HP system, but even a proper business can be achieved in systems only benefitting from reductions in the distribution loss. Critical customer initiatives have the shortest payback period for large heat customers. Small heat customers have generally a slightly longer payback period.

There is also little difference in payback periods between the techniques to improve the critical heat customers. However, it relies on the assumption that the heat customer already was planning to renovate his house. If the heat customer is not, the heating system design solution would require a smaller initial investment and be preferred by critical heat customers, who have poor access to capital.

From a DH company's perspective, it may be preferable that the heat customer chooses an energy renovation, because it presumably free up more hydronic capacity than a heating system design solution. The drawback is a relatively poorer competitiveness to individual heating solutions, which is an aspect that will not be investigated.

Consequently, the analysis suggests that critical heat customer initiatives are prioritized in heat supply systems with a large share of HPs, large heat customers and with energy renovation.

5.6 PRELIMINARY CONCLUSION

It can be concluded that a critical heat customer initiative can reduce the problem of hydronic bottlenecks in distribution grids and bring environmental benefits in terms of reduced primary energy consumption. The better business case is found in heat supply systems

- With a high variable heat production price.
- With multiple heat production technologies, where a low temperature benefitting production unit can replace a more expensive production unit.
- With a high production share of HPs, which have the largest production efficiency gains
- Systems with production units that have production efficiency gains and high fuel, tax and operation and maintenance costs

The sum of the dynamics brings the largest savings to HPs systems covering 60% of the heat production. The lowest savings are achieved in condensing systems (wood) covering, where a wood chip boiler covers 100% of the heat production.

It can also be concluded that reasonable payback periods can be realized for all the investigated systems except for the condensing system (wood), why critical heat customer initiatives should be prioritized in most DH systems. Large customers have a slightly shorter payback periods than small heat customers. An energy renovation solution has slightly shorter payback period than heating system design improvements, if the critical heat customer was about to renovate anyway. Consequently, one may choose to prioritize energy renovation initiatives in areas where more large customers are located, if there are hydronic bottlenecks in the distribution grid of the area.

6 THE ROLE OF KNOWLEDGE IN CUSTOMER INITIATIVES

This chapter will respond to the second sub question:

How can critical heat consumers be identified? In the process of convincing critical heat customers to improve, what knowledge barriers between heat customers and DH companies may be faced, and how could they be addressed?

The chapter analyses cases regarding methods applied to identify the critical heat customer and to develop solutions for the critical heat customer. Best-practice examples are extracted as well as the relevant barriers. The barriers are verified through scientific literature to the extent it has been possible.

6.1 THE IMPACT OF KNOWLEDGE

The implementation of a critical heat customer technique does, according to the theoretical scope chosen for this thesis, depend on the degree of knowledge existing among both critical heat costumers, plumbers and DH companies.

Knowledge has impact and determines how DH companies shape and target their heat customer initiatives. In Viborg, they have been proactive at inscribing knowledge from research institutes and consultants when trying to change critical heat customers. Diget (2019) mention DTU, Niras, Envidan, and Termis as examples on actors that have provided them with insights on how to tackle critical heat customers and implement lower DH temperatures. Diget states:

"We had a couple of reports made… …In the NIRAS report, they recommend not to look at the building envelope and radiators as the costs of renovating these parts would be too big compared to the savings because it is only 600 hours in a year, where radiators are the dimensioning factor [In Viborg]." (Diget 2019)

The reports influenced Viborg to aim at reducing the DH supply temperature mainly in the summer period and consequently targeting the critical heat customers that have a DHW system which requires supply temperatures above 50°C.

AVA has also participated in a research and development project which led to the implementation of an ultra-low-temperature area called Geding. Practical experiences seem to heavily impact the perception of what can be considered future applicable techniques for heat customers. AVA states about the new techniques applied in Geding:

"when our customer group gets more diversified, it is actually a challenge to us." ..*"We learned a lot about ourselves and our procedures; instead of embarking into something new, we need to have it embedded into our organization"* ..*"Usually, those who start it, does not operate it afterwards"* ..*"everytime we have new special area, there is lot of employees that we need to train to handle these customers."* (Thøgersen and Brizarr 2019)

The essence of the statement is that techniques applied at customers should not be radically new because the operation of a DH system requires knowledge to applied fast and efficient. In other words, it requires an intuitive knowledge level that only comes with a lot of experience, according to section 3.2.

For a large DH company, the challenge may be even larger. Problems of creating and transferring knowledge in an organization is, according to Davenport and Prusak (1998), a challenge because knowledge is most efficiently transferred from unskilled to skilled employees through conversation and collaboration. The challenge is that an unskilled employee does not seek conversation and collaboration with the most skilled employee. Instead he seeks the one he perceives most skilled in his proximity as a trade-off between the efforts it takes to obtain knowledge and the perceived value that knowledge will provide him. For large organizations with a higher degree of specialization there may be a larger distance between the skilled and unskilled employee which makes it even harder to adapt a radical new technology.

To summarize, DH companies may commit themselves to critical heat customer initiatives, based on reports and analyses that prove economic benefits. Reports are essentially just information but become knowledge when the author is trusted and the information fits into the DH company's existing knowledge base. Practical experiences from radical heat customer initiatives show that especially large DH companies may have difficulties adapting because of the challenges related to transferring intuitive knowledge in a large organization.

6.2 THE HELPLESS CRITICAL HEAT CUSTOMERS

From a critical heat customer perspective, knowledge is needed to take the right decisions on how to improve their building heating system.

Some heat customers become critical to the DH company because the operation of the building heating system is poor, which result in high return temperatures. Thøgersen and Brizarr (2019) points towards one potential reason why heat customers perform poorly:

"Once me and Henrik were young, we had these janitor-a-like types, who nurtured their building heating system. … They knew how their system functioned and should be operated ...all these guys have been saved away, because now we have CTS-systems and all sorts of smart things. The result is no one who knows anything, and the automatic systems are only great once they are adjusted correctly..."

DH companies have sought different ways to increase heat customers understanding of their building heating system to avoid that they operate their building heating system poorly.

AVA states: "*We encourage our customers to observe their consumption on Ebutler, then they can look themselves how their system works*" (Thøgersen and Brizarr 2019). In Albertslund they also have a platform where heat customers can learn about their energy consumption and compare themselves to neighboring districts. None of the DH companies report that the communication platforms have been widely used by their heat customers. To the knowledge of Albertslund DH company, only the nerdiest customers have used their platform (Hansen & El-khatib 2019). In HOFOR a traffic light is in the development phase, which communicate to the customer, the condition and performance of their building heating system through relatable colors; red, yellow and green, which they believe will make the heat customer become knowing of their building heating system (Skov 2019; Honeré 2019). AVA considers, as an alternative to send personal messages when their substation has a poor cooling and high return temperature, but concluded that the customer probably would find it more annoying than useful (Thøgersen and Brizarr 2019). It seems that informing heat customers through internet platforms with performance data is not an efficient communication method to improve critical heat customer performance. The methods all have in common that they provide information to the heat customer but, according to Davenport and Prusak (2019), information is not knowledge. Information becomes knowledge when it is needed to solve a problem, and when the information has been processed through comparison, conversation and prediction of consequences. The applicability of internet platforms may therefore be insufficient either because heat customers does not care about heat prices and energy consumption or because they don't have the necessary capability to process the information.

HOFOR leads a project called Energispring which provides an alternative way of reaching the heat customer. The focus is on large buildings, where owners, administrators, and interest organizations are invited to compete through benchmarking of their performance. The project is similar to what has been done in Albertslund, but benchmarking is combined with workshops on how to improve performance and they put up goals for energy savings and cooling performance. The competitive environment makes poor performance problematic, and the workshop creates a space that enables heat customers to process information about their performance into knowledge on how to improve. The project has shown that the combination of guidance and a partnership where heat customers are brought into a competitive environment can result in energy savings at 3 %. (HOFOR 2016).

The heat bill is an indirect communication from the DH company to the heat customer If the heat customer has operated his building heating system poorly, the bill gives him motivation to learn how he can improve his heating system. The intention is to make heat customers understand and improve their building heating system through an economic message, but several challenges makes the motivation tariff a less efficient communication tool to build up knowledge.

"We started looking at a new tariff structure, [because] the problem with the current structure is that people do not understand it, they think it is weird" (Thøgersen and Brizarr 2019)

Nielsen (2019) recognizes the same problem in HOFOR and state that heat customers rarely know how much they pay in motivation tariff, due to a poorly operated or designed building heating system. Especially for large heat customers with a larger organization set-up, he experiences that the lack of awareness on the motivation tariff is often reinforced due to poor internal communication between the administration, the heating system manager, and the building owner. In these cases, the motivation tariff sometimes ends up as part of the budget even though it is excessively high and could be reduced in a cost-efficient way. In his opinion the problem may be reduced if the heat customers receive the motivation tariff on a separate bill to make it more visible.

The response from the interviewed DH companies highly suggest that it is difficult to set-up structures where heat customers help themselves to improve the performance of their building heating system. It seems as some external person needs to push the heat customer to improve. That external could, according to Diget (2019), be the plumber because: *"The plumber talks with the customer in different contexts and sees that the customers installation can be made more efficient"*.

However, when a DH company wants to reduce supply temperatures and have the critical heat customers prepared for it, it may be very demanding, as Hansen & El-khatib (2019) put it:

"It requires us to help them [critical heat customers]. *That we support and facilitate and give them subsidies, so it requires a lot of work, it does. They don't just do it by themselves"*

6.3 Identifying and solving the critical heat customer

Under the assumption that critical heat customers are not able to identify themselves as critical heat customers, then the DH company must be able to identify the critical heat customer to prepare and plan an initiative. But can DH companies from their current knowledge about their heat customers identify the critical ones? And do they have enough knowledge about heat customers to develop adequate initiatives?

As defined in section 1.3, three critical customer types exist. Those customers that are poorly performing, those customers that cannot obtain thermal comfort and those customers that cannot guarantee DHW without legionella at reduced supply temperature.

Critical customers with a poorly performing building heating system

Today most DH companies have remote reading of its heat customers on an hourly time resolution, from where data about consumption, cooling, water flow rates, supply and return temperature can be accessed (EWII Energi, Grøn Energi og Transition 2019).

Thøgersen and Brizarr (2019) describes how these data can be combined with a stepwise reduction of the supply temperatures to identify critical heat customers. When supply temperatures are reduced 2°c, they typically see one or two customers having a remarkably impaired cooling. These customers are critical and will need improvements.

Critical heat customer can also be identified without a supply temperature reduction. Høje Taastrup, AVA and HOFOR draw out lists frequently with the highest return temperatures and flow rates. Currently, the DH companies tend to focus more on the largest and worst performing customer within the entire utility area, rather than focusing efforts into one distribution grid and subsequently reduce supply temperatures (Birnbaum 2019; Nielsen 2019; Thøgersen and Brizarr 2019). But as data with geographical location of heat customers exists and all DH companies know the jurisdiction of their distribution grid, they could easily adjust their identification procedure.

The problem arises once the DH company wants to identify the specific faults without necessarily visiting each customer. AVA has several concerns on how to properly check for faults: *"We don't know the customers building heating system; therefore, we don't know if a yearly average cooling is good or bad for this type of building"* (Thøgersen and Brizarr 2019).

According to HOFOR, identifying faults is also about distinguishing between the DHW system and the SH system. Although the DHW consumption share is smaller than the SH consumption share, both systems impact the system equally negatively if they are malfunctioning. This impact is due to similar pipe-dimensions to each part of the building (Nielsen 2019). Currently, remote meters measure the combined performance of the two systems and not the impact of each system. The lack of detailed measurements seems to create challenges in identifying the specific faults. *"We don't find building heating systems that are wrongly designed, but single components with faults that suddenly appears"* (Thøgersen and Brizarr 2019). A study suggests that introducing more measurement points might be helpful to improve the ability to detect faults through data. (Månsson et al. 2019)

Once there was a more positive vibe on the use of currently available heat customer measurements:

> *"The machine learning experts had a foaming mouth [motivated to make sense out of heat costumer data], certain that it could be done [identifying specific faults]. And probably you might be able to, but this is not where we are today"* (Thøgersen and Brizarr 2019).

AVA concludes that they haven't found the philosophers stone yet. The statements regarding the applicability of machine learning is in line with Månsson et al. (2018), who published on automated statistical methods to detect faults in the DH substation and conclude that their model is promising and proves that two common faults can be detected. These are the loss of remote reader connection and drifting supply temperature meter. As many more faults exist, they conclude that the machine learning model requires further development.

The inability to detect faults through data has not stopped Albertslund DH company. They say: *"We have screened the whole city. We have been at every customer, and we know what they have of installations"* (Hansen & El-khatib 2019). Knowing how the heating installations have been designed in every heat customer is something that is requested by most DH companies, but only Albertslund and Viborg are currently taking the required steps. Viborg and Albetslund differ from AVA in that they have a clear plan to reduce supply temperatures, which makes them motivated to do so. The difference may, according to Hansen & El-khatib (2019), be due to an inherent difference between how large and small DH companies govern: *"I don't think HOFOR [large DH companies] is geared to it [customer visits and involvement]. I think they are too big. I think they do it top down"*.

Albertslund and Viborg combine their efforts with another method, which is also applied by Høje Taastrup. They offer the heat customer to have their substation replaced with a new one through a leased model where the substation is owned and serviced by the DH company. The new substations are installed either by the DH company themselves or by a trusted plumber. Thus, the substation leasing model gradually makes the heat customers' heating installation more homogeneous and improves the DH company's knowledge of the heat customers (Birnbaum 2019; Diget 2019; Hansen & El-khatib 2019).

AVA finds that the problem is not only spending time on identifying faults, these efforts are useless if the heat customer does not do anything about it: *"we can lure and try to convince the existing customers that they need to redesign their one-looped system* [A one- and double-looped space differ in the ability to deliver low return temperatures. One-looped are significantly poorer performing]*, but we cannot impose them to do it, we have no legal base to do so."* (Thøgersen and Brizarr 2019)

CRITICAL CUSTOMERS THAT CANNOT OBTAIN THERMAL COMFORT

DH companies access several types of data which can be used to indicate if a customer would be unable at obtaining thermal comfort at lower DH supply temperatures.

First and foremost, DH companies receive complaints from customers that feel cold. On the condition that a DH employee has visited the heat customer and concluded that the customer was lacking thermal comfort because of the DH supply temperature, then the DH company would know for sure that this single customer is critical. In Aarhus, they have provoked customer complaints by reducing the supply temperature and waited for the customers to call with the purpose of documenting the critical customers and through visits also to propose improvements (Thøgersen and Brizarr 2019).

In Albertslund, they apply a process of elimination. They identify the critical customers by comparing initial heat consumption at the buildings' construction year with the current heat consumption of the costumers. When data about initial heat consumption is unavailable, a theoretical consumption for the building type is assumed. When a significant reduction between initial and current heat demand can be documented, it is assumed that the building has been renovated, and that DH supply temperatures can be reduced with no problems (Hansen & El-khatib 2019). This assumption is supported by section 1.4 which states that energy renovated buildings constructed in the 1900s can be heated at DH supply temperatures below 60°C. The elimination method leaves a pool of non-energy renovated houses that might be critical heat customers. The elimination method is not bullet proof as there is no data on the heating installations. Heaters could for example have been under-dimensioned from the beginning, been removed or muffled up. Then the costumers could still become critical heat customers when supply temperatures are reduced. To be certain not to make wrong adjustments about who are critical heat customer, Albertslund have combined the method with on-site visits (Hansen & El-khatib 2019). Figure 21 shows the results of their identification procedure, which has been published on their website and made available to all heat customers. The red marked buildings are the critical buildings, whereas yellow buildings need only a few apartments improved. Light green buildings are low-temperature prepared but has performance problems, and the darker greens are prepared assuming that the buildings execute their renovation plans.

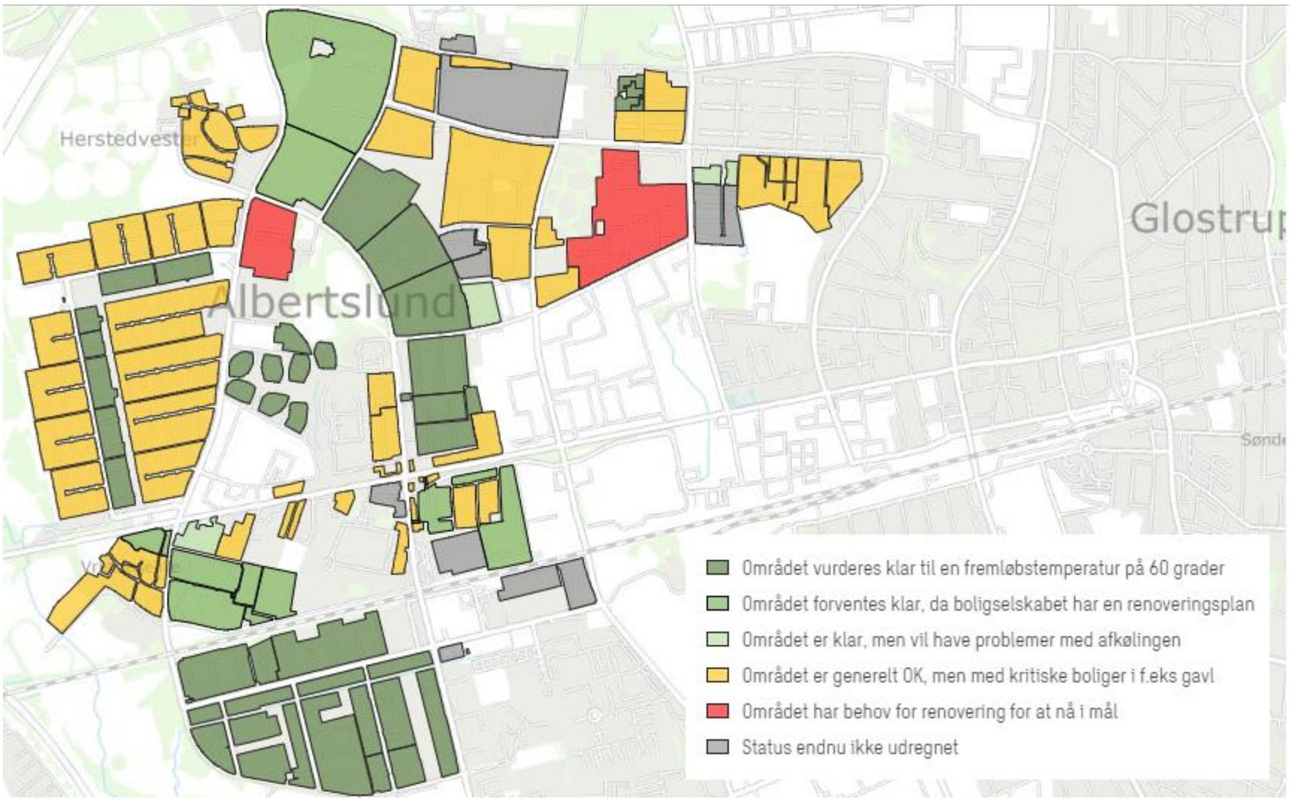


FIGURE 21: CRITICAL HEAT CUSTOMER MAP APPLIED BY ALBERTSLUND DH COMPANY (AF 2019)

Availability of heat costumer consumption and performance data is a requirement for these identification methods, which DH companies have. Therefore, it should be possible for other DH companies to identify customer that cannot obtain thermal comfort.

Once those who cannot obtain thermal comfort at lower supply temperatures have been identified, the real challenge starts since the heating power and building heat loss are likely to differ from building to building. Consequently, the DH company is forced to develop solutions for every heat customer if they want to reduce supply temperatures. From a generation of knowledge perspective, DH companies will have a hard time reaching the intuitive knowledge level where knowledge can be applied fast and efficient. This is due to the fact, that every solution needs to be fitted to the individual heat costumer, why consistency and routine will never be obtained.

Certain circumstances can help reduce the challenge. As Hansen & El-khatib (2019) state "*We have two-thirds which are standard houses for which we can make standard solutions*".

For these standard houses they wish to develop a catalogue, where the burden is taken away from the heat customer. The goal is to have a solution prepared which the heat customer could choose from without knowing anything about insulation standards and the heating power of their radiators. They compare it to their current substation leasing model:

" The smart thing about TAO [leasing agreement where the DH company replace and take ownership of the customer's substation] *is that we are responsible for everything. If we could do that* [have legal basis to plan and execute] *when renovating a house, we would probably have done so."* (Hansen & El-khatib 2019)

Although buildings may be built with similar heating system and insulation, the occupants will never be similar and have similar preferences. Therefore, standard solutions may not fit everyone. Albertslund has supported their energy renovation strategy by directing customers to the national energy saving scheme called BedreBolig (AF 2016). The scheme provides the heat customer with an energy consultant who makes an overall renovation plan in collaboration with the heat customer. The process of planning enables tailored solutions that fits with the heat customer's need but also helps the heat customer obtaining knowledge on energy renovation. An evaluation of the scheme concluded that BedreBolig-consultancy made people carry out more extensive renovation. Meanwhile some people did not find it worth to pay for the scheme, partly because they felt they achieved the same knowledge from conversations with craftsmen (NIRAS 2016).

Although Albertslund find it weird that heat customers are unwilling to pay a small fee for energy consultancy, they responded to the problem by offering free and independent in-house consultancy which has been a great success:

"I think that consultancy provides some sort of comfort in choosing right, because they can call and talk .. ..They could call and say: now I had this offer, or I consider to replace windows, what do I need to remember and think about?" (Hansen & El-khatib 2019)

Albertslund's strategy to energy renovate the critical heat customers are not finalized, which makes it difficult to state which knowledge aspects that are crucial for the motivation. However, they did finalize a demonstration project called: 'The concept of Albertslund' where three archetypical heat customer buildings were energy renovated to demonstrate to other critical heat customers how it could be done (Teknologisk institute 2014). Hansen & El-khatib (2019) state about the demonstration project:

"We have participated in renovating a few buildings, to show [heat customers] how. And I am unsure about the level of success we had from it."

Hansen & El-khatib (2019) experience that energy renovation is usually driven by single persons, so called fireballs. Fireballs may be characterized by being a trusted, popular driving force among heat customers. Theory on knowledge argue that information provided by trustworthy senders are more likely to take the step from simple information to knowledge (Davenport and Prusak 2019). The demonstration project has presumably helped fireballs establishing even more credibility in the promotion of energy renovation because they could refer to the results of the demonstration project. The results showed energy savings at appr. 50% and that energy renovation was cost-efficient (Teknologisk institut 2014). But the demonstration project did not create a boom of energy renovation. One of the limitations is that it is not a product on a shelf which can just be copied between buildings, which means that the demonstration project was unable to remove all uncertainties heat customer had about energy renovation with the same success as consultancy. This is one of the reasons why Albertslund currently are motivated in developing solutions catalogue for each heat customer type (Hansen & El-khatib 2019).

From a knowledge perspective it seems as an overwhelming task to ensure thermal comfort through energy renovation because solutions requires heat customer involvement to a higher degree. Albertslund explains why it makes sense:

> *"When 60% of the housing stock is expected to be renovated in 5-10 years and is low temperature prepared, and we have a newer private housing stock [which is also prepared], you could run two separate systems or you could choose to give more than half of the building stock too high temperatures. Alternatively, one could choose to motivate the rest of the building stock to get ready for lower temperatures."* (Hansen & El-khatib 2019)

Back in 2014, AVA tried to promote energy renovation and reduce supply temperatures at 8 heat customers (DEA 2014e). All were visited to promote energy renovation. The heat customers were motivated by subsidies to replace their substation, radiator valves and building envelope. Although subsidies covered 50% of the substation investment cost, not everyone chose to invest, and only 2 houses made improvements to the building envelope. The demonstration project failed at achieving 60/30°C operating temperatures as targeted and show that higher subsidies and solutions for increased heating power are needed (DEA 2014e). Both Albertslund and another published study conclude on the challenge of promoting energy renovation. Both mention the fact that the success depends on the current status of the heat customers life regarding motivation, age, economics etc. (Hansen & El-khatib 2019; Mortensen et al. 2016).

Whether Albertslund will succeed or not in the implementation of energy renovation is not known yet. They explain how small heat costumers living in terraced houses make up a great challenge since the connection of the houses make changes to the building envelope disharmonious and impossible. In order for such a change to happen, all costumers have to be convinced at once. Until now they have seen it happen once, and it was driven by one of occupants that was a building constructor (Hansen & El-khatib 2019). The example confirms that energy renovation is driven by fireballs and also indicates the fact that the knowledge possessed by fireballs can help them achieve ends. One of Albertslund's strategies has been to participate in as many general assemblies in housing associations as possible to share their knowledge and built up heat customers awareness and knowledge on the energy renovation possibilities and low-temperature district heating. Today, they see small networks of heat customers popping up trying to share ideas and find energy renovation solutions and help one another in obtaining knowledge (Hansen & El-khatib 2019). The DH company's efforts in sharing the low-temperature strategy, and the tendencies of small networks popping up are from a knowledge perspective crucial to the success of the strategy. It provides opportunities for heat customers to discuss and compare information about low-temperature energy renovation which transform information into knowledge and help them in the decision-making process (Davenport and Prusak 1998).

When obtaining knowledge about energy renovation, a customer might come to the conclusion that he or she is not interested in the renovation. For a DH company it is therefore also about having alternatives which their critical heat customers can apply instead. Albertslund offers help to increase the heating power of radiators which is a less extensive intervention in the heat customers life and requires a lower initial investent (Hansen & El-khatib 2019).

Critical customers that cannot guarantee DHW without legionella

The identification of critical heat customers that cannot guarantee DHW without legionella seems rather simple. All DH companies have a set of technical requirements for their heat customers. As a part of these requirements, the DH company guarantees a minimum DH supply temperature. Given that the DH company never changed the minimum DH supply temperature, it means that all heat customers probably have a DHW system designed for this temperature requirement. Thus, making all heat customers critical when reducing the minimum DH supply temperatures.

That seems at least to be the conclusion in Viborg DH company that aims at reducing the minimum DH supply temperatures by replacing all the heat customers substation with one that enables DHW production at 50°C. Diget (2019) states about the approach of reducing the minimum DH supply temperature:

> *"In the areas where we want to reduce the [minimum DH supply] temperature we have around 6000 substations, where some have been replaced to a newer substation, but a considerable amount of them are still dimensioned for 60°C [DHW system], and especially those substations where an AVTB valve* [older type of control valve] *controls the domestic hot water system, risk to short-circuit and deliver return temperatures as high as supply temperatures, therefore we need to replace these units"*

In Viborg, they moreover found it useful to distinguish between large and small customers in the critical customer identification process. Large customers have one substation that through a circulation system provides every single flat with DHW. The circulation system is vulnerable to legionella growth due to large volumes of potentially stagnant water, see section 2.1, and is too expensive to rebuild into flat stations (where DHW heat exchanger is placed at each flat). Consequently, Tom Diget has concluded that these heat customers must be identified to find an alternative solution. The challenge of large heat customers is also recognized in scientific literature (Lund et al. 2018).

Research conclude that faults in DHW systems are related to both the installation and the adjustment of the system, which both may lead to legionella growth. Faults are; dislocated sensors, set-point errors, malfunctioning valves, and too small heat transmitting surface in the heat exchanger (Li and Nord 2018; Månsson et al. 2019). It means that the replacement of a substation is not a guarantee that it is legionella safe as it may be wrongly installed and adjusted. The plumber is typically responsible for adjustments, design and installation. Consequently, it becomes of high interest that the plumber is skilled to design, adjust and install properly. Back in 2012, DEA asked 53 plumbers to evaluate the skills of their colleagues. They were asked about skills in general in the field of energy, but also specifically skills related to adjustment, installation and designing of the building heating system. They found that plumbers tend to think that their colleagues lack the necessary skills (DEA 2013a). The plumbers' organization agrees with the conclusion that plumbers need more knowledge and skills to service building heating system more energy efficient but think they will be obtained once the heat customer starts requesting energy efficiency (Christiansen 2019). Viborg DH company states:

> *"We see that if we not already in the planning phase chooses the right solution, then solutions will pop up which does not fulfill the requirements we have, and whenever a substation has been built, they are difficult to modify. As a result, we have always had a close dialog and required that if there is a bigger project then we need to approve it beforehand"* (Diget 2019).

The roll out of DHW system improvements are best assisted when the DH company beforehand considers which substation technology is applicable for the desired supply temperature reduction and implements the improvements together with a trusted plumber. Some DH companies find it easier than others: *"We have not approved anyone [plumber], we do not have a list of approved plumbers, other than those we have that handle our TAO* [Substation leasing model]. *…We have realized that this is something we cannot manage."* (Hansen & El-khatib 2019)

Diget (2019) did not find it difficult to implement improved DHW systems for all their small heat customers because: *"We have a product on shelf, that they save [money] from at day one" (Diget 2019)*.

Where Viborg plan to reach supply temperatures at 50°C they have not yet managed it. Experiences from Høje Taastrup, with small heat customers, indicate that problems are not purely solved by the introduction of a new substation. On the demonstration site Sønderby, they equipped all small heat customers with a new substation with an instantaneous heat exchanger (Redan Akva Lux II VX) and demonstrated DH supply temperatures at 53°C, but report on problems to achieve adequately high DHW temperatures due to some of the existing installations. The demonstration generally required visits and adjustments of the installation both before, under and after the operationalization (DEA 2014d). Experiences from AVA's demonstration site, Lystrup, reveal that similar efforts in adjusting a building heating system, may allow supply temperature as low as 50°C with a domestic hot water tank installed at small heat customers (DEA 2014c).
For large heat customers, implementing improvements are slightly more difficult. Diget (2019) states:

> *"The biggest challenge or the most untried, is the large 90 customers... … we haven't experienced any problems with Danish clean water* [Company producing chlorine disinfection techniques for DHW in large heat customers], *but to those who don't like this solution, we need to find an alternative with an inbuilt heat pump. .... we need to plan and test the solution this year, to experience how it works. ... I am not sure if it is challenge, as it has already been tested elsewhere"*

Improvements for DHW systems are more radical as it either involves the introduction of chlorine or the introduction of a local production unit to boost DHW temperatures. Especially chlorine in the DHW had worried some of the heat customers that fear to experience side-effects such as eczema. One also claimed that she could smell chlorine, which made her complaint. Diget (2019) could explain that there was no reason to fear eczema and that the smell of chlorine was not related to the normal operation of the legionella disinfection system. Despite highlighting the system's cost-efficiency compared to a local temperature boost, he had been unable to convince all the large building owners that this was the preferable solution. Thus, among other things, the implementation of chlorine disinfection techniques in the DHW system relies on the DH company's ability to make the heat customer become knowing that DHW will be as good as before and do no harm.

Facing the knowledge barrier and distrust from heat costumers regarding these chemical treatment methods, alternative technologies such as a local temperature boost of the DHW has been investigated by the DH companies, even though they are considered more expensive. However, before such a solution could be promoted, the DH companies needed to know how it worked, why demonstration projects were planned (Diget 2019).

AVA has experiences with local temperature boost of their heat customers from a demonstration distribution grid, Geding. And as already mentioned, they felt that too many technologies only created more organizational challenges as they needed to retrain their employees to operate the area. Technically, they experienced that the local temperature lift was malfunctioning when the DH supply temperature was increased on cold winter days (Thøgersen and Brizarr 2019).

In HOFOR, a third option is envisioned. They want to investigate if DH supply temperatures can be reduced to e.g. 50°C by ensuring that temperatures are preliminary increased from the main plant one or two times a week (Honeré 2019). Such a solution would be much less radical and would avoid heat customers being concerned about eczema and chlorine smells. On top of that, it would remove DH companies' organizational, technical and economic concerns on local temperature boosts. Though legionella disinfection techniques exist to produce DHW at 50°C, not all DH companies feel sure about lowering supply temperatures due to a lack of more robust regulation to guard their back. Thøgersen and Brizarr (2019) states:

"Regarding the entire legionella issue, I think there is a need for more robust guidelines in terms of what the temperature need to be" "Who is to blame for legionella? .. I don't know if it is regulation or maybe knowledge that is needed"

Today, a water installation norm DS439 exist which recommends 50°C at the tapping point. Research in the area seems a bit contradictory, since some state temperatures at 50-55°C to be legionella safe (Lund et al. 2018), whereas other say that there might be a legionella risk at temperatures above 46°C (Averfalk and Werner 2017; Li and Nord 2018). Meanwhile, some legionella incidents are not caused by too low DHW temperatures but due to stagnant water in e.g. the shower head. Reducing supply temperatures for the DHW system is not only about having the technique to function but also to increase the knowledge of what causes legionella and have some more robust common guidelines for all DH companies by which they can justify their temperature levels.

In summary, achieving supply temperatures at 50°C is partly a question of DH companies' ability to transfer knowledge about the safety of the new DHW system, but also to help the plumber in building up the necessary skills to avoid legionella incidents. Lastly, scientific knowledge in the area on legionella risks are requested, and regulation that clearly states the responsibility of the DH company regarding legionella.

6.4 Preliminary conclusion

It can be concluded that DH companies are influenced by the knowledge embedded in their organization, which may prevent especially large DH companies from implementing radical new customer solutions. Reports written by trusted consultants may on the other hand push for technological development at the critical heat customer level. DH companies have the expertise to process heat customer data and can identify critical heat customer that are poor performing, lack thermal comfort, and are not legionella safe. However, they cannot use big data to develop adequate solutions, as also visualized on Figure 22.

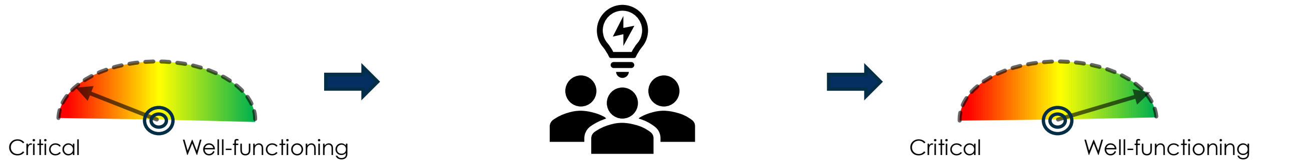
Identifying and develop solutions for critical heat customers

Poor performing	Thermal discomfort	Legionella-risk
✓ Highest return temperatures ✓ On-site visits	✓ Initial vs current energy consumption ✓ Complaints ✓ On-site visits	✓ Large heat customers ✓ On-site visits

FIGURE 22: OWN FIGURE SHOWING THE PROCEDURES DH COMPANIES APPLY TO IDENTIFY AND SOLVE CRITICAL HEAT CUSTOMERS

Consequently, proper identification of solutions involves in most cases on-site visits by a skilled DH employee. Best-practice examples show that it may very well be as Thøgersen and Brizarr state: *"..you need to go to every single customer to say something clever about their building heating system, which is resource-intensive"*. It may also be that small DH companies has an advantage in being more adaptive to such resource intensive tasks. The small DH company of Albertslund explain how they adapted to taking ownership of substations: "*Panic. Well we haven't hired any extra, maybe we just reorganized and restructured."*
Figure 23 summarizes a series of barriers, and solution to those barriers, that hinders the critical heat customers identifying themselves as critical, and to obtain enough comfort and basis for decision-making. Heat customers does not know that there is a problem, are unaware of costs associated with it, lacks know-how to solve it. Therefore, it is not priority to become well-functioning. From a knowledge perspective, energy renovation strategies are more resource-intensive because such solutions are more invasive to the heat customers everyday life compared to increasing heating power, replacing components or the substation. Chemical legionella disinfection requires the critical heat customer must be convinced that it will be harmless.

Assist the heat customer in generation of knowledge



Customer barrier:
- Doesn't see a problem
- Unaware of costs
- Lack of know-how
- Low priority

Knowledge generation:
- Understandable tariff structure
- Space for collaboration and competition
- Outreaching consultancy (free and impartial)
- Uniform heating systems
- Assist fireballs
- Demonstration of techniques

Customer outcome:
- ✓ Sees a problem
- ✓ Know how to solve it
- ✓ Basis for decision-making
- ✓ Comfort to invest

FIGURE 23: OWN FIGURE SHOWING HOW KNOWLEDGE CAN ASSIST A CRITICAL HEAT CUSTOMER IN BECOMING A WELL-FUNCTIONING

Assisting heat customer in generation knowledge may be accommodated by the following: A more understandable motivation tariff which will enable customers to realize an economic problem. Bringing customers into a competitive and collaborative environment in the presence of "experts" allow heat customers to obtain more knowledge about how the problem is rooted in their building heating system. Impartial and free consultancy provides comfort and a basis-for decision making. Some plumbers lack skills but are also challenged by a large diversity in building heating system. Making building heating systems more uniform will both assist plumbers and DH companies in their efforts of improving critical heat customers. Demonstration projects may show the customer that new techniques are harmless and adequate for their building heating system.

7 The creation of an actor-network

This chapter respond to the third supportive question:

How have the interests of key social actors been aligned to allow critical heat customer improvements?

It does so by analyzing the interests of actors (plumbers, DH companies and heat customers) in improving critical heat customers. It investigates how DH companies can exert power to align diverse interest through alignment strategies. Lastly, it investigates which obligatory passage points, see section 3.2, that has been applied to stabilize the actor-network. The investigation is based on the interviews of the DH companies Viborg, HOFOR, Albertslund, Høje Taastrup and AVA that all successfully addressed critical heat customers to lower DH supply temperatures.

7.1 The motives of actors

DH Companies

All DH companies have a major interest in having low temperature prepared heat customers. As stated clearly by the manager of Høje Taastrup:" *Low temperature district heating is not in particular relevant to us, it is relevant to everyone*" (Birnbaum 2019). Both AVA and Viborg highlight the ability to stay competitive with individual solutions as a reason to lower DH temperatures. As AVA points out: *"The lower temperatures, the lower heat losses, which is the vulnerable point of DH system compared to individual solutions".* AVA continuously points out that customer satisfaction is also a key parameter that cannot be neglected. *"From a competition perspective it has great relevance to us, to keep the supply temperature as low as possible, without disturbing our customers too much – it is a delicate balancing act."* (Thøgersen and Brizarr 2019)

While all DH companies tend to agree on abovementioned interest, there are also different interest between the DH companies. The variation in interest seems to correlate with the size of the DH company. Small/medium DH companies tends to emphasize service and proximity when talking about improving customer performance. In Høje Taastrup they state: *"We think it is a service to develop and guide and improve the efficiency of the heat customers"* (Birnbaum 2019). Albertslund adds: *"We may show that you can come a long way with proximity and a higher service level"* (Hansen and El-khatib 2019). The proximity is clearly manifested in Albertslund, where all heat customers are represented through a user-group. Hence, as a citizen in Albertslund you are a member of either a landowner association, cooperative housing association or a social housing association, and each association is represented with a seat. In total, it forms a user-group consisting of 58 seats. The user-group has concretely acted as advisory board in the implementation of the low-temperature strategy. About the advantages that follows from having a user-group, Albertslund highlights that it fosters political courage to take big decisions and provides the example that: *"There is no other than us who have set a date for low temperature for an entire district heating area"* (Hansen and El-khatib 2019). Also, Viborg reports about how they arrange sessions where they invite their heat customers to hear about the future heat planning. These sessions are rewarded by the customers which generally find the DH company trustworthy (Diget 2019).

The proximity towards heat customers contrasts the large DH company of AVA and HOFOR. In these DH companies the connection between heat customers and the DH company is sparse. AVA states that: *"Often customers experience that we are far away from them"* (Thøgersen and Brizarr 2019) AVA has two persons employed to visit 60,000 customers, which is not enough according to themselves. They also imagine that customers in a small DH company would have a more familiar relationship to the DH company. Nielsen (2019) also emphasize that they are short-handed for the task of improving the critical customers, which is one of the reasons why they currently focus their efforts on the largest and most critical heat customers. So, while large DH companies also value service and proximity, they do not prioritize it.

Ownership also seems to influence. Both Albertslund and AVA are municipality owned and administrated, in contrast to Viborg and Høje Taastrup that are privately owned by the heat customers. When municipalities own and administrate the DH company, the municipal strategy and DH strategy can reinforce one another and provide the DH company with a legitimate political agenda. This is seen in Albertslund, where the DH company in 2015 achieved political support of their low-temperature strategy. Hansen & El-khatib (2019) explains:

"The municipality they had reported that we should be CO_2-neutral by 2025, so I thought, well then we must try to test if they are ready, then we wrote into the vision that we should be a low-temperature city in 2025. It sounded good, so they all nodded."

The low-temperature plan not only sounded good, it was also coherent with the resource strategy and the municipal goal to recycle 60 % of the waste production. Low-temperature is equal to lower heat losses and consequently less heat from the waste incineration plants are needed (Hansen & El-khatib 2019).

In conclusion, all DH companies have the common interest to stay competitive through low heat prices and customer satisfaction. Both interests are served when the number of critical heat customer are reduced. Consequently, DH companies are motivated to help critical heat customers.

Small DH companies tend to further their interest in improving critical customers, as it improves the service level and create proximity between customer and company.

The owner structure of the DH company also influences which solution are perceived most optimal. Solutions perceived in municipal owned companies may to a larger degree reflect the municipal strategy, which makes energy renovation a more appealing way of correcting critical customers.

HEAT CUSTOMERS

While DH companies generally has a great interest in reducing DH operating temperatures, the situation is different for the heat customers. All the investigated DH companies consider heat customers to have a low interest in their heat supply system and in DH at all. As AVA put it: *"There is no one [heat customers] who thinks we are especially interesting"*. Even when significant changes to the DH supply are announced as in Albertslund, when they informed all 7500 of the heat customers of a future maximum supply temperature at 60°C, only a few responded and only one reader's letter made it to the news (Hansen & El-khatib 2019).

Christiansen (2019) represents the plumbers' organization and points out that from his experience the heat customer tends to lack the necessary understanding of what low temperature DH means. Often customers think that their radiators will not provide them with enough heat if lower temperatures are implemented. He also finds that heat customers have little knowledge on the energy efficiency aspects of their building heating system, and that heat customers generally aims at having their building heating system serviced at lowest possible cost.

This is in line with experiences from Albertslund when they announced that every heat customer must be prepared for lower DH temperatures. The heat customers responded:

"Oh no, I'm going to freeze now. ...I don't have any money, I can't invest. ...I'll die soon, anyway, so why would I invest?" (Hansen & El-khatib 2019)

As seen from the quote, thermal comfort is the immediate concern, but economy also means a lot to heat customers. This is also how the interest of heat customers are perceived in Viborg DH company. Where Diget (2019) states: *"if the customers experience that they can have a better heat source from making something individually, then we see customers choosing to pursue it rather than adhering to district heating."*

The interplay between the heat customers' interest in something that makes economic sense and provides thermal comfort is addressed by Hansen & El-khatib (2019), who explains how heat customers are convinced to make an energy renovation:

"It starts with: we [customers] do it for the sake of money, and then, when they are finished, they discover that it is a better indoor climate they have got."

Some heat customers have also environmental concerns as stated by AVA: *"There are people who want to try something green"* (Thøgersen and Brizarr 2019).

A published study adds that a wide range of factors are determining for their interest in energy renovation. The factors can be boiled down to the heat customers current place in life. Young heat customers that only lived for a short period in their home provides an example on a place in life where energy renovation typically is of more interest, whereas it is the opposite case for people of older age with a low income. This group lacks both financial capacity and a reasonable time-horizon for the investment to payback. Many more different types of heat customer groups can be identified. Therefore, the study suggests that the promotion of energy renovation takes place through various approaches even though it will be resource intensive (Mortensen et al. 2016).

HOFOR experiences that heat customers do not optimize the operation of their building heating system, despite having employed a heating system manager. The heating system manager has often several things to care for, and a proper heating system optimization is inconvenient and of low priority. Instead of fixing operational issues at each apartment, they tend to find reason as to why their building heating system cannot operate optimally (Nielsen 2019). In other cases, the heating system manager has grown used to high supply temperatures and has concluded that the building cannot operate at lower supply temperatures (Nielsen 2019). Nielsen (2019) sees the need for a change in attitude of the employed heating system managers.

In summary, the interest of heat customers to improve their heating system is low. They want a heating system that provides thermal comfort at low cost and at minimum efforts. Solutions to improve critical customers must adhere to these claims, unless the DH company succeed in changing the attitude of the heat customer. Some heat customer also values a green and sustainable development which may be used to advocate solutions that involve some costs and efforts.

Plumber

Plumbers is often the man connecting the heat customer and the DH company through his role of servicing and designing the heating installation. Consequently, he has a key role in ensuring that heat customers have an efficient operating heating installation.

According to Christiansen (2019), the interest of a plumber is not in between the DH company and the heat customer, but totally on the side of the heat customer. He experiences that DH companies wear "*blinkers*", when they think that all that matter is an efficient DH system. Christiansen (2019) explains that costumers share a common interest in having a heating system that provides thermal comfort and at low cost. The plumber responds to the heat customers desires, because his interest is in getting as many customers as possible. Plumbers tend to see low costs as low investment costs:

"They have [plumbers] *fear of suggesting an investment [*which could improve the performance*], because suddenly* [the service] *becomes more expensive. … They have a deeply rooted approach where they say: we should preferably profit as little as possible on our customers"* (Christiansen 2019)

The plumbers' organization tries its best in convincing plumbers that higher investment/service costs could be in the interest of heat customer as it could reduce motivation tariff costs. Thermal comfort is however the highest priority. So, when components in a building heating system is over-dimensioned, it may be caused by a plumber, who wants to ensure that his customer will enjoy thermal comfort. Christiansen (2019) provides the example that when servicing large heat customers, an efficiently operating building heating system that delivers a high cooling and low return temperature may be compromising thermal comfort for some apartments if the system is in hydronic imbalance.

In many DH supply areas, motivation tariffs are in place with the purpose of ensuring an efficiently operated and designed building heating system. The tariffs also pay off from an economic perspective. But according to Christiansen (2019), the heat customer is rarely aware that a motivation tariff exists and how a plumber can help regulate the costs/income from it. It is not in the interest of plumber to explain the customer that; if he is paid more, some of that money can be saved later through the motivation tariff. This is because it is hard to explain to the customer and therefore also difficult to convince the customer to go for a higher service standard. The plumber risks his credibility in trying to convince the heat customer because, as Christiansen (2019) put it: "*he is not necessarily a salesperson*". If a plumber has enough knowledge and communicative skills to address problems at critical customer level, and a motivation tariff is in place, he will try to improve the building heating system efficiency.

7.2 Actor-alignment strategies

According to the motivation of the investigated actors, DH companies must make low-temperature preparation economic attractive, not compromise thermal comfort, and deliver solutions that requires minimum efforts. Plumbers will follow the demand of heat customers, which means that heat customers also need to care more for the energy efficiency of their system. Due to the general lack of competences among plumbers, the DH company also need to find ways to improve the design, operation and adjustment of building heating systems.

Flow limiter

The highest priority of critical heat customers is seemingly thermal comfort. In HOFOR, they have realized that this might be a key insight in achieving improvements at the critical heat customer level. The installation of a flow limiter on the building heating system of poorly performing critical heat customer would ultimately take away thermal comfort from the heat customer. A flow limiter reduces the water flow rates passing through an uncontrolled building heating system and lower the return temperature. The aggregate is cheap to install, and according to HOFOR, it is only fair to the rest of the heat customers that critical heat customers are not allowed to stress the grid excessively and reduce the heat production efficiency through high return temperatures (Nielsen 2019; Skov 2019; Honeré 2019). The plumber's organization support this initiative. By implementing this, the plumber can avoid arguing or convincing costumers to go for an improved service level, since it is simply in the heat customers interest (Christiansen 2019). Thus, the flow/return temperature limiter is presumably an effective tool to align the interests of the actor network.

Financial aid

Economy matters to critical heat customers. Currently, all the investigated DH companies have a motivation tariff in place to motivate heat customers to make improvements. Høje Taastrup use the DH policy tool actively by lowering the required return temperature and thereby continuously motivating improvements (Birnbaum 2019).

However, the motivation tariff does not address financial aspects. There will obviously be a large difference between the financial opportunities of heat customers. Some of them can be tempted to invest in improvements when they experience a unique opportunity for financial support. AVA experienced from one of their own subsidy schemes that customers suddenly were deeply interested in replacing their heat exchanger. They reflect on the reason to be: "*The psychological aspect of being given a subsidy can push some of them to fix it, even though the subsidy is a small amount*" (Thøgersen and Brizarr 2019). Investments subsidies have been an element in all the investigated cases where DH supply temperatures were reduced by addressing critical heat customers. Substations in both Viborg, Høje Taastrup and Albertslund are paid through monthly or yearly fees with no investment costs for heat customer, and they are very popular (Diget 2019; Birnbaum 2019; Hansen and El-khatib 2019). Therefore, to the extent possible, DH companies should take the financial burden to improve critical heat customers.

While subsidies have a role in making critical heat customers improve themselves, there are limits in how effectively they can be used to. Especially when it comes to energy renovation. Chapter 5 identified that improvements may be related to considerably large investment costs, which would require some heat customer to obtain a loan to finance the investment. Such process may put the heat customer into two significant economic barriers. First, banks are not used to estimate the value of such loans, why they reluctant to grant loans or take high rents. Secondly, the heat customer tends to overestimate the negative aspects of risk and initial investment costs, which refrain them from investing (Copenhagen Economics 2015).

In England, they invented a loan called Green Deal which was attached to the building itself and not the building owner. The lender of the loan was paid back through the heat bill and the building owner achieved a reduction in the yearly expenses. The new type of loan effectively removed the financial barrier that some building owners had unfavorable credit capability hampering investments in energy renovations. However, only a limited number of applicants for Green Deal were received, indicating that other barriers in the promotion of energy renovation are also important resolve before interests can be aligned (Copenhagen Economics 2015).

Both Albertslund and AVA have experiences from promoting energy renovation with financial aid. AVA received R&D funding from Danish Energy Agency in return for a demonstration of energy renovation as a way to achieve lower DH temperatures. Some of the funds were allocated to heat customers on the demonstration site who chose to energy renovate. The combination of funding and on-site consultancy convinced 1 out 8 heat customers to go for an extensive energy renovation.

The other customers could be convinced to less extensive solutions such as increasing heating power of radiators and replacing radiator valves. (DEA 2014e).

Funds for critical heat customers can also be allocated through the energy saving scheme. The scheme is a national policy that expires by 2020. It obligates DH companies to carry out energy savings which is financed through the heat bill (Skov 2019). The DH companies are encouraged to promote energy savings in large heat customers because energy saving is cheaper in large customers compared to small. However, Albertslund use their energy saving responsibility strategically to address critical heat customers, including small heat customers, and offer the highest energy saving support at 1 DKK/kWh (AF 2016), even though national level policies does not motivate it: *"The way it has been put together[* [The energy saving scheme]*, you don't have to focus on the citizen at all, you are almost penalized for focusing on the citizen despite the fact that they pay 60% of the bill for the scheme."* (Hansen and El-khatib 2019). Even though Albertslund provide a high energy saving support compared to other DH companies, the amount is small compared to the total investment costs the heat customer faces (Hansen and El-khatib 2019). AVA also find the energy saving scheme difficult to use for improving critical heat customers and suggests that the method for calculating energy savings does not include the total amount of saved energy:

"We have the energy saving funds, but they do not give much… if we solve a large bad cooling customers it gives the DH system a large energy saving.. but the single customers' energy saving is not present because they don't save kWh they save money, why they cannot receive funds from the energy saving scheme.

The points from AVA and Albertslund touch upon a problem with national energy saving policy. Energy savings are measured at building level and not on heat system level. It reduces its applicability for DH companies when they try to target critical heat customers and have DH supply temperatures lowered and harvest the greatest energy savings.

Persistent dialog with customers

Being prepared for lower DH temperatures may also require the internal heating installations to be replaced, an energy renovation to take place, or the implementation of a radically new DHW legionella disinfection technique. In that sense, there are no solution that are frictionless implemented. Customer may not be sparked by the idea of lower DH temperatures immediately, because it requires some of them to change their installation.

In Albertslund, where they are going for some of the most comprehensive customer solutions, they also admitted that: *"It has taken a long time with the user group to convince them that it was a good idea [to become low-temperature prepared]."* (Hansen and El-khatib 2019). Agreement was, according Hansen and El-khatib, a result of a persistent communication focusing on the future benefits of both environmental and economic character.

To all the investigated DH companies, there are no doubt that more extensive solutions, requires that DH company visits the critical heat customer. Viborg states what a customer visit can provide:

"A direct dialog with the landlords, where we explain what installations that are needed and we offer our help to examine their installations to see if something simple can be done, and whether it requires investments, has made us come a great step ahead" (Diget 2019)

The persistent dialog ensures that the customers sees all the benefits and steps to get there become clear. All DH companies conclude that customer visits provide results, but that such initiatives are resource intensive. The required efforts are reduced when a pool of similar critical heat customers can be addressed by one customized solution (Hansen and El-khatib 2019).

Substation leasing and tender model

Knowing that heat customers are mostly concerned when the building heating system does not function and when money can be saved, it is easy to imagine that initiatives targeted customers must be easily implementable. Time and resources spend on improving the building heating system must be coherent with the value that the heat customer attribute low temperature prepared heating installation. Additionally, customers low valuation of a building heating system should not be decisive for plumbers' service level.

Both Høje Taastrup, Albertslund and Viborg reported on successful and popular substation leasing schemes, where the DH company install, takes the ownership, and removes the burden of service and maintenance from the customer, while also guaranteeing savings immediately (Birnbaum 2019; Diget 2019; Hansen and El-khatib 2019).

In Viborg, it has been a tradition to ensure that all bigger heat customer projects are approved by the DH company before being established, because once they are built, they are hard to change (Diget 2019). The initiative has been combined with a tender process for plumbers. Diget (2019) reflects upon the choice organizing a tender for the substation leasing scheme: *"We think that it makes it more complicated to the customer if he need to find the plumber .. from our tender model we ensure that the plumber fulfills our requirements and that the price is reasonable".* Albertslund choose a different strategy to ensure quality in the service of heat customers' substation. Firstly, they stated in their technical requirements for the utility area, that new installations on building heating system carried out by a plumber must be approved by the DH company. They realized that the task was too resource intensive and that they did not manage to be in control with all the different plumbers (Hansen and El-khatib 2019). Instead, they decided themselves to deliver the installation and maintenance of all their new leasing substations. Rather than enrolling the plumbers in the actor-network, they were simply excluded. A last option was presented by HOFOR, which worked on a certification of the plumbers working in their utility area. The certification should build up the necessary skills to ensure that plumbers were qualified to work in their utility area (Nielsen 2019). The idea was backed by the plumbers' organization, on the condition that it would improve the skills of plumbers (Christiansen 2019). Currently, the initiative is stranded do to conflicts on financials, indicating that such an initiative is too comprehensive for DH companies to execute.

7.3 Obligatory passage point

The alignment strategies of section 7.2 presumably leads to the formation of an actor-network consisting of plumbers, heat customers and a DH company, who are all eager to transform critical heat customers into well-functioning. However, the actor-network may destabilize due to the unpredictable nature of humans interacting with techniques. It may lead to abandoning the idea of transforming critical heat customers. In actor-network theory, techniques may prompt such a destabilization. E.g. in Viborg they planned to implement chlorine disinfection methods in their large heat customers, but they realized that some customers did not like the techniques. Figuratively speaking, the actor-network was destabilized. Stabilization is reached when a "machine" is built, which ties both actors and actants together in an alliance. It is a so-called obligatory passage point. This section will look closer into what obligatory passage point that presumably tied the actors and actants together in the low-temperature success cases of Albertslund, Viborg, Høje Taastrup, AVA and HOFOR.

HOFOR and Albertslund

For both HOFOR and Albertslund, municipal plans played a central role in tying actors and actants together, but for different reasons. In Albertslund, the municipality agreed on a low-temperature strategy because the combination of energy renovation and low-temperature implementation was in line with the municipal resource strategy and the municipal goal to become CO_2-neutral by 2025. In the document, the critical heat customers are addressed with energy consultancy and financial aid ensuring that everyone will be offered a technique which will prepare them for low-temperature DH heating. Techniques are defined as energy renovation, increased heating power and, if necessary, local temperature boost. Moreover, The DH company takes the responsibility to ensure that all substations are operated and designed properly through a substation-leasing model, and thereby exclude the plumber from the actor-network. By the dual promise that they will lower DH temperatures but also provide help and assistance, the strategy ties DH company, critical heat customers and the municipality together (AF 2016; Hansen and El-khatib 2019).

The municipal of Copenhagen created a plan in 1991 that aimed to improve the area of Inner Vesterbro physically, socially, and culturally. An overrepresentation of socially marginalized people was living in the area, and the buildings had poor sanitary conditions and were worn down. A large share of the buildings had individual heat solutions which, as part of the improvements, should be converted to DH. Consequently, completely new substations were built and together with the energy renovation, maximum DH operating temperature at 75/45°C could be realized, 20°C lower than for other distribution grids in the area (Skov 2019; BTK-KK 2005). The retrofitting plan came with national funding for energy renovation and general improvements at 600,000,000 DKK (BTK-KK 2005) for an area that today consist of 225 heat customers. Through funding and a persistent involvement of the building owners, the municipality aligned the interests of actors (BTK-KK 2005). In that sense, improvements of critical heat customers became a spin off from the retrofitting plan, which really was the obligatory passage point. All the DH company needed was to separate the distribution grid from other distribution grids, ensure a proper substation design of the heat customers and inform the heat customers of Inner Vesterbro that they would be low-temperature supplied (HOFOR 2019).

In both Albertslund and Copenhagen, the inclusion of the municipality was defining for the establishment of an obligatory passage point. Through the municipality came more financial power and an expertise in both energy saving activities and involvement of citizens that fostered the alignment of interests. It tied energy renovation and heat customers together.

Viborg

In Viborg, the removal of a CHP production subsidy has resulted in very high heat prices. This has made the DH company aware that heat customers are not loyal to the DH company at any cost (Diget 2019). In Viborg, plans on lower DH temperatures became a question of how can we lower the heating price and serve the interest of our heat customers? (Diget 2019). They had a consultancy report made by both Envidan and NIRAS showing how a future heat price could be lowered, which pointed towards lowering the DH temperatures in the summer season through the improvements of the DHW system and implementation of heat pumps. The calculative approach of energy system modelling efficiently accomplished to commit the DH company towards improving the heat customers. Diget (2019) recommends all DH companies to conduct calculations showing whether it is the SH system or the DHW system which is mostly feasible to lower supply temperatures since it has convinced them to work for the DHW system improvements. Although the low-temperature planning was not directly involving the heat customers, they had small sessions for heat customers where the plan was introduced, and Diget (2019) did not report any conflicts of interest between the heat customers and the DH plans. It indicates that probably the consultancy reports have acted as an obligatory passage points, convincing both the DH company and the heat customers that replacing critical heat customers DHW system to lower DH supply temperatures was in everyone's interest. The involvement of DTU, Danish Clean water and Krüger in a couple of demonstration projects has also helped defining the techniques to achieve the lower DH supply temperatures. However, the obligatory passage point may be destabilized because the heat production company Energi Viborg is not convinced that lower DH supply temperatures is feasible. They published their own report (EV 2018) and argues for supply temperatures at 60-65°C rather than Viborg DH company's goal for 50-55°C. They want to broaden out the discussion to not only be of economic debate, but also a debate about health and social factors. They argue that the legionella risk is real as people has died from it, and it has also been documented in the DHW storage tank of one of their customers. Therefore, they don't want to "gamble" with supply temperatures towards 50°C. Moreover, they fear that the investment burden to improve critical heat customer will be hitting socially unequal, especially for large customers that needs either a booster HP or chemical treatments. Hence, the techniques for achieving lower DH supply temperatures have not yet been stabilized (Boysen and Sönder 2019). The plans for a future merge of the two organizations may put the conflicts of interest on hold and reinforce the obligatory passage point. As it is now, the heat production company might destabilize the actor-network and remove the obligatory passage point through the communication of their report and concerns of lower DH supply temperatures to their owner, the municipality, and to the heat customers.

Høje Taastrup and AVA

A third variation of an obligatory passage point was seen in AVA and Høje Taastrup that had areas converted to lower DH temperature through participation in a research and development program funded by DEA. Høje Taastrup had 75 small heat customers living in the area of Sønderby. They were unsatisfied with the fact that they had to pay a large heat bill due to significant distribution heat losses, and they took the DH company in court for justice and lost the case (Schleiss 2016). A settlement of the conflicts of interest came when the 75 heat customers were offered to participate in the demonstration project, which offered them a replacement of their substation and the promise of heat savings. All 75 heat customer agreed to participate (DEA 2014d). In Tilst and Lystrup, similar commitments were made from 40 and 8 heat customers, respectively. Some even committed themselves to energy renovations (DEA 2014c; DEA 2014e). It proves that a research and demonstration program may work as obligatory passage point, convincing costumers that they can serve their interests. The demonstration projects were characterized by the involvement of experts in the field of building heating systems and low-temperature implementation and a product development which put efforts in making the low-temperature products work as efficiently as possible. Consequently, they were able to demonstrate large heat savings shortly afterwards (DEA 2014a).

Summary of cases

Table 19 provides an overview of the obligatory passage point of each case and which techniques and actors that were enrolled in the actor network.

TABLE 19: THE TABLE SHOWS WHAT OBLIGATORY PASSAGE POINT THAT HAS BEEN ESTABLISHED IN EACH CASE, AND WHICH TECHNIQUES AND ACTORS THAT HAS BEEN INVOLVED. ACTORS MARKED IN BOLT WERE PROJECT LEADERS.

	Obligatory passage point	Techniques	Actors
Albertslund	Municipal strategies and Low-temperature strategies integrated.	Energy renovation and substation replacement	Politicians, User group (housing associations), **DH company/municipality**,
Viborg	Consultancy reports	Low-temperature DHW substation, chlorine treatment, booster HPs	**DH company**, Plumber, consultant, DTU, Danish Clean water and Krüger, 90 large heat customers.
Høje Taastrup	Research and development project	DHW system	DH company, **COWI**, Danfoss and Teknologisk Institut, 75 heat customers.
AVA (Tilst and Lystrup)	Research and development project	Energy renovation	DH company, Teknologisk Institut, Kamstrup, Danfoss, **COWI**. 8 and 40 small heat customers.
HOFOR (Vesterbro)	Urban retrofit plans	Energy renovation + new substations	DH company, **Municipality**, housing associations.

Common to all cases is the fact that there is some sort of plan or report that defines a clear goal, the critical heat customers, the techniques, and the benefit of reaching the goal. The technique also seems to influence which experts that can be engaged into the efforts of improving critical heat customers. The technique of energy renovation serves the interest of municipalities who are "experts" in creating public participation. The implementation of radical new techniques, like e.g. new DHW systems, can engage product-developers into the low-temperature DH projects. They are "experts" and committed to make their products work together with existing techniques as seen in Lystrup, Tilst and Sønderby. Essentially, the choice of techniques plays a major role for DH companies, as it determines which "experts" they may have available. The enrollment of "experts" help further in the interest of the actor-network and helps DH companies in reaching a point where the critical heat customers are put in a position of: "*Whatever you want, you want this as well*" (McLoughlin 1999).

7.4 PRELIMINARY CONCLUSION

Critical heat customers and plumbers have interests in conflict with a DH company that wish to reduce DH supply temperatures. Critical heat customers want a building heating system that delivers thermal comfort at low cost and efforts. The plumber adheres these interests and deliver service at low *investment* costs and may over-dimensioned system components to ensure thermal comfort. The DH company has several tools they can apply to make the actors align. Among these are the installation of a flow limiter, subsidies specified critical heat customers, and leasing models. A stabilized actor-network is reached when DH companies obtain support from the actors through a document which describes the goal of the critical heat customer initiative, the benefits of reaching the goal, and the techniques that the involved actors must apply. However, the path towards obtaining heat customer support seem to require the enrollment of "experts" into the network. Experts such as municipalities that can assist the DH company in the comprehensive process of involving critical heat customers and improve the legitimacy of lowering supply temperatures by integrating it with municipal goals. Product experts, such as product developers, can ensure that technical improvements work better with the already existing techniques.

8 Discussion

This chapter will present a summary of the main findings. It will discuss how critical heat customer initiatives should be implemented, and under which conditions initiatives may have success. Theories and methods are discussed for its impact on the results, and it is discussed which alternative theories and methods could have been applied to obtain other important insights.

8.1 Summary of main findings

The results of the analysis indicate that it is profitable to make a critical heat customer initiative in a wide range of heat supply systems suffering from hydronic bottlenecks. It even includes heat supply systems that has no heat production and only distributes heat. Hence, DH companies should have the economic motivation for a critical heat customer initiative everywhere, unless they cover the entire heat production with a cheap and efficient wood chip boiler or similar.

The exploitation of the economic gains is challenged by knowledge barriers. Heat customers do not know that they are critical. DH companies face a resource intensive task in letting them know, identifying the exact problem, and in developing adequate solutions since heating systems and costumers differs a lot.

Heat customers need to know that they are critical, know what can be done to solve it, have a basis for decision-making between different solutions, and have the comfort to invest in solutions.

The problem of being a critical heat costumer may be known if a more understandable tariff structure is implemented, and if spaces are created for heat customers to compete and collaborate on improvements. Outreaching, free and impartial consultancy may provide the critical customer a basis for decision-making and the comfort to invest. The plumber must be assisted to ensure he has skills and knowledge to correct customers. More homogeneous building heating systems may help both the plumber and the DH company because it enables customer initiatives and services to be specific and replicable in order to reduce the need for generation of new knowledge.

Knowledge strategies should be supplemented by actor-alignment strategies because heat customers, DH company, and plumbers have conflicting interests. Heat customers want thermal comfort and legionella safe DHW at low costs and efforts, and the plumbers adheres to these requirements. Installing a flow limiter at the critical customers removes thermal comfort from them, which presumably initiates a motivation for increased heating power, energy renovation, or improved heating system at the costumer level. Financial aid deals with the low-cost barrier among heat costumers. Removing substation responsibility reduces the efforts required by the customer. Enrollment of the plumber comes with certification of his qualifications, tender, or by overtaking the plumbers' tasks internally at the DH companies. Tying actors and technical solution into the actor-network and stabilizing relations comes with the process of agreeing to some sort of critical customer plan. Such a plan can be in various shades: consultancy reports, municipal development plans, or a plan for a research and demonstration project. The sort of plan also seems to influence the enrollment of other types of actors, such as municipalities and product developers. These other actors bring new expertise to the network, such as citizen involvement and skills to implement and operate new techniques.

8.2 PRIORITIZING BETWEEN INITIATIVES

Through the analysis, the importance of using various initiatives when trying to improve critical heat costumers from a DH company perspective has been shown. In this section, customer initiatives will be ranked based on the expected impact of the initiative.

As suggested in the very beginning, three critical customer pathways exist. Either a supply temperature reduction leading to hydronic bottlenecks, thermal comfort issues or the risk of legionella growth. With the choice of pathway, come the implementation of very distinct techniques because techniques are targeted differently, either at overall performance, space heating, or at the DHW system. It inevitably affects which customer initiatives that should be prioritized and which actors that should be enrolled in the actor-network. Table 20 presents how initiatives and actors should be prioritized based on their impact and importance.

TABLE 20: THE FIGURE SHOWS THREE CRITICAL CUSTOMER STRATEGIES WITH A DISTINCT PRIORITIZATION OF INITIATIVES AND ACTORS

Choose critical customer strategy

DH temperature reduction boundary:	Hydronic bottlenecks	Thermal comfort boundaries	Legionella-risk
Building heating system scope:	Overall performance	Space heating	Domestic hot water
Rank of initiatives:	1. Flow limiter 2. Understandable motivation tariff 3. Substation leasing and tender model 4. Competition & collaboration	1. Persistent dialog with heat customers 2. Outreaching free and impartial consultancy 3. Financial aid 4. Empower fireballs	1. Persistent dialog with large heat customers 2. Demonstration 3. Financing aid 4. Substation leasing and tender model
Rank of actors to enroll: (excl. heat customers)	1. Plumber	1. Municipality 2. Plumber	1. Product developers 2. Plumber

The enrollment of plumbers is of highest priority for customers with performance issues. The plumber is usually the one servicing the heating system but may lack of interest or skills to explain the customers the importance of a better service, and customers may not request it. The problem and solution may be simple, e.g. to break the vicious circle by installing a flow limiter. It will remove thermal comfort from poorly performing customers and make them demand a service that provides proper performance, because it is now linked to thermal comfort. Consequently, a flow limiter is of highest priority to critical customers with performance issues. There may be situations where it should be prioritized differently. If e.g. many plumbers in a DH system aren't skilled enough to ensure that building heating system can increase its performance. There may also be a discussion on what measure are fair and appropriate. Reducing flow from critical customer may be fair from the collectives' viewpoint, because the critical heat customers cause everyone's costs to rise. However, from the critical customers' viewpoint, a flow limiter is quite drastic, in that it removes the product the customer is paying for. It could result in complaints and a poor image, and for the same reason, some DH company may choose not to install it. In that case, the best initiative would probably be to lure customers into a substation leasing scheme, where the installation of the system is controlled through a tender for plumbers. Alternatively, if DH company has the organization for it, they could install and service the substations themselves. Thereby, the DH companies have control of the performance of the substations.

The nature of thermal comfort problems is different. It is more pervasive to the critical heat customer as it requires changes inside the home of the heat customer. To convince customers to implement a technique, it may be necessary to foster a collective spirit focusing on what a district of customer jointly can achieve from its commitments, e.g. more sustainable and cheap heat. Therefore, persistent dialogue with the heat customer should be of highest priority. For the same reasons, it becomes of high interest to enroll municipality into the network because they are experienced with public participation processes and have local policies that help legitimizing the critical heat customer initiative by linking efforts to other policies and goals.

However, it could also be that the list of initiatives should be prioritized completely different. If e.g. the heat prices are excessively high, everyone may be eager to carry out energy renovation. In this case, it would be more important to ensure that heat customers access financial aid that allows them to borrow money. Heat savings may not convince the bank to lend the costumers money. However, most likely all the listed initiatives will be necessary, and probably some additional initiatives that has not been identified due to the limitations of the theory and methods applied. At least past experiences tell that it is very difficult to promote energy renovation (Mortensen et al. 2016; NIRAS 2016; Copenhagen Economics 2015; DEA 2014e).

Risk of legionella is again a third situation. For this type of critical customer initiative, it is suggested to prioritize dialogue with large customers. Large customer has a DHW circulation system, in contrast to small heat customers, where risk of legionella growth is higher. Consequently, techniques to solve large heat customers are more radical than for small heat customers. Small heat customer may be solved simply by replacing the old substation, while large heat customers need e.g. chlorine disinfection techniques. It requires the buildup of trust through dialogue and demonstrating that these radically new techniques work as intended. Therefore, I argue that initiatives to dialogue and demonstration should be prioritized. The involvement of product developers should also be prioritized, because they have practical experience with these new technologies. On the other hand, the DH company could also choose a less radical technology, such as central temperature elevation strategy, and then product developers would be of less interest.

In summary, it can be concluded that for the three types of critical heat customers strategies, that the hydronic bottleneck strategy is probably the strategy that requires the least of DH companies. Simple actor-alignment strategies such as the implementation of a flow limiter may bring DH companies a significant step ahead. Strategies towards the customer boundaries of thermal comfort and legionella-risk require more knowledge-oriented initiatives. And thermal comfort is especially extensive in its requirement for outreaching impartial and free consultancy of the critical heat customers.

Generalizability concerns

Table 20 might give the impression that initiatives uncovered from the analysis will enable all DH companies to succeed in improving critical heat customers and lower DH supply temperatures. However, the identification of initiatives is based on case-studies, which means that there are bound to be some context depending aspect that constrain the replication of their successes. The intention was to identify some of the constraining factors for replication by comparing the investigated cases. Due to large diversity between the cases, it was hard to state whether something was surely constraining. Table 21 highlights case-specific aspects, which from the analyses seems to find the basis for a successful critical customer initiative. The reason why these bullet points are determining for success are explained below.

TABLE 21: POTENTIAL EXPLANATIONS FOR A SUCCESFULL CRITICAL HEAT CUSTOMER INITIATIVE

Poor performance	Thermal comfort	Legionella-safe
✓ Motivation tariff on return temperature ✓ Few large customers with a large internal organization ✓ DH company in expanding city	✓ Large share of ▪ Standard houses ▪ Social housings ▪ Renovated houses ✓ Municipality committed to save energy ✓ DH company and municipality share jurisdictions ✓ Small DH company	✓ Few large heat customers ✓ Substations generally worn-out ✓ Pressure to lower costs

Initiatives targeted poor performance are constrained to make most sense in grids suffering from hydronic bottlenecks because it allows supply temperatures to be lowered. Hydronic bottlenecks are likely to be an issue in expanding cities. Moreover, DH companies with motivation tariffs on return temperatures seems more suited for the task. All investigated DH companies have motivation tariffs, but measure in differently in flow, return temperature or cooling performance. Customers may find the motivation tariff unjust because supply temperatures vary from customer to customer due to heat losses in the grid. That problem is minimized when the tariff is put on the return temperature because the supply temperature is not as influencing (Birnbaum 2019; Lindblom 2019).

Initiatives targeted thermal comfort require the most extensive efforts and tightest customer relations. To minimize efforts, it is preferable that a large share of the heat customers live in standard houses, social housings, or renovated houses. Such type of heat customers reduces the burden of the DH company. Moreover, small DH companies may be better suited for the task because they are closer to customers than large DH companies (Thøgersen and Brizarr 2019; Hansen and El-khatib 2019). Assistance from municipalities can be of great help, such assistance may be more likely if the DH company are committed to energy savings and share the same jurisdictions as the DH company, because then interests are more likely to be aligned.

DH companies that seeks new boundaries of legionella-safe temperatures may be more successful when they have few large heat customers. Large heat customers are more problematic due to circulation systems. It also helps if heat customers' substation (DHW system) is worn out because it may foster a demand for a new substation. If DH companies take control, it will allow the installation of substations that can ensure legionella-safe DHW at lower DH supply temperatures. Finally, a DH company, which are under pressure to deliver cheaper heat, will probably be more likely to apply more radical techniques, which may be required to affect large heat customers.

IMPLICATIONS OF HEAT CUSTOMER TYPES

The analysis has not been structured to highlight the differences between barriers and initiatives for small and large heat customers. It has rather focused on identifying initiatives across heat customers. However, it should be emphasized that there could be some inherent differences between large and small heat customers, which influence what initiatives that may be considered most effectful. In Figure 24 some potential differences are highlighted which all relate to the three analysis on profit, knowledge, and actor-network.

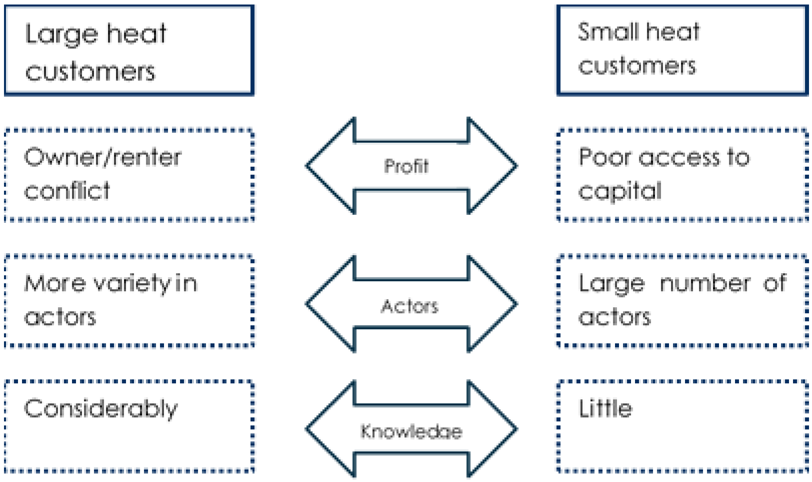


FIGURE 24: OWN FIGURE SHOWING SOME POTENTIAL DIFFERENCES BASED ON THE ANALYSIS TOPICS OF PROFIT, ACTOR-NETWORK AND KNOWLEDGE.

From a profit perspective, it was shown that initiatives at large heat customers have a slightly shorter payback period than for small heat customers. However, there may be other more important economic concerns. Some large buildings are owned by a person, who lends out apartments. It is argued that such a relationship can become a big profit barrier because the owner cannot necessarily increase the rent and have his investment paid back (Copenhagen Economics 2015). It suggests a more structural problem associated with some large heat customers, why financial aid may not be enough. For small heat customers, the financial aspect may to a larger degree be associated with borrowing money and taking the risk to invest (Copenhagen Economics 2015). Consequently, the type of heat customer may require profit and financial initiatives to be ranked differently.

From an actor-network perspective, it should also be highlighted that large heat customers may have a large internal organization, which infers that more types of actors become essential to drive changes to the building heating system. The organization may include a heating system manager, responsible for the operation of the building heating system, an accountant, responsible of paying the motivation tariff, and an owner, responsible of financing improvements. If the three of them do not communicate, no one would know there is a problem or would be able to finance solutions (Nielsen 2019). An area of small heat customer infer that the DH company needs to deal with a larger grand total of actors. For small heat customer the owner of the building and customer is one person. It means that dialogue and consultancy for small heat customers also can lead to energy behavioral changes. One could imagine that initiatives become more deeply rooted and result in more extensive building heating system changes than for large heat customers like it has been the case for energy renovation (NIRAS 2016).

Knowledge wise, large and small heat customers may also differ. A heating system manager may be employed at large customers, why they will have a considerable knowledge level on their building heating system. Small heat customers, on the other hand, can be characterized by the absence of a heating system manager, why they presumably have little knowledge available on their building heating system. It infers that knowledge initiatives for large heat customers could play into the professional pride that heating system managers presumably have. Initiatives where heating system managers compete against one another, like Energispring, see section 6.3, may motivate heating system managers through their professional pride and motivate generation of knowledge and improvements. Contrary, small heat customers may be harder to motivate, consequently, service concepts such as a leasing model seems suitable.

Finally, it should be noted that one size does not fit all. Small and large heat customer can be divided into an endless number of categories, the variety of heat customers makes the impact of initiatives hard to predict

8.3 Reflection on theories and methods

The choices of theories and methods have had implications to the design and results of the analyses. This section will present some reflections concerning the implications and how choices of different theories and methods could have led to other types of results.

Theory

The investigated technological framework is not about developing a new technique because techniques to solve critical heat customers-related issues already exists. It is rather about analyzing components of technological change; profit, knowledge and actor-network in the local context to see how technological change was forced through. According to actor-network theory the ability of one actor to exert power above another are drivers for technological changes. It implies that the actor-network analysis may lead to the finding of unethical explanations for technological change at critical heat customers. Other theories suggest a more normative approach that clearly determine the conditions for an ethical technological change. E.g. innovative democracy emphasizes the importance of having democratic structures which ensures broad involvement of interests in policymaking. It allows policies and goals to be established in an unbiased manner, which improves conditions for a transition into a renewable energy system (Hvelplund 2011). The Choice Awareness theory also emphasize the importance of establishing an unbiased decision-making process by ensuring that energy system analyses are conducted with fair comparison to alternatives (Lund 2014). These theories assume the presence of a political process before a technological change, but DH companies only entitled to conduct a real political process when implementing "*new larger collective heat production units*" or "*larger changes to the existing system*" (Ministry of Energy, Utilities, and Climate 2019). It would therefore be artificial to investigate political structures that does not exist. Consequently, these theories were found inadequate to understand the drivers for technological change in the success cases in Viborg, Copenhagen, Aarhus, Albertslund and Høje Taastrup. However, the theory of innovative democracy also provides a framework for understanding the relationship between the micro and macro level of technological change. It states that national policy making creates the opportunities and constraints for technological change on the micro-level (Hvelplund 2011). The chosen theoretical framework is limited to explore only the micro-level being the local context of the success cases.

Methods

A heat supply modelling has been chosen to answer where a critical heat customer initiative should be carried out. It does so by establishing 6 theoretical heat supply systems with identical DH operating temperatures, heat customers, heat demand and losses, but with different heat production technologies. It identifies which system that has the largest profit from a critical heat customer initiative.

The approach is subject to several limitations. First of all, it can be questioned whether profit is the most suitable evaluating factor to determine where a critical heat customer initiative make sense. It may be suggested that CO_2 emissions could be an equally important factor. From the interviewed DH companies there was clearly a difference between how much emphasize they put on economy.

In Viborg DH company an expired capacity payment has led to high heat prices which forced the DH company to show heat customers that future heat prices will be lowered. Therefore, profit was suitable as explanatory factor for a DH company like Viborg. In contrast to Viborg, profit seemed to play a minor role in Albertslund or at least they interpreted profit differently. They had estimated that customer initiatives would indeed pay off, but in the very long run. The explanations for their commitment were to a larger degree rooted in a story of a sustainable and fossil free future, and the DH low-temperature strategy was fused with municipal goals and policies. It suggests that the question of where critical heat customer initiative should be carried out, should be answered in a broader perspective than only evaluating profit. Further research should at least also investigate CO_2 reductions, because it matters in the decision-making of some DH companies.

The results of the heat supply system analysis do face issues of generalizability. The effect of reducing DH supply temperatures have been based on measured data from the grid of Vesterbro, but the effect of supply temperature reductions depends on the building heating systems of each distribution grid. Consequently, the potential supply temperature reduction from a critical heat customer initiative may differ from distribution grid to distribution grid and depend on the mix of customer installations in the area. To my knowledge, theories and models of the influence of supply temperature on return temperature only exist on building heating system level. Consequently, choice of using measured data has been in the absence of better alternatives.

Moreover, the specific setting of a DH company may infer that production savings from a critical heat customer initiative are hardly allocated to the heat customers. E.g. it may be that the production is outsourced to another company that has a long-term contract with fixed prices.

There may also be context specific issues that refrains DH companies from lowering supply temperatures. A DH system may consist of many distribution grids attached to one another, which infers that supply temperatures cannot be reduced because the neighboring distribution grid still need high temperatures. In other cases, it may be that the grid operator simple does not like the idea of lowering DH supply temperatures because he has always operated at these temperatures (Sönder & Boysen 2019; Mygind 2019).

The qualitative data investigated sought to identify how DH companies should address critical heat customers. Interviews were conducted with DH companies which all had been involved in successful improvements of critical heat customer that allowed DH supply temperature reductions. Moreover, it was chosen to interview plumbers because they were believed to play a central role. In reflection of the study, broadening the scope of actors with more interviews, could have brought more understanding and provided a broader range of recommendations for a critical heat customer initiative. It has become evident throughout the analysis that also municipalities, product developers, and banks may play a role in addressing critical heat customers.

Furthermore, instead of interviewing one actor at a time, a different data generation strategy could have been chosen. Gathering all presumably important actors in one focus group interviews would have allowed DH companies to challenge one another's insights, and thereby immediately ensure reliability of the data. Assuring reliability has instead been achieved by comparison with scientific literature and through an everyday life in the DH company of HOFOR. Focus groups could potentially also have allowed the interviewees to discuss at a professional level. Instead, interviews have been constrained by my own knowledge on the topic with the implication that interviews in the end of the project has been more focused and interviews in the beginning broader. However, the interviewees have willingly responded to follow-up questions, which have ensured that all important topics have been covered. And maybe the participants in the interviews, compared to focus-group interviews, spoke more freely and open minded about the topic when not being accompanied with colleagues or business partners.

9 Conclusion

This thesis has addressed the research question:

Where and how could DH companies address critical heat customers to lower DH supply temperatures in existing district heating distribution grid?

The research question has been operationalized by the formulation of three sub questions

- What type of heat supply system would benefit the most from critical customer initiatives in concern to profit? In addition, what is the payback period of investment of the critical customer initiatives in the given heat supply system?
- How can it be known who the critical heat customers are? In the process of convincing critical heat customers to improve, what knowledge barriers between heat customers and DH companies may be faced, and how could they be addressed?
- How have the interests of key social actors been aligned to allow critical heat customer improvements?

To answer the question, multiple case study approach has been applied. The approach is twofold. One part investigates cases from a quantitative perspective, through the establishment of 6 heat supply systems which vary in heat production technology but are similar in operating temperatures, heat demands, and distribution heat losses. This part of the investigation answers the first sub question.

The other part is a qualitative investigation of 5 cases where DH companies successfully addressed critical heat customers to lower DH supply temperatures. This part answers the following two sub questions.

From the heat system analyses it was found that a critical heat customer initiative can reduce the problem of hydronic bottlenecks in distribution grids and bring environmental benefits in terms of reduced primary energy consumption.

The results indicated that it is profitable to make a critical heat customer initiative in a wide range of heat supply systems suffering from hydronic bottlenecks. It even includes heat supply systems that has no heat production and only distributes heat. Consequently, DH companies should have the economic motivation for a critical heat customer initiative everywhere.

Critical heat customer initiatives should be prioritized in:

- Systems with a high variable heat price
- System with multiple heat production technologies where a low temperature benefitting production unit can replace a more expensive production unit
- Systems with a high production share of HPs, which have the largest production efficiency gains
- Systems with production units that have production efficiency gains and high fuel, tax and operation and maintenance costs

From the investigated cases, a system where the heat production is covered 100% by a wood chip boiler has the lowest economic value.

To enable DH supply temperature reductions, it was assumed that critical heat customers either energy renovate or improve their building heating system design. Moreover, it was assumed that heat supply system benefits were allocated to the critical heat customers. The payback period of both solutions for large and small heat customers were found to be between 4-15 years, except for customers in a system with heat production purely covered by a wood chip boiler. Large customers had a slightly better business case than small heat customers. Energy renovation was also slightly better if the customer were about to have a renovation anyway. Hence, systems with large heat customers that are about to renovate should be prioritized from an economic perspective.

Before the economic benefit can be realized, the critical heat customer must be known, and the DH company must convince itself that it is worth the efforts. It is a process in which knowledge plays a role.

DH companies have or can access the expertise to process heat customer data and can roughly identify critical heat customer that are poor performing, lack thermal comfort, and are not legionella safe. However, they cannot use big data to develop adequate solutions. Consequently, proper identification of solutions involves, in most cases, on-site visits by a skilled DH employee, which is resource intensive. It is indicated from the cases that small DH companies have an advantage in being more adaptive to such resource intensive tasks.

Despite efforts in identifying critical heat customers, knowledge associated problems are not over because customers need to know that they have a problem. The cases indicate that customers do not know of their problem, are unaware of costs associated with it, lacks expertise to solve it, and the plumber may not have enough skills to help them. When confronted with solutions, the costumer may need comfort in knowing that the solution is adequate and safe. Therefore, they are not prepared to prioritize improvements.

Consequently, the DH companies are recommended to:

- Have a more understandable motivation tariff which will enable customers to realize an economic problem
- Bring customers into a competitive and collaborative environment in the presence of “experts”, who allow heat customers to obtain more knowledge about how the problem is rooted in their building heating system
- Provide impartial and free consultancy which give customers comfort and a basis-for decision making
- Uniform building heating systems, because it makes problems easier to identify and solutions easier to plan and execute. It helps the plumbers and DH companies in doing a more efficient job
- Demonstrate techniques to let customers know how it works and looks

A critical heat customer initiative also faces barriers in conflicting interests between critical heat customers, plumbers, and the DH company. It seems from the cases, that critical heat customers want a building heating system that delivers thermal comfort at low cost and efforts. In most cases, the plumber adheres to these interests, and deliver services at low investment costs and may over-dimension system components to ensure thermal comfort.

The DH company has several tools they can apply to further their own interest in improvements of critical heat customers. These are

- Install a flow limiter. It takes away thermal comfort if building heating system performs poorly

- Financial aid specified critical heat customers. Some customers are lured by the special opportunity for being given a subsidy. Others overestimate risk of investing in improvements, and have poor access to capital, why an alternative financing model may be needed.
- Persistent dialog with heat customers, where the DH company ensures that the customers know the benefits of improvements.
- Offer substations through leasing models and control the installation of them through tenders for plumbers. It effectively reduces the efforts required by the heat customer because the DH company takes responsibility to service it. Moreover, it creates competition among plumbers to deliver on the DH company's interest

Even though interests may be more aligned from abovementioned tools, they may become diverging again. A stabilized actor-network with aligned interests may be reached when DH companies obtain support from the actors through a document which clearly describes the goal of the critical heat customer initiative, the benefits of reaching the goal, and the techniques that the involved actors must apply. However, the path towards obtaining heat customer support may require the enrollment of "experts" into the network. Experts such as municipalities that can assist the DH company in the comprehensive process of involving critical heat customers and improve the legitimacy of lowering supply temperatures by integrating it with municipal goals. Product experts, such as product developers, can ensure that technical improvements work better with the already existing techniques.

In the evaluation of initiatives for three types of critical heat customer problems; poor performance, thermal comfort issues, and legionella-risk, the poor performance problems were found most effortless when addressed by the DH company. Simple actor-alignment strategies such as the implementation of a flow-limiter may bring DH companies a significant step ahead because it suddenly becomes in the customers interest to ensure proper operation of the building heating system. It is likely to trigger plumbers to deliver a better service because their focus is to deliver thermal comfort for customers.

Strategies towards the customer boundaries of thermal comfort and legionella-risk may require more knowledge-oriented initiatives because the potential of a better plumber service is low. Larger investments and potentially radically new techniques may be required. Thermal comfort is especially extensive because some customers need outreaching impartial and free consultancy to have comfort and a basis to make decisions on improvements.

Moreover, it is worth distinguishing between small and large customers for a critical heat customer initiative. Small heat customers may have financial problems associated with access to capital, whereas large heat customers may have problems in dividing investment and savings between them. A customer initiative in an area of small customers would require more place to visit and be more resource extensive, but initiatives may be more effectful as the heat customer and the occupant is the same person. Initiatives at large heat customers may involve a larger diversity of actors; administration, heating system manager, and owner, where communication on improvements regarding the building heating system operation may be challenged be internal communication problems. On the other hand, the larger heat customer has a heating system manager, who may have a professional pride, where a competitive environment between heat customers may provide results faster. Small customers may simply prefer that someone else take responsibility for an improved operation of their building heating system.

Validity of results

The validity of the economic evaluation of a critical heat customer initiative is reduced by the absence of sensitivities. It may be that electricity prices, taxes, and fuel cost change. It may also be that the estimated DH supply temperature reduction was too high or low, and that the production benefits were over or underestimated. In neither of the cases has critical customer initiatives been compared to replacement of pipes or production units, which are alternatives to lower costs in a DH system. Consequently, the profitability of a critical heat customer initiative may be relatively poor compared to other alternatives. Lastly, the profitability of a critical heat customer initiative is based on theoretical cases that are like real systems, but not identical. The only valid conclusion is therefore that critical customer initiatives seems to be profitable in many types of distribution grids of hydronic bottlenecks.

Similarly, the recommended customer initiatives that enable DH company to lower DH supply temperatures are based on cases. These cases are investigated qualitatively. A high validity is ensured by the fact that these initiatives indeed worked for the investigated DH companies. However, it may be questioned whether these initiatives will work in other heat supply systems because the context differ.

Outlook

This thesis has investigated where and how DH companies should address its critical heat customers. The investigation has focused on the DH company as the key actor to promote technological change at the critical heat customers.

Throughout the analysis it has become clear that other actors might as well drive the technological change. When it comes to critical heat customer initiatives, which are extensive and requires a high degree of heat customer involvement, it has become evident that municipalities have often played a role. Either directly, as in the transformation of Inner Vesterbro from worn out buildings to energy renovated and low-temperature prepared heat customers, or indirectly, as in Albertslund where the DH company and municipality are within the same organization.

Most DH companies are unexperienced with customer involvement processes. Traditional DH projects are planning and implementation of pipes and production units, where no involvement of customers is required (Danish Ministry of Energy, Utilities, and Climate 2019).

Municipalities are used to conduct public participation processes and have often committed themselves to energy saving activities. Instead of a heat customer, the municipality sees a citizen that has various needs beside thermal comfort, at low cost and efforts. The municipalities have the possibility to connect customer initiatives with citizen initiatives such as urban renewal, why they probably have a more legitimate cause than DH companies.

When it comes to the implementations of radically new techniques, often associated with lowering supply temperatures in the DHW system, product developers have played a dominating role, compared to DH companies. Product developers are offered a dominating role through national funding schemes, where they receive funds to demonstrate their product. They are experienced with making their products work and are motivated to make them work. Where on the contrary, DH companies may be reluctant to these techniques because their organization is not prepared for it.

It may therefore be inappropriate to see DH companies as always being the key actors to drive technological change at the critical heat customers. It has been uncovered how DH companies access data and how they have the knowledge and tools to analyze data and identify critical heat customers.

It may therefore be a question of combining the skills and know-how of a wide range of actors to transition critical heat customers. Strategic energy planning is a voluntary energy planning concept that has been developed with the purpose of ensuring a better collaboration across sectors, policy levels, and actors. It puts the municipality in the center as the link between national goals and policies to the local implementation level (DEA 2013b).

National goals for energy savings are in place and policies for cost-efficient renovation strategies will come, as explained in section 1.5. Critical heat customer initiatives present itself as cost-efficient strategies but may require support from municipality and assistance from national level in terms of robust legionella guidelines and funding for demonstration projects. Consequently, further research could investigate the applicability of the strategic energy planning concept to promote cost-efficient critical heat customer initiatives.

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Appendix

Production efficiencies of heat supply system technologies

TABLE 22: CHANGES IN PRODUCTION EFFICIENCIES CAUSED FROM A CUSTOMER INITIATIVE

System	Production unit	Production efficiency	No customer initiative	Critical customer initiative
Condensing system (Natural gas)	Natural gas motor	Total efficiency	102%	103%
		Electricity	41%	41%
		Heat	61%	62%
	Natural gas boiler	Heat	103%	104%
CHP incineration system	Biomass CHP	Total efficiency	102%	103%
		Electricity	29%	29%
		Heat	73%	73%
	Incineration plant	Total efficiency	115%	115%
		Electricity	15%	16%
		Heat	100%	100%
HP system	HP	Heat	330%	348%
Condensing boiler system (wood)	Wood Chip boiler	Heat	110%	111%
Solar collector system	Solar collector	Heat (increase)	0%	2%
Temperature independent system	Transmission grid	Heat	100%	100%