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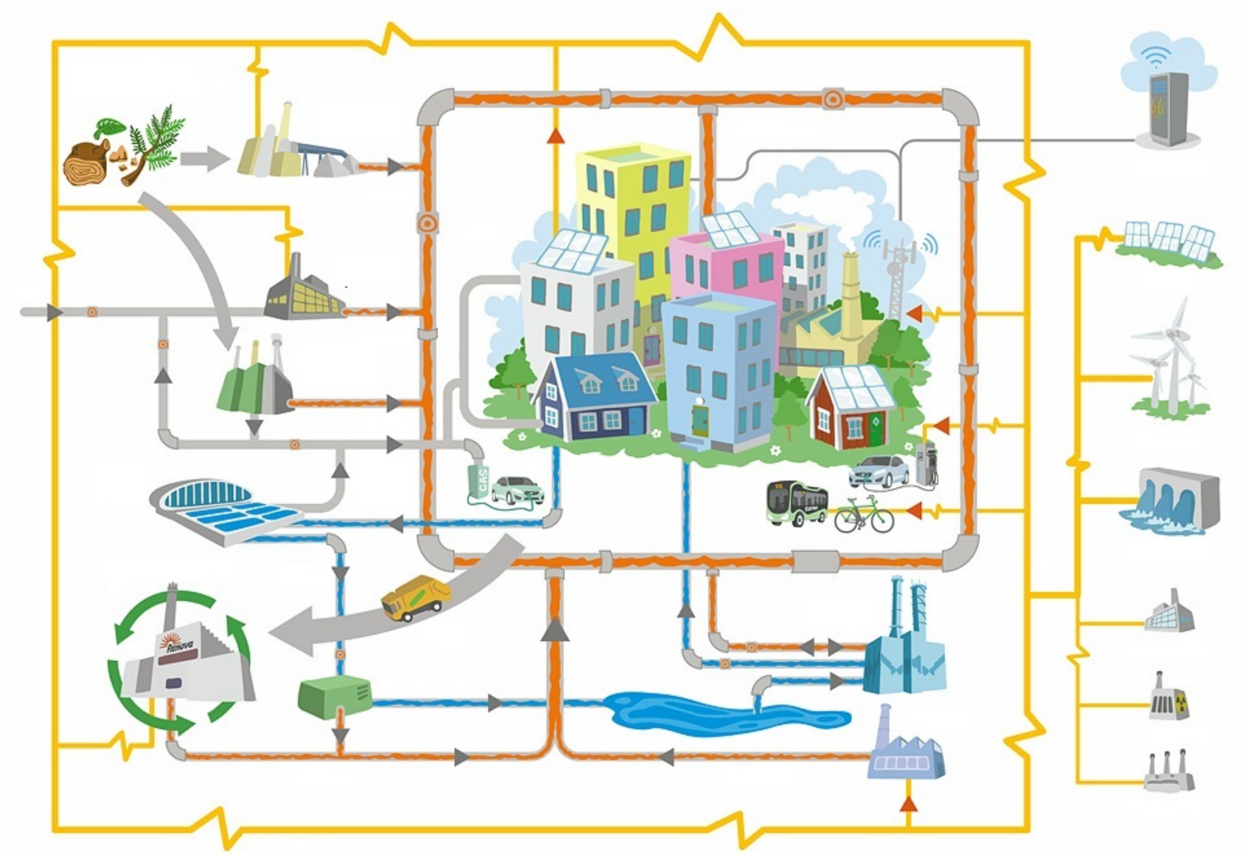

Fourth Generation District Heating - The prospects of Gothenburg

An investigation of the 4GDH concept and the motivations to implement it in Gothenburg

Master's thesis in Sustainable Energy Systems

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Gothenburg, Sweden 2020

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Cover: The Energy System of Gothenburg [1]

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Abstract

Fourth Generation District Heating (4GDH) enables the District Heating (DH) system to be an integrated part of a future sustainable energy system and has the potential to make new markets accessible where current DH technology is not a viable option. The combination of smaller heating demands from low-energy buildings and more renewable energy sources being utilized in the energy system requires current DH systems to evolve.

Previous generations has been identified by higher supply and return temperatures, compared to the suggested temperature levels of the fourth generation of (50/20) $°C$. One aim with 4GDH is to secure the role of DH in a future sustainable energy system. Cost and resource efficient heat production and distribution is essential to remain competitive as a DH company. Lower temperatures could enable reduced heat losses from the distribution system along with improved performance of several production technologies, namely in low-grade heat utilization.

This thesis investigates the 4GDH concept in a literature study followed by the impact of reducing the temperature levels in the DH system of Gothenburg. An estimation of the potential operating cost savings of the present system is preformed through a simulation study by calculating the annual variable operating cost for decreasing system temperature levels. The starting point is a system temperature of $(90/45)°C$, close to the annual average system temperature in Gothenburg 2017 of $(90/43)°C$. The supply and return temperature are reduced simultaneously by steps of 1 $°C$ to $(75/30)°C$. At present temperature levels the saving potential is found to be about 2.3 SEK/MWh and decreases linearly towards 1.7 SEK/MWh at $(75/30)°C$. The saving potential throughout the year is found to correlate with the outside temperature, being negligible off heating season. No claim is made that this represents the exact savings potential for the DH system of Gothenburg, however the general trend and the saving potential diversified throughout the year are of greater interest, supporting further analysis of the value in transitioning towards 4GDH in Gothenburg.

Technologies supporting the lower DH temperatures includes larger heat transferring surfaces in substations and internal heating systems along with individual substations (one per apartment). A third distribution pipe is also introduced, dedicated to recirculating supply water in times of low demand, thus enabling lower return temperatures. The third pipe is found to potentially increase the total distribution losses whilst mainly reducing the return temperature summertime when the operating cost of DH is low and the saving potential is small.

Using the results acquired earlier, the operating cost savings related to introducing a third pipe (not considering the investment or impact on distribution losses)

for a contemporary case and a future case (with a high penetration of low-energy buildings) is found to be 0.5 % and 8 % respectively.

The impact of reduced temperature differences in terms of flows and distribution losses for varying system temperatures is also investigated. A trade of in distribution losses, considering heat losses and pump-work, when transitioning towards lower temperatures and implicitly smaller temperature differences is found. In Gothenburg, along with similar mature DH systems, a smooth transition between present DH system design and 4GDH could be enabled by maintaining a high temperature in well established parts of the DH systems, whereas individual subsystems with strategic locations and well suited customers can incorporate at least parts of the 4GDH concept. In addition, this partial approach can lead to better utilization of present distribution systems and provide aid in congested parts of the system.

Contents

1
Introduction

District Heating (DH) is an important part of many energy systems of the northernmost northern hemisphere [2]. Besides being an efficient way of distributing heat in densely populated areas, DH also has the potential to do so consuming little primary energy, utilizing low-grade heat sources [2]. In an evolving energy system, with the global warming being an important driver, the potential of DH is good also in a future energy system [3]. However, with an also evolving building stock, with lower heating demands, as well as more fluctuating electricity prices, future district heating faces many challenges and competition from other ways of heating. Fourth Generation District Heating (4GDH) aims at securing the role of DH in a future sustainable energy system [4]. This masters thesis will describe the concept of 4GDH, why and how DH has to evolve and more specifically the prospects of 4GDH in Gothenburg. Specific features of the DH system of Gothenburg is the high availability of waste heat and expected population growth in a mature system.

The concept of 4GDH involves lowering the system temperatures (supply/return temperature) to increase the DH system performance, which should be supported by technology as well as an institutional and organizational framework, enabling a smart, more resource efficient energy system[4]. How these solutions can be implemented and the motivation to do so is well motivated on a principle level and the direction for the development of future DH is quite clear. However, how to actually implement the new concept in a current system and the value of doing so remains less certain. Previous work has investigated general ideas and smaller sub-systems, there even exist demonstration facilities proving the function of the concept small scale [5].

1.1 Aim

This thesis aims at describing the concept of 4GDH and its potential in a system like the one of Gothenburg. Besides the already established benefits to the overall energy system the motivation to implement 4GDH, or parts of it, in Gothenburg should also be investigated.

The following research questions has been defined to support the aim of this thesis:

- What are the preconditions for implementing 4GDH in Gothenburg?
- Can the reduced operating costs from lower system temperatures motivate a shift towards 4GDH i Gothenburg? Specifically the introduction of the third pipe and the smaller system temperature difference.

1.2 Scope

An initial literature study will provide a thorough description of the concept of 4GDH and the preconditions of Gothenburg. In particular the second research question will be answered further by modelling the DH system of Gothenburg, in 2017 based on recorded data. The model will be equipped with corresponding production facilities and optimized for minimal operating cost. By altering the system temperatures, efficiency and heat output will vary for the production facilities, affecting the total cost of operation. The temperature difference between the supply and return pipe will be held constant, implying no change in flow rates. The distribution heat losses however will be affected from the lower system temperatures. An optimization model is created in GAMS[1] for the two scenarios which is ran within a MATLAB interface for varying temperature levels. The result is constituted by the dispatch and total cost of operation for the varying system temperatures, also differentiating the cost components, which will illustrate the potential gains and serve as a tool when moving towards 4GDH.

The *savings potential* above, from now on referred to as Cost Reduction Gradient (CRG), is further used to evaluate some key concepts related to 4GDH. Those concepts are namely a third distribution pipe and reduced temperature differences in the DH system, in terms of heat losses and pump work.

This study is focused on the case of Gothenburg in particular and Sweden in general. Yet, the results should be relevant to similar system. No attempts to estimate any investment costs are made, however the magnitude of potential investments are mentioned on a principle level.

4GDH is the development of toady's DH system, thus most aspects of DH and the surrounding energy systems will be affected. This thesis however does not claim to cover all of the part affected by such a transition. A literature study will focus on the background to and concept of 4GDH, identifying some key aspects. The later parts of the thesis will, based on the findings of the literature study, try and answer some general questions which has arisen. Answering those questions, calculating exact figures are of little interest, instead overall trends are sought for. In terms of calculating the CRG, especially the distribution representation will be significantly simplified. Neither will the varying system temperatures be considered in terms of time and space throughout the DH system.

[1]"The General Algebraic Modeling System (GAMS) is a high-level modeling system for mathematical programming and optimization." [6]

2

Literature Study

This chapter will serve as a description of the background to and concept of 4GDH. The aim is for the reader to acquire a through understanding of the energy system with emphasis on DH, in particular the parts relevant for the introduction of 4GDH in Gothenburg.

2.1 Background to district heating

This section will provide some general background to DH and previous generations as well as the energy system as a whole, ending with a description of the DH system of Gothenburg.

2.1.1 A brief history of district heating

The fundamental idea of DH is to transfer heat from a source to a sink, satisfying a heating demand, within a district. Thus, surplus heat is the ideal source for DH and should by definition be utilized whenever accessible. DH also benefits from economy of scale and has historically been a way to deliver affordable heating from centralized facilities with relatively good fuel economy and low emissions, compared to individual solutions. [2]

Liquid water, or steam, has traditionally been, and still is, the media in which the heat is distributed. The temperature of the media has come to be associated with the technological advance level of the DH system and four technology generations can be identified based on that indicator. Simultaneously the DH system has improved, particularly in terms of resource efficiency. 4GDH is the forthcoming technology which this report will be centered around. The previous three generations and the drivers behind their development will briefly be described below.

Previous generations

The first district heating system developed in the USA during the 1880s, using low temperature steam ($< 200°C$) as a heat carrier, acquired from the already existing steam power plants. The technology was dominant in both USA and Europe until the 1930s and some steam systems still remains in for example New-York, Paris and Copenhagen. [2]

Until the 1970s the second generation DH was dominating, utilizing pressurized hot water above 100 °C, distributed in insulated steel pipes within culverts. Early Swedish DH systems was based on this technology and remains from the second generation can still be found in parts of many older systems, including the one of Gothenburg. [2]

The dominant technology today is the Third Generation of DH (3GDH) which utilizes lower supply temperatures, generally below 100°C, for both new installations and retrofittings. Besides moving towards lower temperatures less material intensive equipment and prefabricated, insulated steel pipes have become standard. More efficient heat transferring equipment has enabled lower system temperatures, although those units historically have been expensive and thus as small as possible, limiting the potential heat transfer. The pipes are commonly buried directly into the ground, no longer in culverts, either separated but parallel or within the same jacket (twin-pipe). They are composed of an inner carrier steel pipe, a layer of insulation and an outer jacket. The dimension of the pipes are standardized and they are delivered and assembled on site to form the distribution network. [2]

The development in Sweden

The first Swedish DH system emerged in 1948, in Karlstad, followed by the mayor Swedish cities, including Gothenburg, in the early 1950s. Coal was the dominant fuel at that time which was later replaced by oil as the DH systems of Sweden developed continuously. In the 1960s the *Million homes program*[1] was initiated leading to a burst in the coordinated DH development as well as improved air quality as the individual heating solutions was replaced by larger DH plants. [7]

DH in Sweden has undergone three significant reformations; The *diversification* following the oil crisis of the 1970s. Later the *electrification* of the heating sector due to less expensive electricity following the introduction of nuclear power in the 1980s. Most recently the *decarbonization* imposed by environmental awareness since the 1990s [7]. Today most DH systems remains diversified, relying heavily on recovered energy (51 %) but also renewable energy (40 %), dominated by biomass, only some fossil production remaining (7 %), the remaining parts originating mainly from peat and some nuclear electricity used in Heat Pumps (HP)[8].

2.1.2 The energy system

Besides DH, the energy system is comprised by other sub-systems such as; generation and distribution of electrical power, gas, District Cooling (DC), industry and transportation[2]. The system is expected to rely on Renewable Energy Sources (RES) to a significant degree, if not exclusively, moving forward. Such a development is mainly driven by the effects of today's excessive use of fossil fuels and the vast environmental impact and global warming that follows.

More RES also implies a shift from centralized generation to more distributed generation in local facilities. An increase in integration between the different parts of the energy system is also desirable, in order to achieve more flexible system. From a system perspective, high quality energy carriers should be avoided when intending to produce low-grade heat, such as DH. Generally, electricity and refined

[1] 1 million homes was built in Sweden from 1965 to 1974, mainly in urban and sub-urban areas.
[2] The system boundary could be extended further, including additional sub-systems.

fuels has both higher environmental, as well as economical, potential in other parts of the energy system than for heating applications, at least when using electricity directly. There are of course exceptions to this rule, for example when there are surplus electricity in the system, which is expected to happened more reoccurring in the future [9].

Furthermore, the competition for resources are expected to increase in the future, as the dependency of fossil fuels continuously decrease. Ultimately the issue involves land-use as consumption of biomass is expected to increase within the energy sector, also for transportation, displacing land previously dedicated for food production. Thus, effective resource utilization will be of even greater importance in a future system. Primary energy use defines the amount of primary resources required for delivering useful energy, for example heat or electricity. DH has the potential of very low primary energy consumption as low-grade heat can be utilized to a large extent, compared to electricity production that has higher requirements.

Heating and cooling

Half of the European energy consumption is used for heating and cooling, within the building and industry sector, 27 % for space heating. Two thirds of that energy originates from fossil fuels (42 % from natural gas), only 9 % from DH. [10]

The EU 2020 package [11] sets three key targets for the union to be accomplished in 2020; a 20 % cut in green-house gas emission (compared to 1990), 20 % of the energy from renewable sources and 20 % improved energy efficiency (compared to forecast levels). In 2030 the corresponding targets is 40, 27 and 27 % [12]. In 2050 EU has agreed to reduce its green-house gas emissions by 80-95 %, in order to comply with the $2°C$-target [13]. DH is identified as an cost-effective mean to reach those targets by a transition towards a fossil free energy system, due to its excellent potential to utilize low-grade heat sources [3].

The *Energy efficiency directive* [14] and the *Energy Performance of Buildings Directive*[15] (EPBD) constitutes EU's main legislative instruments to promote energy efficient buildings. With 75 % of the European buildings considered inefficient, with a renovation rate of some 1 % per year, there is a potential in significant energy savings from the building sector. A building from 1980 can reduce its energy consumption by half if renovated in accordance with the mentioned directives [16].

The Swedish environmental targets corresponds to a a 40 % cut in green-house gas emission, 50 % of the energy from renewable sources and 20 % reduced energy intensity, enabling the energy use to increase as long as its done more efficiently [17]. In 2045 Sweden's net green-house gas emissions should be zero, corresponding to reduced emissions within Sweden of 85 % (compared to 1990) [18].

2.1.3 District heating in Sweden

In 2016 57 TWh of DH was produced in Sweden, of which 46.3 TWh (81 %) was used for Space Heating (SH) and Domestic Hot Water (DHW) preparation within the residential and service sector. The remaining 7 and 12 % went to industry and distribution losses respectively [19]. About a third of the final energy use within the residential and service sector was covered by DH. As can be seen in table 2.1

more then half of the heating load of the residential and service sector was covered by DH, mainly for multi-family and non-residential buildings.

Table 2.1: Key figures of the Swedish building stock and DH systems [19].

Building type	Single-family	Multi-family	Non-residential	Total
DH [TWh]	5.5	24.0	16.8	46.3
Total [TWh]	32.1	26.6	21.9	80.5
DH share [%]	17	90	77	57
A_{Temp} [Mm^2]	302	196	176	674
E_{spec} [kWh/m^2]	106.3	135.7	124.4	119.6

District Heating in Gothenburg

The DH system of Gothenburg emerged in 1952, supplied with heat from a Combined Heat and Power (CHP) plant in Rosenlund [20]. Today the DH network ranges from Ale in the north to Askim in the south and Partile in the east, showed figure 2.1. It is operated by Göteborg Energi (GE) and consists of over 1350 km of pipework and is connected to neighbouring municipalities; Kungälv and Mölndal, supplying heat to 90 % of the multi-family houses, some 12 000 single-family houses as well as numerous industries, commercial activities and offices [1].

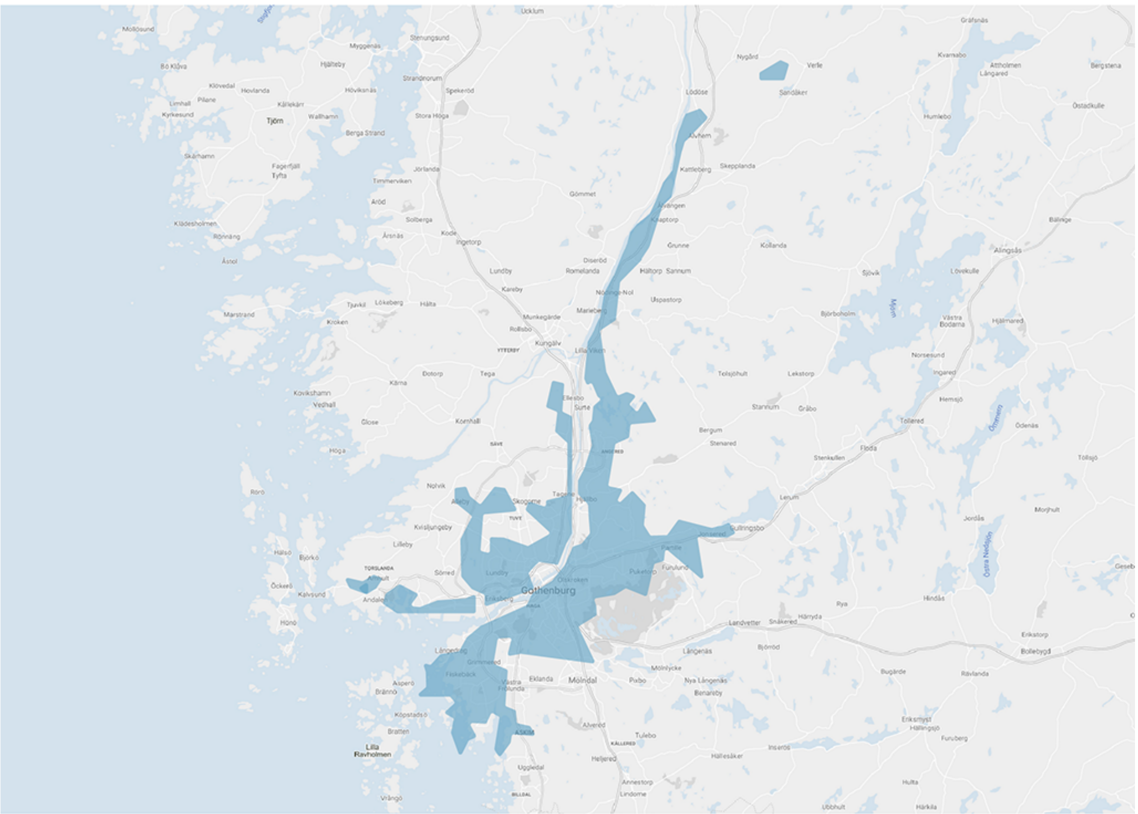


Figure 2.1: The coverage of the DH system of Gothenburg [21].

The city faces an expansive phase and the population is expected to increase with some 150 000 inhabitants by 2035, corresponding to a population growth of almost 30 % compared to today, mainly densified than growing outwards [22]. Although densification is beneficial for a DH system[2] this development still imposes a major challenge in satisfying a new demand. The energy demand though is not expected to increase as significant, due to efficiency measurements being taken in parallel[23]. By 2030 the DH production of Gothenburg should also become fossil free, i.e. a normal production comprised only of renewable or recovered energy [24].

Today, the vast majority of heat is delivered to the DH system of Gothenburg from recovered sources, about a fourth from waste incineration and a third from industry surplus. There are also two major CHP plants in the system of Gothenburg, one fuel by wood chips and one fueled by natural gas. An industrial HP-facility, heated by processed sewage water, supplies Gothenburg with most part of its remaining demand, besides some central peak production as well as throughout the system from numerous small Heat Only Boilers (HOB). Furthermore an accumulator tank is under construction to be utilized as short-term storage. GE also operates the DC system of Gothenburg, interconnected with the DH system as absorption HPs, driven by waste heat, are used in combination with free cooling from the river and compressor driven cooling machines.

2.2 Background to 4GDH

Much like previous DH generations the driving force towards 4GDH originates from increasing efficiency requirements throughout the energy system. A reduced need for space heating in the future building stock in combination with the transition towards a more resource efficient and eventually fossil free energy system, incorporating more Renewable Energy Sources (RES), is the reason for this demand. By reducing the temperature levels of the DH system, i.e the temperature of the supply and return flow, distributions losses could be reduced. Lower temperatures also allows for higher efficiency in heat generation processes as well as enables new, low-temperature, heat production to be feasible in a large scale setting, such as utilization of solar panels, geothermal heat and low-temperature waste heat from industries or other activities. Further system integration and increased storage opportunities is also a part of the transition towards 4GDH [4].

2.2.1 Low-Energy Buildings

Buildings are the single largest energy consumer in Europe, consuming 40% of the final energy[15], also in Sweden [19]. The future building stock however will require significantly less space heating as building technology improves. It is expected that future new buildings will have a specific heat demand of $< 25\ kWh/m^2, year$ [4], comparable to today's average demand of $100 - 150\ kWh/m^2, year$, in accordance with figure 2.2. Long term this will result in lower heat density in the DH system, as the building stocks cumulative heat demand decreases. Also the load profile is expected to change, with lower space heating demands, thus more DHW dominated.

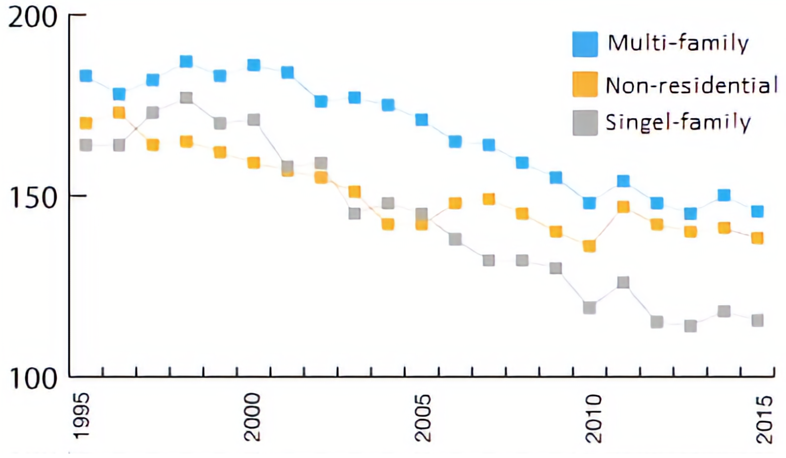


Figure 2.2: Specific heat consumption $[kWh/m^2, year]$ for space hating and DHW preparation of the total Swedish building stock historically [25].

The specific energy used associated with DHW preparation can be estimated to be 20 kWh/m^2 for single-family houses and 25 kWh/m^2 for multi-family houses [26]. Due to the varying kinds of non-residential premises it is difficult to estimate the size of the individual demands, however for an office building the DHW usage can be expected to be small whilst the demand for space cooling could dominate.

Swedish building code regulates the energy performance of new buildings. In table 2.2 the maximum specific energy consumption[3] of a new building in Gothenburg, utilizing DH is expressed (deducting on-site renewable energy utilization, for example from solar energy or ambient heat for HPs), according to BBR 24 [27]. These restrictions however will be sharpened shortly with the introduction of Nearly Zero Energy Buildings (NZEB[4]).

Table 2.2: Specific energy demand for new buildings in Gothenburg, utilizing DH.

Building type	Single-family	Multi-family	Non-residential
Specific Energy Consumption	80 kWh/m^2	75 kWh/m^2	65 kWh/m^2

Nearly Zero Energy Buildings

As of 2021 all new buildings within the EU should be NZEBs (as of 2019 for publicly owned and operated buildings), in accordance with the Energy Performance of Buildings Directive (EPBD)[15]. The EPBD states that a "*'nearly zero-energy building' means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby;*". Its further stated that buildings undergoing major renovations, corresponding to 25 % of the buildings surface area or the value of the building envelope and its technical systems,

[3]Energy used for space heating and cooling, DHW preparation and property energy per tempered area.

[4]NNE-buildings - *Nära Noll Energi byggnader* in Swedish.

relative the property value (excluding the value of the land on which it stands on), should comply with the same directive.

"The aim of the proposal is to promote energy efficiency in buildings and to support cost-effective building renovation with a view to the long term goal of decarbonizing the highly inefficient existing European building stock. This will also be a major contribution to reaching the EU's 2020 and 2030 energy efficiency targets."[28]

The EU energy efficiency directive [14] states that the primary energy use in 2020 should be 20 % less than the prognosis made in 2007 of the same year, buildings being identified as an inefficient sector with potential to improve. It further emphasizes the importance of individual metering, stating: "*Member States shall ensure that, in so far as it is technically possible, financially reasonable and proportionate in relation to the potential energy savings, final customers for electricity, natural gas, district heating, district cooling and domestic hot water are provided with competitively priced individual meters that accurately reflect the final customer's actual energy consumption and that provide information on actual time of use.*"

It is up to each member state to interpret and enforce the EPBD, in Sweden *Energimyndigheten*[5] and *Boverket*[6] are responsible of interpreting the directive and set a cost-effective level for Sweden. As of July 2017 the Swedish building code was updated to BBR 25, the main difference being the introduction of an energy performance number, replacing the specific energy consumption, in accordance with the EPBD. The energy performance number also considers the origin of the energy used in the building by introducing a primary energy factor for each energy carrier (as of now 1.6 for electricity and 1.0 for DH), expanding the system boundary. This imposes no major changes in the energy performance of the new buildings today (BBR 24 also differentiated electricity from DH), however before the EPBD will actually be enforced the primary energy factors will be further refined and the limitations sharpened.

Critique has been put froward by the DH community regarding the new (and old) building code saying that it is not technology neutral neither incentives efficient buildings as it only considers the bought energy, favouring on-site solutions (such as HPs). The introduction of a primary energy factor could indeed help level the playing field in terms of technology neutrality but it could also worsen the phenomenon due to the complexity in setting a representative primary energy factor for the different energy carriers. However as also maximum installed capacity for electrical heating, the U-value of the building shell and the air leakage are also limited it should be possible to ensure efficient buildings whilst honoring the EPBD. [29]

[5] The Swedish Energy Agency

[6] The Swedish National Board of Housing, Building and Planning

2.2.2 Temperature in DH systems

In 2013 the Best Available Technology (BAT) of an ideal DH sub-station, consequently the Swedish DH system, could support temperatures as low as (69/34) °C [2], possibly even return temperatures as low as 29-30 °C [30], on yearly basis. The time averaged temperatures of Gothenburg in 2017 was (90/43)°C, which corresponds roughly to a typical Swedish system (84/47)°C, far from target temperatures for 4GDH of (50/20)°C [4]. The temperature in the system of Gothenburg will be returned to later in this section and is depicted in figure 2.5. In figure 2.3 the supply and return temperatures of most Swedish DH systems is depicted, including the BAT of 2013.

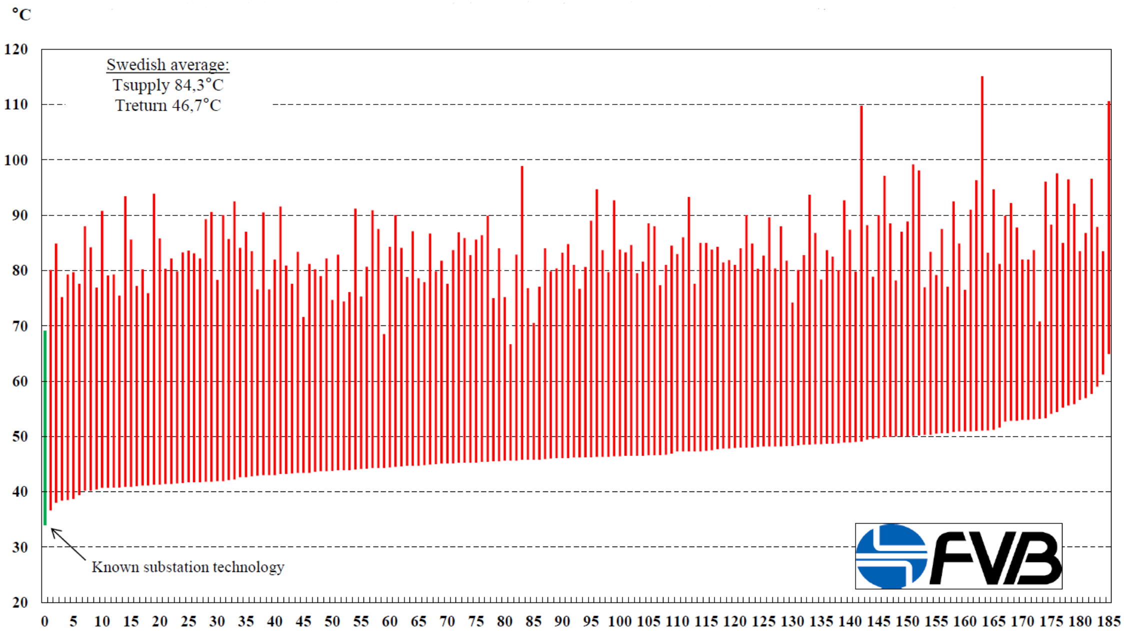


Figure 2.3: Supply and return temperature of 185 Swedish DH systems [31].

Significant variation between DH systems can be observed, for various reasons, two of which is costumer requirements and network limitations. In a congested network increasing the supply temperature, thus the temperature difference, could be a way to increase the delivered heat without increasing the flow. In fact, by increasing the supply temperature to a substation the corresponding return temperature could actually be cooler. As the temperature difference is the driving force of the heat transfer a higher temperature on the warm side enables a lower temperature on the cool side, nothing else changed. However since the flow on the primary side of such a HEX implicitly would be lowered the heat transfer coefficient of the HEX would also be somewhat lowered restricting the transfer slightly. In a system benefited less from lowered supply temperatures than return temperatures, alternatively having a congested DH network, this phenomena might very well be utilized.

Yet, most system fails to reach these lower return temperatures due to four main reasons stated below[2].

- Intentional or unintentional bypass between the supply and return flow.
- Too low supply temperatures, enforcing higher flows and indirect bypass.
- Faults in the customers heating system.
- Faults in the sub-stations.

These issues originates from the 3GDH and would be addressed with the introduction of 4GDH, however continuous efforts to reduce such flaws will still be necessary in a future system. GE initiated a project to reduce the system temperatures in 1995, which is ongoing since, showing successful results in 2004 with lowered overall return temperatures of some 5 °C [32].

As the heat delivery is dictated by the mass flow and temperature difference, rather than actual temperatures, the main benefit of reducing the return temperature is actually generally the possibility to reduce the supply temperature for the same mass flow[2], according to equation 2.1 below, reducing distribution losses and increasing process efficiency. The mass flow consequently dictates the pump work required in the distribution system, further discussed in section 2.6.3, which will have to be taken in consideration when optimizing the system.

$$\dot{Q} = \dot{V} \cdot \rho \cdot c_p \cdot \Big(T_s - T_r\Big) = \dot{m} \cdot c_p \cdot \Delta T \tag{2.1}$$

With $\dot{Q}$ corresponding to the heat delivered per second (heating power), $\dot{V}$ the volumetric flow, ρ and c_p the density and heat capacity of water respectively (minor temperature dependency neglected in this report) and finally T_s and T_r the supply and return temperature.

Cost reduction gradient

The short-term system savings related to reducing the temperature levels simplistically corresponds to increased uptake of low-grade heat, displacing the use of more expensive heat sources, as well as increased efficiency in HPs and CHP plants. To some extent reduced distribution losses contribute to similar savings. Thus, by lowering the temperatures in a system the variable costs of a DH company can be decreased. Calculations of the CRG has been preformed by FVB Sweden for 42 Swedish DH system, including GE, with the results observable in figure 2.4.

The CRG is calculated as the cost savings related to reducing the system temperature, with the unit SEK/MWh,°C. The temperature difference between the supply and return flow has been held constant and the results averaged over a 5 °C temperature reduction to limit the effect of inconsistent model behaviour.

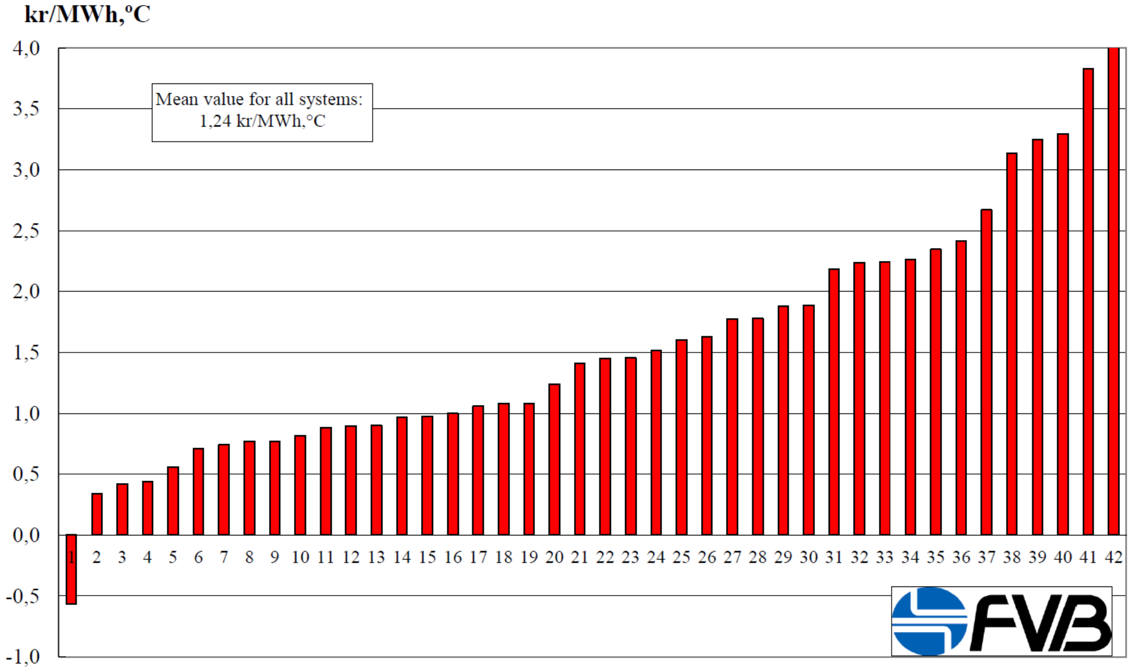


Figure 2.4: Cost reduction gradient for 42 Swedish DH systems [31].

As depicted in figure 2.4 the CRG of the different systems varies greatly, with an energy weighted mean of 1.24 SEK/MWh,°C. Parts of the variations can be explained by varying age of the data (the calculations made for GE being from 2006) assuming highly influenced by fuel and electricity prices of that time. Another factor is the system size and composition, for example, the one system with a negative CRG is dominated by waste incineration, thus when lowering the temperatures and increasing the efficiency of the process less waste is incinerated which actually comes at a negative cost reduction. For systems on the right hand side of the figure the production mix is likely to include utilities affected by the lowered temperatures, displacing some expensive production for several hours. GE being on the left hand side, among the less affected systems with a CRG of approximately 0.75 SEK/MWh,°C is likely to have an overall cheap production and/or not being very affected by the reduced temperatures. In the case of Gothenburg the earlier explanation makes the most sense, considering the good access to waste heat throughout the year and most marginal production originating from inexpensive CHP or HPs.

The previously mentioned project conducted at GE [32], lowering the return temperature, estimated the CRG to approximately 1 SEK/MWh,°C. More recent work preformed at GE in 2014 found the CRG to be closer to 2 SEK/MWh,°C [33], which was recently adjusted to above 2 SEK/MWh,°C. In that study the reduced distribution losses was approximated to correspond to roughly 0,5 SEK/MWh,°C and the remaining savings originating from improved performance and displaced peak production. Thus, with a roughly estimated yearly production of 4 TWh and savings corresponding to 2 SEK/MWh,°C, total savings of approximately 8 MSEK could be achieved yearly from lowering the system temperature 1 °C in Gothenburg.

Its tempting to allocate the saving from reducing the system to an individual customer, reducing its temperature accordingly, yet such a temperature reduction will quickly be diluted and have a marginal impact on the total system why a direct transfer of those cost to the customer might not be representative. Yet many DH companies wants to provide incentives for their costumers to reduce their temperature requirements, due to the positive system impact, by charging or rewarding the costumer based on flow or temperatures that can be achieved [30].

Temperature requirements and implications

The DH customer is guaranteed a supply temperature throughout the year, depending on outside temperature. For Gothenburg that temperature is specified according to the control curve of figure 2.5. The guaranteed temperature enables the costumers internal heating systems to function properly at high loads, i.e low outside temperatures. The benchmark temperature is set by GE to ensure sufficient supply temperature, throughout the system, especially in the periphery parts. The temperature increase at high outside temperatures is to ensure the function of the absorption cooling machines throughout the DC system, driven by waste heat distributed by the DH system. Along with the at times congested distribution system this is the main reason why GE has a relatively high supply temperature compared to other Swedish systems in figure 2.3.

Furthermore, due to the cubical relationship between pump work and mass flow, according to equation 3.7 it's not possible to achieve a sufficient regulation of the DH system by only altering the flow. In the congested DH system of Gothenburg the system operator is thus forced to also increase the temperature difference in order to archive sufficient transmission capacity during hours with high loads, thus the temperature difference of the supply and return flow is not constant throughout the year. This is another reason for the high supply temperatures at high loads.

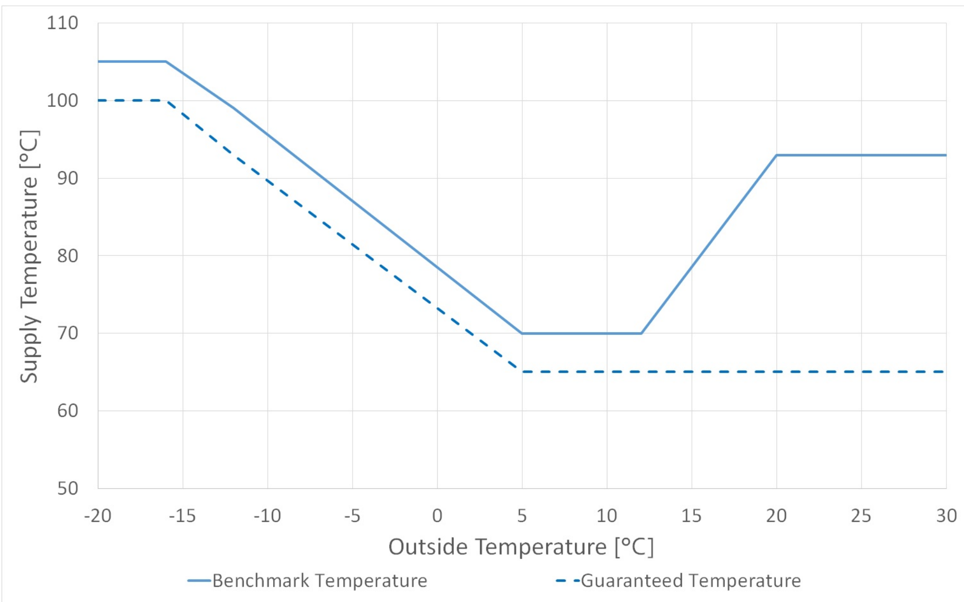


Figure 2.5: Control curve for the DH system of Gothenburg, depicting benchmark and delivered supply temperatures based on outside temperature.

Some non-residential and industrial costumers might require particularly high supply temperatures, however the vast majority of the DH costumers is residential or commercial whose supply temperature requirements is set by their Space Heating (SH) and DHW preparation systems.

Swedish building code restricts the DHW temperature to maximum 60 $°C$ due to the risk of scalding, this is also the lower limit for accumulated DHW in order to avoid the growth of Legionella bacteria, thriving at temperatures below 46 $°C$. The lower temperature limit in any part of the DHW system (at the tap or when using Hot Water Circulation (HWC)) is 50 $°C$, also to avoid Legionella growth. This implies somewhat higher temperature requirements of around 55 $°C$ for the DHW leaving the DH substation. [34]

Since 1982 Swedish building regulations restrict the supply temperature of radiator systems to maximum 55-60 °C, prior to that radiator temperatures of 80/60 °C was common [2]. Today most buildings use low temperature systems of mostly (60/45), (60/40) or (55/45)°C [35].

A survey conducted in collaboration between GE and Chalmers in 2016, investigating 109 radiator systems through Gothenburg found a maximum supply temperature on the secondary side of 81 °C at DUT, with a mean of 64 °C for all the systems. At higher outside temperatures lower supply temperatures was required and for an outside temperature of 5 °C all investigated systems operated with supply temperatures of 55 °C or less. Most of the investigated buildings were built between 1950-1980. [36]

It's common for radiator systems and substations to be somewhat over dimensioned, either by default or after retrofitting of the building shell [36]. It seems to be practise to install somewhat over dimensioned radiators, either due to intentional safety margins or having to choose a too big radiator due to the step-wise design process when dimensioning radiator systems [35]. As radiators come in fixed sizes its usually a margin already build in, also assuming some additional safety margin in terms of radiator size and a value in having a uniform size of radiators in a building its not to far fetched to assume a significant potential to reduce the primary supply temperature in terms of satisfying the demand from even older buildings.

2.3 Definition of 4GDH

The concept of 4GDH was introduced some ten years ago [5] by Henrik Lund and Sven Werner, whom have been forerunners within the field [37]. They have, together with co-authors, collaborated on a report where the concept and implications of 4GDH is defined [4]. Their definition, together with five crucial challenges for the future DH system, which implicitly should be solved by transitioning to 4GDH, is presented below.

"The 4th generation District Heating (4GDH) system is consequently defined as a coherent technological and institutional concept, which by means of smart thermal grids assist the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. The concept involves the development of an institutional and organizational framework to facilitate suitable cost and motivation structures."

Challenges for future DH systems:

1. Ability to supply low-temperature district heating for space heating and domestic hot water to existing buildings, energy-renovated existing buildings and new low-energy buildings.
2. Ability to distribute heat in networks with low grid losses.
3. Ability to recycle heat from low-temperature sources and integrate renewable heat sources such as solar and geothermal heat.
4. Ability to be an integrated part of smart energy systems (i.e. integrated smart electricity, gas, fluid and thermal grids) including being an integrated part of 4th Generation District Cooling systems.
5. Ability to ensure suitable planning, cost and motivation structures in relation to the operation as well as to strategic investments related to the transformation into future sustainable energy systems.

In combination with reduced temperature levels three additional system improvements are suggested to cope with the new requirements of 4GDH [38]. These technical changes will tackle a number of faults related to the current system and some which are necessary to support the lowered temperature level, expressed below and depicted in figure 2.6, where also improved Information and Communications Technology (ICT) is emphasized.

- A tree-pipe (3P) system - Introducing a third distribution pipe supporting a second, re-circulating, return flow.
- Introducing individual, through-flow, Heat Exchangers (HEX) in substations.
- Longer thermal lengths in substations and SH systems.

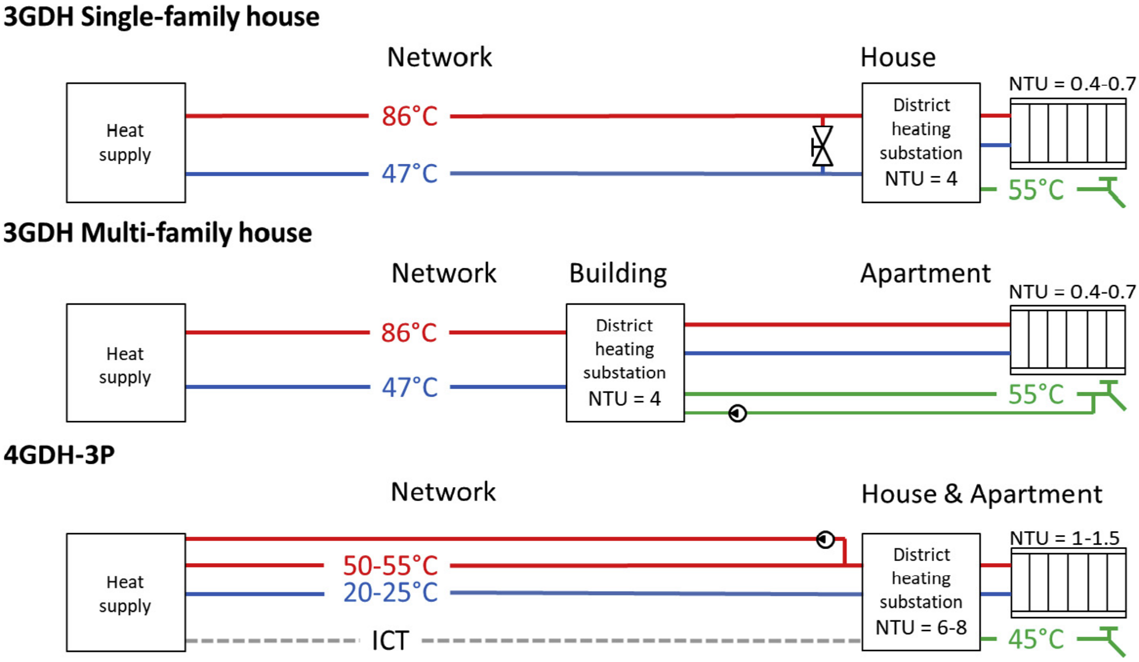


Figure 2.6: Principal figure depicting the 4GDH-3P concept, compared to the conventional 3GDH setup for single- and multi-family houses. The new concept includes lower system temperatures, a third distribution pipe, longer thermal lengths, individual through-flow HEXs and ICT [39].

Low Temperature District Heating (LTDH) is identified as a part of the 4GDH concept, with target temperatures of $(50/20)°C$ as yearly average [4]. Danish guidelines defines LTDH systems as able to operate with supply temperatures of 50-70 $°C$ [40]. At such low supply temperatures as 50 $°C$, compiling with Swedish building regulations becomes impossible (without using a complementing heat source) since DHW must be heated to above 50 $°C$.

LTDH potentially offers reduced storage and distribution losses as well as benefits to the production processes in terms of increased output and resource efficiency.

A third distribution pipe (3P) would be introduced to reduce the undesirable by-pass in substations, meant to ensure sufficient supply temperatures in times of small demand and poor flows, much like the HWC in todays multi-family buildings. At those times the distribution losses might actually cause the supply temperature to drop significantly, affecting the costumer in terms of inadequate deliveries. This is not as much of a problem for the major distribution pipes but rather the smaller service pipes closer to the customer where not only the flow will fluctuate more, where also the losses relative the size of the pipe is larger. A third pipe would thus be added to ensure sufficient flow to compensate for distribution loses and maintain the desired temperature for deliveries, without enforced by-pass, polluting the return-flow. [39]

Individual substations could help deal with one major issue when transitioning towards 4GDH and LTDH, which is how to deal with the risk of Legionella. Today circulation and accumulation of DHW is common in multi-family buildings, in order to ensure quick access to hot tap water. One way to reduce the risk of Legionella would be to restrict the amount of DHW between the substation and the tap, as the volume of the water is strictly correlated to the growth of the bacteria. In order to active this smaller volumes though, current setup of DHW re-circulation and local storage is unfeasible, instead individual through-flow HEX are suggested, also in multi-family dwellings. The introduction of individual substations would also comply with the EU energy efficiency directive in terms of individual metering, as mentioned in section 2.2.1.

Longer thermal lengths, expressed in Number of Transfer Units (NTU)[7], is another suggestion for 4GDH. This is a necessity in a LTDH system when the temperature differences is reduced, both in the substation and for the SH equipment, such as radiators. Thus there is an increased investment associated with lowering the temperature as the heating equipment must comply with the lower temperature levels.

However this might happened either way as future buildings are expected to utilize more underfloor heating[8] and heating by ventilation (especially as future buildings will allow less air leakage thus requiring forced ventilation rather than natural ventilation). Such heating systems can operate closer to room temperature, air preheaters even lower as the outside air is heated. With lower temperature differences comes greater comfort even at lower temperatures, although at the expense of less compact units due to higher NTU. [41]

2.4 Smart Energy System

From an energy system perspective, increased integration of subsystems is a crucial aspect moving towards a sustainable energy system. A comprehensive description of a smart (100 % renewable) energy system and its interconnections can be found in [42], the cover page of this thesis is depicting the energy system of Gothenburg.

Due to the way DH is already integrated in the surrounding energy system it can be concluded, depending on system boundary, that for example increased uptake of excess heat is likely to affect electricity generation, biomass consumption and electricity consumption in DH systems [43].

2.4.1 Power to heat

The concept includes strategic use of electrical power for heating, either using a HP or an electrical heater, preferably when the electricity price is low i.e. when there

[7]NTU is an index of the heat transfer potential, relatable to the UA-value.

[8]Contemporary buildings, with high performing windows, no longer require radiators to avoid drought [41]. A window with a thermal conductivity of 1.2 W$/m^2, K$ the most will work well in combination with underfloor heating being heated to only 22-24 $°C$ to achieve a room temperature of 20 $°C$ [50].

is surplus electricity in the system due to low demand or excess generation. The opposite effect can be achieved utilizing CHP, preferably with a variable power to heat ratio (α-value), where power and heat can be interchanged to a certain degree, displacing one another [9].

Although GE posses their own electric power generation they will be a price taker on the electricity market of Nord Pool[9].

2.4.2 Flexibility and synergies

Interconnecting the DH and DC system, heat can be used for cooling using absorption HPs. DH and DC system could also be combined to, with or without upgrading, exchange hot and cold flows within a system.

Project like *Ectogrid* strives for this on a small scale, within a closed system, utelizing several temperature levels to ensure thermodynaically optimized operation and high resource efficiency [45].

Further flexibility is added to a system when allowing trade, strongly beneficial for the power market with its high transmission capacity to surrounding systems, not so much for DH systems, generally being isolated in a local setting. The DH system of Gothenburg though is connected to Mölndal in the south where both systems benefits from trade. The connections in the north to Kungälv, where a HEX is used, is less utilized. When transitioning to 4GDH different temperatures in surrounding systems might be an issue, only allowing for trade in one direction or not at all.

Furthermore, flexible loads and Demand Side Management (DSM) is also expected to be a crucial part of a future smart energy system, particularly for the power system but also useful for DH. Research has been conducted in co-operation between GE and Chalmers, finding a reduction in peak demand of 25 % possible if 20 % of the connected DH costumers in Gothenburg allows for heat storage in their buildings thermal mass, i.e. DSM [46].

2.4.3 Storage

Energy storage is expected to be a crucial feature of the future energy system, due to the fluctuating nature of RES such as wind and solar, becoming more common in the energy system. This is as the power system, compared the DH system, incorporates little inertia and electricity thus has to consumed instantaneously. Electrical energy storage, for example in batteries, tends to come at a high cost. By instead utilize the interconnections between the electricity and heating sector, through power to heat and CHP, thermal storage can fulfill the same purpose over time.

Storing hot water can be done in different scales, either for daily or seasonal variations. One unit of thermal energy storage comes at cost in the order of approximately 100 times lower than a corresponding electricity storage and storing energy chemically is again 100 times less expensive then storing heat[47]. Accumulator tanks are commonly used for covering daily variations and can be used to remove load peaks from the system, by shifting the load, thus smoothing the production.

[9] The interconnected Nordic electricity market[44]

Energy storage in building has also been showed to provide good opportunities for short term storage, as mentioned above [46]. Seasonal variations corresponds to increased heating demand during winter which can be partially covered by storing heat summertime in large volumes, for example in caverns or boreholes [48].

2.4.4 Smart Thermal Grid

Much like the smart energy system a smart thermal grid is empowered by digitization and ICT, enabling a smarter system operation.

In contrast to the smart electrical grid, mainly challenged by the integration of fluctuating RES, the main challenge for the smart thermal grid is to connect low-energy buildings with low-temperature heat sources efficiently. Both systems favours small-scale distributed conversation, in opposite to today's mainly centralized heat and power systems, with potential of *prosumers* [4].

2.5 Production

When lowering the DH temperatures, namely the supply and return temperatures, improved performance can be acquired from most production utilities. The general assumption is that lower DH temperatures enables bigger temperature differences in HEXs throughout the system, improving the characteristics of as well as the potential heat transfer. Consequently more heat can be made useful from the same process at lower temperatures, previously inaccessible due to little or no temperature difference. It should be noted that the supply temperature might have same same effect if too high, limiting the available heat, which has been experienced by GE when trading with its waste heat suppliers, as confirmed during discussions with Preem and returned to later in this report [70].

To some degree most processes are affected by both the supply and return temperature, however certain processes are more sensitive to one or the other. These are categorized below and discussed for the affected production facilities of GE later in this report.

Processes affected by lowered supply temperature:

CHP By lowered supply temperature the pressure in the turbine condenser of a back-pressure CHP facility could consequently be lowered. This would enable increased electricity output, at the expense of reduced heat delivers, as electricity is generally more valuable then heat this is often desirable.

HP's The COP of a HP relates to the temperature lift and consequently the compressor work relative the heat uptake. As a lower supply temperature would enable a smaller temperature lift the performance of the HP would be improved.

Low-grade heat Heat sources such as solar, geothermal or industrial/commercial surplus available at low temperatures would be made accessible and/or more efficient to take up by lowered supply temperatures.

Processes affected by lowered return temperature:

Flue Gas Condensation/economizers Processes utilizing economizers or Flue Gas Condensation (FGC), affected by the return temperature would be benefited as the stack temperature of the flue cases could be reduced.
In a conventional boiler the DH (return) flow enters the last stage of the plant. Thus, the lowest temperature of the flue gases is set by the DH return temperature. Various restrictions applies for different plants, depending on fuel, flue gas cleaning and operation time, some flue gases though could be further cooled down.
Dry fuels such as coal and wood pellets wont benefit very largely from FGC whilst moist fuels such as wood chips or municipal waste would, enabling a large latent heat uptake at low temperatures ($< 70\ °C$). Also the flue gases from burning dry natural (and bio) gas has a high moisture content as methane reacts with oxygen according to $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$, compared to the reaction when for example burning coal ($C + O_2 \rightarrow CO_2$) [2].

Low-grade heat Besides the sources mentioned the heat uptake from most other low-grade heat sources would also be improved at lower return temperatures as the temperature difference over which the heat is acquired would increase.

It should also be mentioned that the potential to store heat at little losses is improved at lower supply (and return) temperatures. However this could also be achieved by improved insulation. Furthermore a low-temperature storage would require a larger volume to store the same amount of heat due to the smaller temperature difference.

2.6 Distribution and consumption

The interface between the distribution system and the costumer is the DH substation, as of 4GDH will further interconnect the two parts. The primary side of the substation refers to the DH distribution system whilst the secondary side refers to the costumers Space Heating (SH) and DHW system.

2.6.1 The DH substation

The DH substation is essentially two (or more) HEXs, regulated to transfer heat from the DH system at the primary side to the costumers secondary side including SH and DHW preparation. Two connection principles are the most common in Sweden; the *parallel connection* and the *2-stage connection*, the later being somewhat more complex but also enabling lower return temperatures [49][2].

With a substation connected in parallel the SH system has one dedicated HEX and the DHW system another. As the DHW system enables lower return temperatures due to the cool incoming fresh water. Consequently, when mixing the two flow an intermediate temperature will correspond to the primary side return temperature.

The 2-stage connection instead aims at maximizing the low temperature heat exchange of the DHW system, preheating the freshwater as the return water from the SH system is cooled further, finally ensuring sufficient DHW temperature using a third (second stage) HEX dedicated to the DHW only.

Although the cascade connection is the ideally optimal principle, due to its ability to ensure the lowest combined return temperature, this is only true when there is DHW demand. For applications with little or very infrequent DHW demand, or when using HWC, this connection principle tends to be a poor choice as its also more expensive. In a 4GDH system, with mainly individual substations, the parallel connection is likely to be most practical.

Considering DHW storage and HWC it can obviously be times with little tap water demand, particularly for single-family house and non-residential premises when ensuring a low return temperature becomes challenging due to the high temperature of the the storage tank or the returning HWC. In such cases the connection principle is of less importance and maintaining low return temperatures is likely to be challenging, particularly during summertime with little SH demand.

2.6.2 The 4GDH substation

The main difference for the 4GDH substation is the suggestion to transition towards individual substations, in order to reduce DHW volume between the substation and the tap. The German code of practice (W551)[51], originally intended to ensuring short waiting times for DHW, does not restrict the minimum DHW temperature for systems with less then 3 liters between the substation and the tap, which would enable primary supply temperatures of 50 $°C$ in line with the 4GDH target. This practice is used also in Danish LTDH systems [5], enabling pipe lengths of up to 38 m to the tap for DN10 pipes.

There are still comfort requirements for DHW and temperatures much lower than some 45 $°C$ might not be desirable.

Individual substation though is already common in single-family houses (many Swedish systems is likely to struggle ensuring 50 $°C$ at the tap at all times [52]).

One of the main benefits with DH as a heat carrier is the simplicity and compactness, a conventional substation of a single-family house does not require more space than a bathroom cabinet [53]. Although a 4GDH substation would operate at lower temperature differences, with higher NTU, thus being somewhat less compact.

However, when introducing individual substation the interface between the costumer and the DH company is transitioned further into the building. Today its common for the DH substation to be positioned in a technical room from where the heat is further distributed to the inhabitants of the building by the property owner. By transitioning to individual substations that border is shifted. This does not only imposes a question of ownership and responsibility of operation, it also requires the DH provider to be more integrated in the early design process of the building.

One way to approach the target temperatures of 4GDH would be to remove another HEX (causing a minimum temperature difference), the one used for SH system, having DH water going directly through the radiators. This type of directly connected heating systems is in fact not that uncommon, for example in Denmark. Traditionally though this has not been very utilized in Sweden, due to the risk of damage caused by leakage and the increased pressures. Particularly in Gothenburg with its varying topography (compared to most of Denmark) the pressures throughout the distribution system would vary greatly, only to cover for the elevation. In a smaller subsystem though direct connections might actually be feasible although not necessarily desirable [2]. Yet, with improved metering detecting and restricting leakages is likely to become easier, might enable direct SH connection also in some Swedish systems.

As the suggested individual substations are through-flow HEX, with no storage potential each HEX will have to be dimensioned to satisfy the instantaneous demand from DHW. However storage close to the costumer is still of interest as it has been shown to enable reduced dimensions of also the service pipes, effectively reducing the distribution losses [2], for that reason storage on the primary side are suggested [54]. Another way to limit the dimension of service pipes and sub-stations is by utilizing energy storage potential of buildings, reducing the SH load when there is a great demand for DHW [46].

Legionella

The Legionella bacteria occurs naturally in fresh water, however generally in low concentrations, growing at temperatures between 20-45$°C$ thriving at 38 $°C$. Its not dangerous to drink but imposes a risk as its spread by water mists. The bacteria causes pneumonia-like symptoms, potentially lethal if not treated properly, tough there are very few victims in Sweden. In properly designed tap water systems (hot and cold) both short waiting times for desired water temperatures and minimized risk of Legionella growth can be ensured by small, insulated, pipes, utilizing HWC in large systems. [55]

As the German code of practice (W551) is not applicable in Sweden its thus not feasible to reach the desired 4GDH supply temperature of 50 $°C$ without a supplementary heat source, the alternative is obviously maintaining a higher supply temperature. The combination of time and temperature that limits the growth and eventually kills the Legionella bacteria, (99 % in less then 5 hours at 50 $°C$ or only a few minutes at 60 $°C$). Other options to limit Legionella growth is by treatments such as UV-light, filters or chemicals which is done in for example some pubic baths, although this might not be viable for small installations it could very well be an option for a larger systems. Lastly, the very DH distribution system which indeed will be a source of Legionella growth an a potential work environment hazard in a LTDH system.

There are research going on at RISE currently investigating *The bio-film formation and persistence of Legionella* and *Technical specification and validation of the 3-liter principle* [56]. Such research will be necessary to potentially enable lower DH supply temperatures and reaching the targets set for 4GDH also in Sweden. ’

2.6.3 Distribution

The distribution system connects the production system with the consumers, by the substation, and is comprised by pipes and pumps. Big distribution pipes transfer the supply and return water throughout the DH system and smaller service pipes connects the substations.

The two main losses associated with the distribution system is the pressure and heat losses. The pressure losses corresponds to the required pump work needed to overcome pipe losses to and from the costumer as well as the differential pressure required over the substation.

In a 4GDH system, the heat losses might be reduced due to the lower system temperatures, but the pressure losses would increase as flow requirements and pressure losses over the larger substations increases.

The pump work required to overcome the pressure loss in the direction of the flow corresponds cubically to the mass flow according to equation 3.7. As the energy transferred corresponds directly to the mass flow in accordance with equation 2.1 twice the load requires eight times the pump work for the same pipe dimension and temperature difference. However by increasing the dimension of the pipe the pressure losses could be reduced significantly, yet a larger pipe as larger heat losses.

The heat losses is proportional to the surface are of the pipe and the temperature difference to the ground, also greatly depending on the insulation. System heat losses corresponds to some some 10 % relative the total load for a typically Swedish DH system (which is true also for GE). However it depends greatly on *heat density*, i.e. the head demand per area, and insulation as temperature difference and the actual losses losses will vary throughout the year and within the system. The value of the losses will also vary throughout a year, corresponding to the systems marginal cost of operation. Maintaining a sufficient supply temperature throughout the year is another issued related to heat losses and summertime, with small loads, it might be a challenge. Smaller pipes has relatively bigger heat losses, compared to their transmission capacity, than larger pipes due to the volume to surface ratio [2].

Dimensioning flow rates of 1-3 m/s is common in Sweden, for pipes with a diameter up to 0.5 m, with higher velocities for bigger pipes. However most of the pump work actually translates to heat gains, why big pipes with relatively small heat losses could in fact increase in temperature along the direction of the flow [2].

4GDH does not only imply lower temperatures, reducing the heat losses, but also smaller temperature differences. That would lead to higher flow requirements and consequently larger pipe dimensions, potentially increasing both the required pump work and heat losses. The heat losses could to some degree be compensated for by using more insulation, however its evident that this phenomena will impact the benefit of LTDH which will be investigated later in this thesis. There is also an increasing potential to use other pipe materials, such as plastic, for lower DH temperatures. Offering flexibility and cost reductions. However going for such pipes is in a way irreversible as they wont withstand much higher temperatures if necessary. There are also uncertainties in the risk for oxygen diffusion, causing corrosion in remaining steel components [2]. Also convectional steel pipes would benefit from reduced thermal stress, reducing maintenance costs and prolonging the life time of the pipes [40].

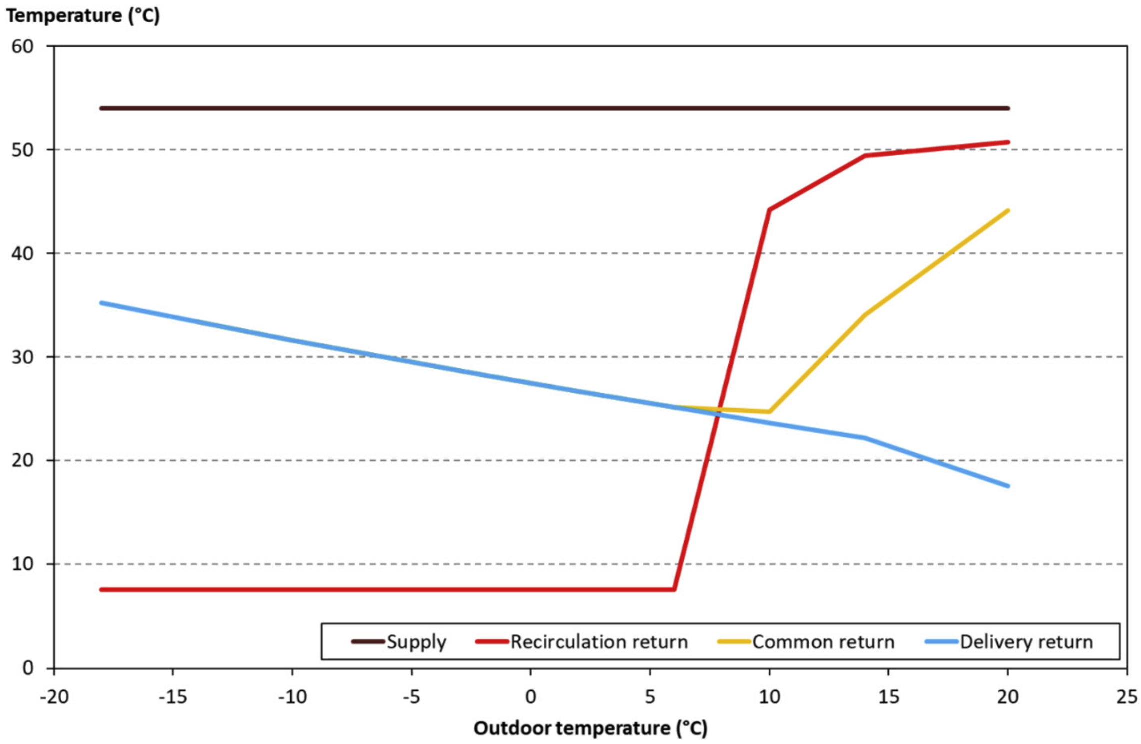
Third distribution pipe

Introducing the third distribution pipe would be a way to avoid the intentional by-pass of supply water in the distribution system, polluting the return flow in terms of increasing its temperature. This phenomena occurs due to little demand mainly in service pipes and in the outermost parts of the DH system and is required to ensure sufficient supply temperature and short waiting times, much like the HWC in multi-family buildings. The third pipe would be mainly used for this purpose during summer time, as the SH demand is negligible and the only heating demand will be for DHW preparation. The same third pipe would also replace the conventional need for HWC in larger buildings as individual substations would also be introduced, shifting the HWC from within the building to the DH network.

A 4GDH system incorporating the third pipe is simulated in the report *Novel low temperature heat distribution technology* [39] for an evolving building stock with decreasing SH demand (132-33 kWh/m^2). The effect of the 3P is assessed in combination with conventional dimensioned heat transferring surfaces and larger surfaces as suggested for 4GDH systems, for an area consisting of 49 single-family houses (140 m^2) with individual substations and fixed dimensions of the DH system. The results include delivered and recirculated DH water volume, not considering the changing pump work, and heat demands (including losses) and also the resulting return and re-circulation temperatures throughout the year for a system supply temperature of 54 $°C$. A contemporary and future case is identified and the results from those simulations are presented in table 2.3 and figure 2.7.

Table 2.3: Properties and results for the contemporary and future case, identified in the simulation study, throughout a year. Source: [39]

Case	**Contemporary**	**Future**
Specific heat demand	121 kWh/m^2	42 kWh/m^2
NTU (Substation/SH)	(0.5/4)	(1/8)
SH temp. (T_s/T_r)	(45/35)$°C$	(45/30)$°C$
SH demand	692 MWh	152 MWh
DHW system demand	137 MWh	137 MWh
Heat losses	57 MWh	69 MWh
Balance point temperature	16.8 $°C$	11.0 $°C$
Delivered flow	31 014 m^3	8 380 m^3
Recirculated/by-passed flow	3 628 m^3	11 273 m^3
Separate return temp. (3P)	24 $°C$	17 $°C$
Shared return temp. (2P)	30 $°C$	38 $°C$



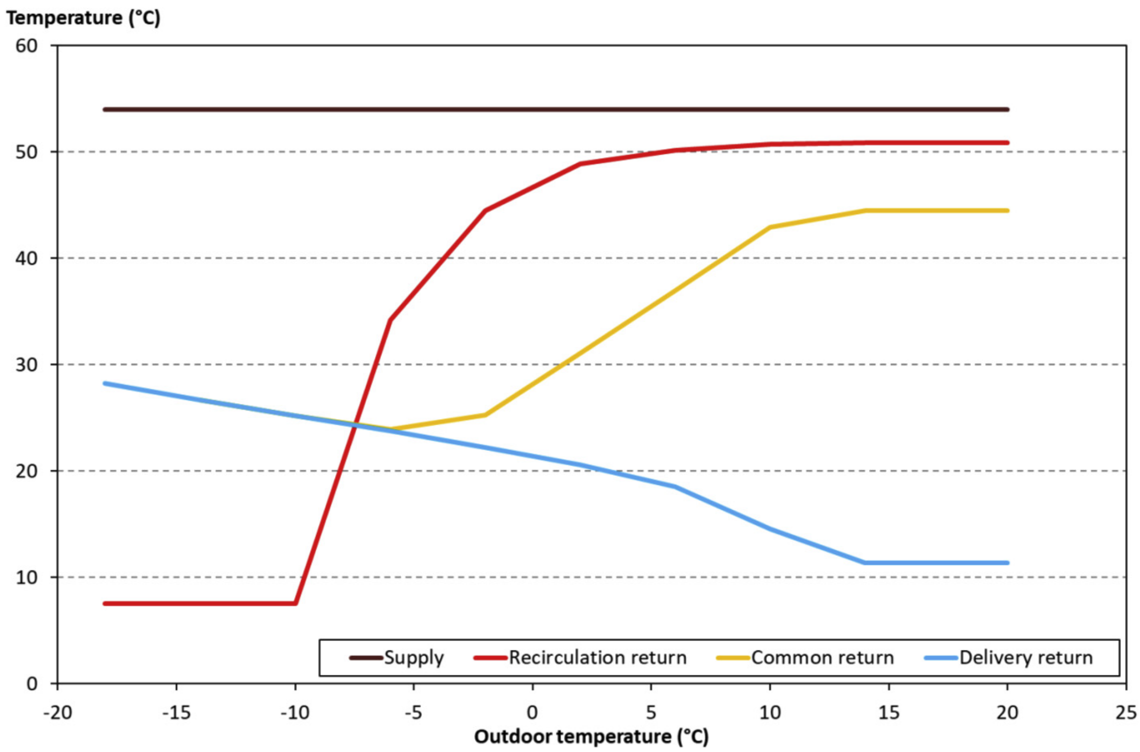


Figure 2.7: The temperature distribution over the course of one year for a contemporary case (above) and a future case (below). The X-axis corresponds to the outdoor temperature and the Y-axis the pipe temperature. The black line represents the supply pipe, the red line the third pipe and the blue and the yellow line corresponds to the return pipe with and without the third pipe in operation [39].

Due to the lower balance temperature in the future case it can be seen in figure 2.7 how the third pipe is much more utilized in the future case, enabling a significantly lower return temperature compared to the 2P-case in accordance with table 2.3. The heat losses to the surroundings however is in fact somewhat larger in the future 3P case, despite the cooler separate return, due to the additional third pipe area.

Since the third pipe would mainly be utilized summertime for the contemporary case the value of the third pipe could be discussed. Especially in a system like the one of Gothenburg, with exclusively inexpensive waste heat deliveries during the summer months. However, as the share of low-energy buildings increase the third pipe becomes more relevant. Its not only a question of the losses though as the temperature also is of great importance and lower return temperatures will help to further bring down the costs of operation, in relation to the CRG. It gets increasingly complicated as the losses from a warm return pipe would be somewhat compensated by the value associated with the CRG[2]. The results acquired above will be further processed later in this thesis, also considering, pipe dimensions, pump work and value of energy and temperature throughout the year.

There are losses and investment costs associated with burying an additional third pipe, although these costs might be worthwhile due to the potentially reduced total operating costs. By pumping the re-circulation flow through the third smaller pipe, as compared to bypassing it through the conventional return pipe, the distribution losses will increase in terms of pump work. As mentioned above the additional heat losses from the third pipe might increase the total losses, however the resulting lower return pipe temperature might enable total reduction in heat losses and associated costs, depending on system composition. The additional costs from installing the third pipe is assumed to be small as the very pipe would be lain together with the others, potentially within the same jacket as the supply pipe. However retrofitting a third pipe would likely be very expensive, if even feasible. This is as the main cost of expanding the distribution system does not lie in the very pipes but in costs related to putting them into the ground, mainly from the excavation [2].

3
Methodology

The investigating part of this thesis consist of initially calculating a CRG for the DH system of Gothenburg. This CRG is analyzed and used for further evaluation of the value of 4GDH, in particular the third pipe.

3.1 Cost Reduction Gradient

When calculating the CRG the total variable cost of operation is initially simulated for a reference scenario throughout one year, based on the production system of today at an assumed average system temperature of $(90/45)°C$. The cost of operation is calculated by an optimization model written in GAMS, minimizing the variable cost of operation. The same model is used with updated input data, in terms of reduced distributing losses and improved performance in some production units, as a result of lowered temperatures. The temperatures is reduced in steps of $1\ °C$ towards $(75/30)°C$ with the temperature difference between this supply and return flow kept constant, as to avoid impacting the mass flows of the distribution system.

The output of the optimization model consist of the hourly cost of operation and its different components. By comparing the total cost of operation for the reduced temperature the CRG can be calculated, normalized over the total heat demand, which is the common denominator for all investigated scenarios, as the load will change due to reduced heat losses, in accordance with equation 3.1. Also the virtual cost of waste heat can be calculated in the post-processing of the optimization, based on a simplified price model.

$$CRG(T \rightarrow T-1) = \frac{TC(T) - TC(T-1)}{Q_{Demand}} \tag{3.1}$$

3.1.1 The optimization model

The optimization model, greatly inspired by the work of Dmytro Romanchenko [9], is an unit commitment model using mixed integer programming in GAMS. The optimal dispatch of the production units presented in table 3.1 is found by minimizing the cost of operation while satisfying the constraints set up by the model, solving the hourly heat balance of 2017 for the system of Gothenburg, not considering trade with nearby system. Compared to other methods, where for example duration diagrams and other ways of sectioning the load distribution of the year, a consecutive set of hours is modeled as to incorporate the impact of electricity price fluctuations, start-up costs and ramp-rates properly.

The variable costs considered corresponds to fuel cost, Variable Operations and Maintenance (VOM) costs [57] and CO_2 and energy taxes. Furthermore there are costs (and revenues associated with consuming electricity and trading electricity certificates. There are also revenue when selling electricity generated in the CHP plants. There are constraints on maximum and minimum heat output of the units along with ramp-up (and -down) constraints on some units as well as start-up costs, corresponding to operating one hour at minimum load if nothing else mentioned.

For all units but the waste heat providers (ST1, Preem and Renova) and Sävenäs CHP there are no ramp-rate constraints. For those units though both the maximum ramp-up and down corresponds to 25, 7.5, 92.5 and 42.5 MW/h respectively.

Compared to the referenced model [9] some simplifications are made in terms of not considering any minimum up and downtime of the production units, neither enabling a variable power to heat value (α-value) for the CHP unit of Rya. Rya CHP utilizes a combi-cycle, with three gas turbines, a heat recovery steam generator with supplementary firing and a steam turbine. It could operate in several modes, however in this model a fixed alpha value is used although the three gas turbine stages are differentiated in the model. The α-value of the three CHP plants (Sävenäs, Rya and Högsbo) are 0.12, 0,83 and 0,93 respectively.

Specific start-up costs used for Sävenäs CHP and the three stages of Rya CHP, corresponding to 200 000, 150 000, 125 000 and 125 000 SEK respectively. The start-up cost of Sävenäs CHP is linked to the additional cost of pre-heating the boiler, using oil or gas, before proceeding with the normal operation. The higher cost of starting up the first stage of Rya CHP is due to the additional start-up of also the steam cycle, which is taken into account for when setting the output constraints.

Table 3.1: Production units and their properties in the DH system of Gothenburg.

Unit name (Type)	**Fuel type**	η_{tot} **(COP)**	Q_{Max}/Q_{Min}	**VOM**
ST1 (Refinery)	Waste heat	1.00	85/35 MW	0
Preem (Refinery)	Waste heat	1.00	60/15 MW	0
Renova (Waste incineration)	Waste heat	1.00	185/0 MW	0
Sävenäs (CHP)	Wood chips	1.11	110/25 MW	57
Rya (CHP)	Natural gas	0.91	295/50 MW	16
Högsbo (CHP)	Natural gas	0.79	14/3 MW	100
Rya (HP) 1-2	Electricity	(3.60)	60/0 MW	10
Rya (HP) 3-4	Electricity	(3.15)	100/0 MW	10
Rya (HOB) 1	Wood pellets	0.92	50/25 MW	20
Rya (HOB) 2	Wood pellets	0.92	50/25 MW	20
Sävenäs (HOB) 1	Natural gas	1.01	90/20 MW	15
Sävenäs (HOB) 2	Natural gas	0.90	50/20 MW	15
Rosenlund (HOB) 4	Natural gas	0.97	140/30 MW	15
Angered (HOB) 1	Bio oil	0.90	35/15 MW	15
Angered (HOB) 2	Bio oil	0.90	35/15 MW	15
Angered (HOB) 3	Bio oil	0.90	35/15 MW	15
Rosenlund (HOB) 1	Fuel oil	0.98	140/20 MW	15
Rosenlund (HOB) 2	Fuel oil	0.98	140/20 MW	15
Rosenlund (HOB) 3	Fuel oil	0.98	140/20 MW	15
Tynnered (HOB)	Fuel oil	0.89	20/8 MW	15

Energy and CO_2 tax is paid for fossil fuels and electricity use in accordance with table 3.2. As of 2017, heat production from CHP plants connected to the EU ETS scheme was excepted from 70 % of the energy tax and 100 % of the CO_2 tax, today only 89 % of the CO_2 tax is excepted [58]. The energy used for electricity production should be 100 % excepted from both taxes [59] and also 20 % of the CO_2 tax was excepted for heat only production (9 % as of today) [58]

Furthermore an electricity certificate scheme is used in Sweden requiring energy companies to fulfill a quota obligation in terms of renewable electricity generation. Thus, the electricity generated in Sävenäs CHP is rewarded with certificates and the electricity generated in the other fossil fueled CHP plants require purchasing certificates. Also the electricity use related to the HP require purchasing certificates. In 2017 the quota obligation was 24.7 % [60] and the average cost of a certificate was 65.3 SEK/MWh [61].

Table 3.2 also depicts the fuel prices used in the model. The prices was acquired from [19], prices for natural gas and oil was adjusted based on guidelines provided by GE. Furthermore the price of waste heat is set to zero when optimizing, as to maximize system well fare. GE pays the waste heat providers a contracted price, here approximated as half the marginal cost of heat as to share the benefit of utilizing waste heat [62] [63]. Lastly the electricity price corresponds to the hourly spot price of Nordpool (SE3) [64].

Table 3.2: Fuel prices and taxes [65] for 2017 .

Fuel type	**Fuel price** [SEK/MWh]	**Energy tax** [SEK/MWh]	CO_2 **tax** [SEK/MWh]
Waste heat	0 (Contract)	-	-
Wood chips	180	-	-
Natural gas	220	86	221
Electricity	Price profile	310	-
Wood pellets	266	-	-
Bio oil	600	-	-
Fuel oil	350	81	306

The model operates under perfect foresight, as the load curve and electricity price (which are the varying parameters) are known for all hours. However, as to speed up the simulations the 8760 hours of the year was divided into 15 section of 696 hours each with an overlap of 120 hours. By trail and error it was found that sections longer than some 400 hours and overlaps of more than some 100 hours was sufficient in order to not affect the results. The time-steps used was found to provide excellent results (as compared full-year optimization) whilst ensuring short running times.

3.1.2 Temperature reduction

The Matlab program used reads the input data for the optimization model of the reference scenario, including heat load, unit performance and outside temperature. By processing that data new inputs can be calculated for the following scenarios, as a function of the DH system temperature, considering heat losses and production performance. By processing the output of the optimizations the CRG can be calculated in accordance with equation 3.1

Heat losses

A simple distribution system heat loss approximation is made based on a proxy of ground temperature as the mean outside temperature of the last four weeks, with fixed pipe temperatures of $(90/45)°C$. The losses, assumed to be 400 GWh throughout the year, roughly corresponding to 10 % of the produced heat, is thus distributed over the course of one year according to figure 3.1. The losses and system UA-value is calculated using equation 3.4, by keeping the UA-value constant the new losses can be calculated as the pipe temperatures are lowered.

The distribution heat losses, originating from a temperate DH pipe, can be calculated according to equation 3.2 [2]. By aggregating equation 3.2 for the whole DH system, a expression describing the total losses can be seen in equation 3.3.

$$\dot{Q}_{Loss,pipe} = K \cdot \pi d L \cdot (T_{Pipe} - T_{Ambient}) = 2 \cdot \lambda_i \cdot \pi L \cdot (T_{Pipe} - T_{Ambient}) \,/\, \ln\left(\frac{D}{d}\right) \quad (3.2)$$

With K being the total heat transfer coefficient $[W/m^2K]$ of the pipe, d the outer diameter of the pipe, L the length of the pipe, λ_i the heat conductivity of the piping insulation and D the outer diameter of the insulation.

$$\dot{Q}_{Loss,system} = U \cdot A \cdot \left(\overline{T}_{Pipe} - T_{Ambient}\right) = U \cdot A \cdot \left(\frac{T_s + T_r}{2} - T_{Ground}\right) \quad (3.3)$$

With U being the overall heat transfer coefficient $[W/m^2K]$ for all the pipes in the system, corresponding to total area A of all the pipes (average perimeter multiplied with total length). $\overline{T}_{Pipe}$ is the average pipe temperature in the system, i.e. the mean of the supply and return temperature. The ambient temperature corresponds to the ground temperature.

$$Q_{Loss,system} = \sum \dot{Q}_{Loss,system} = U \cdot A \cdot \sum \Delta T_{Ground} \Rightarrow U \cdot A = \frac{Q_{Loss,system}}{\sum \Delta T_{Ground}} \quad (3.4)$$

The total heat losses of a DH systems corresponds to the sum of all heat losses throughout the year, being the product of a constant UA-value and the sum of all temperature differences between pipe and ground ($\Delta T_{Ground} = \overline{T}_{Pipe} - T_{Ambient}$). With the losses and temperature differences known the UA-value of the DH system can be approximated.

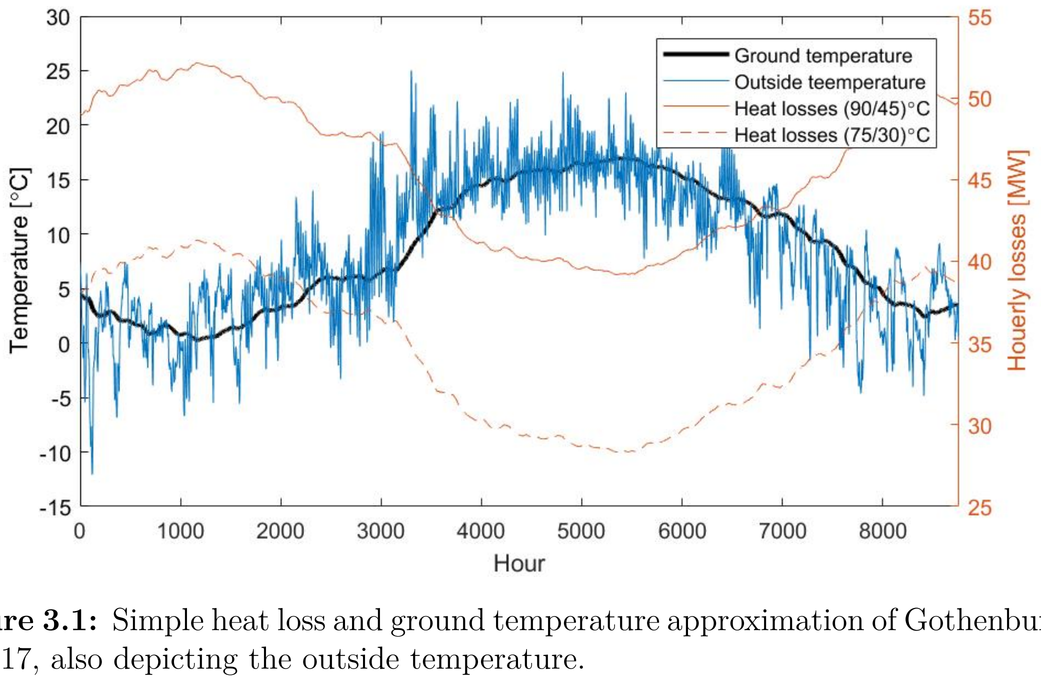


Figure 3.1: Simple heat loss and ground temperature approximation of Gothenburg in 2017, also depicting the outside temperature.

Unit performance

The impact on the performance of some sensitive production units, listed below, are based on the work done by Per Gustafsson [33]. The change in performance is linearized for all units, based on an review of production data from 2010-2014 for hours corresponding to the maximum output. The impact of decreasing supply and return temperature is found below for affected units.

ST1 and Preem Both refineries delivers more heat for lower return temperatures but also somewhat more for lower supply temperatures.

Renova The waste incineration plant can deliver more heat for lower return temperatures.

Sävenäs CHP The CHP plant of Sävenäs, utilizing a relatively small steam turbine, is somewhat affected by reduced temperatures. However, the increased electricity output (and consequently reduced heat output) is found by theoretically altering the state of the steam exiting the turbine. A small increase in electricity output is found due to lowered supply temperatures and a larger increase in heat output for lower return temperatures, due to the use of FGC. The total efficiency is affected due to the increase heat output only, as the electricity output displaces the reduced heat output.

Rya CHP The total efficiency of Rya CHP is kept constant for reduced temperatures. There are however a slight displacement of heat for increased electricity output as of lowered supply temperatures. The effects on Rya CHP is based on the technical documentation of when the plant was inspected after installation in 2006.

Rya HPs The HPs of Rya is affected not only by reduced supply temperatures, as expected, but also by reduced return temperatures causing sub-cooling in the condensers.

Sävenäs HOB1 One of the HOBs of Sävenäs, fueled by natural gas, is also equipped with FGC showing improved heat output as a function of lowered supply temperatures.

3.2 Evaluation and implementation of the 4GDH concept

Based on the CRG calculated according to above, some further investigations in order to evaluate the 4GDH concept is preformed, including estimating the value of 3P and the affects of reduced temperature difference in terms of heat and distribution losses.

Using the results of the simulation study preformed in [39] (a similar study presented more thoroughly in [66]) the 4GDH concept is evaluated, in particular the value of 3P. The CRG calculated for the whole year is recalculated for the specified temperature intervals used in the simulation study. By doing so a more accurate value of avoiding by-pass, consequently maintaining a low return temperature, can be calculated. The CRG can be utilized and the losses from the return pipe are reduced due to lower overall pipe temperature. However, as a third pipe is introduced additional heated surface is put in the ground, increasing the heat losses and pump work (due to narrow pipe), which the implications of also will be investigated.

Additional calculations are preformed for reduced temperature differences, imposed by the transition towards 4GDH. Although the heat losses will decrease from the also cooler pipes the flow and consequently the required pump work will increase. If bigger pipe dimensions are required, the heat losses might also be affected. Equation 3.5-3.8 expresses the equations used when calculating the pump work [2].

$$\Delta p = -\frac{\lambda \cdot L}{d} \cdot \frac{\rho \cdot v^2}{2} = -\frac{8 \cdot \lambda \cdot L}{d^5 \cdot \pi^2 \cdot \rho} \cdot \dot{m}^2 \tag{3.5}$$

Pressure gradient [pa] in the flow direction, with λ being the dimensionless friction factor.

$$\dot{m} = \dot{V} \cdot \rho = v \cdot A_X \cdot \rho = v \cdot \left(\frac{d}{2}\right)^2 \cdot \pi \cdot \rho \tag{3.6}$$

Massflow, A_X being the cross section of the pipe, perpendicular to the flow.

$$P_{pump,direction} = \Delta p \cdot \dot{V} = -\frac{8 \cdot \lambda \cdot L}{d^5 \cdot \pi^2 \cdot \rho} \cdot \dot{m}^2 \cdot \dot{V} = -\frac{8 \cdot \lambda \cdot L}{d^5 \cdot \pi^2 \cdot \rho^2} \cdot \dot{m}^3 \tag{3.7}$$

The pump work is a function of the pressure drop and mass flow.

$$P_{pump,tot} = P_{pump,supply} + P_{pump,return} + P_{pump,diff} = 2 \cdot P_{pump,direction} + P_{pump,diff} \tag{3.8}$$

The total pump work is the sum of the pump work required to cover the pressure losses along both the supply and return pipe as well as the pressure difference over the substation.

4
Results

Starting with the CRG for the DH system of Gothenburg in 2017, this chapter presents the main findings of the report. A sensitivity analysis is conducted before using the CRG further in the following evaluation of the 4GDH concept.

The results of the first part of this study, presented in section 4.1 is plotted for decreasing return (and supply) temperatures, with a constant temperature difference of 45 $°C$ as to avoid affecting the distribution system in terms of flow.

The DH system temperatures are only reduced towards (75/30) $°C$ whilst the suggested 4GDH temperature level is (50/20) $°C$ since further system temperature reductions are assumed to be unreasonable on a system level, considering the current composition. Neither the exact figures are of great interest moving on, its primarily the trends shifting towards 4GDH and lower system temperatures that are of interest. The quality of the calculations will be discussed in the following chapter.

4.1 Cost reduction gradient

The results from the very first optimization, the BAU case with a reference temperature of (90/45) $°C$ is depicted in figure 4.1. Corresponding results was found for the following 15 temperature levels towards (75/30) $°C$. The base load is covered by waste heat (63 → 70 %), followed by Sävenäs CHP (11→8 %). The HPs (16→17 %) and production for Rya CHP (9→5 %) serves to cover most of the remaining intermittent and peak load, depending on the electricity price, although the HPs most often appears first in the merit order. The very last part of the peak production is covered by HOBs (and Högsbo CHP, which mainly operates in times with very high electricity prices) production (1→1 %) , mainly from the HOBs of Rya but also from Sävenäs HOB1 and Rosenlund HOB4.

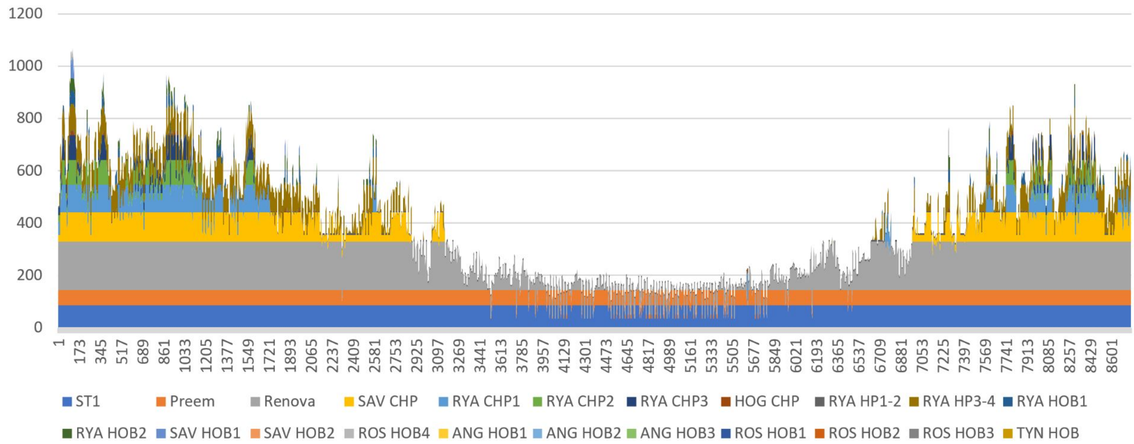


Figure 4.1: The dispatch of the DH system of Gothenburg with hourly heat output [MW] depicted on the y-axis for all hours of 2017.

With a heat load of some 3.8 TWh in 2017 and the total costs depicted in figure 4.2 the average cost of heat in the reference case and the lowest temperature case is 79 and 52 SEK/MWh respectively (129 and 97 SEK/MWh including the cost of waste heat).

The CRG is calculated to be 2.33 SEK/MWh,°C at toady's temperature levels and is depicted in figure 4.3, normalized by the heat demand of 2017, showing a linear decrease for reduced temperatures. The slope of the CRG corresponds to the reduced gradient of the total operation cost in figure 4.2. The CRG$_{\bar{5}}$[1], providing a more general and conservative approximation of the CRG is calculated to be 2.24 SEK/MWh,°C.

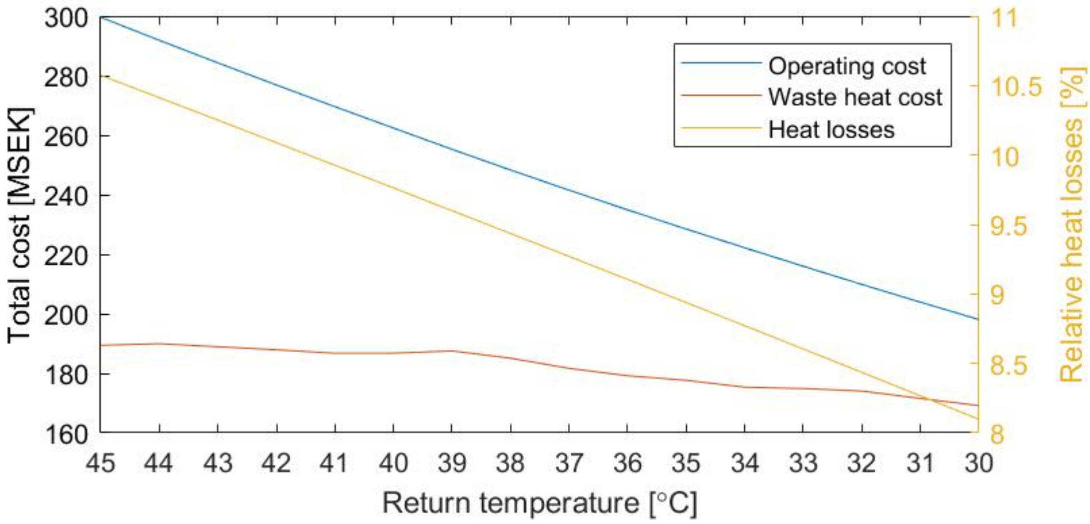


Figure 4.2: The total operating cost and total cost of waste heat on the left Y-axis and the heat losses from the distribution system, relative the total heat load, on the right Y-axis for decreasing temperature levels.

[1]CRG$_{\bar{5}}$ - Calculated as the operating cost savings from (90/45) to (85/40) °C, normalized over 90 % of the reference heat load of that interval and divided over the 5 °C reduction.

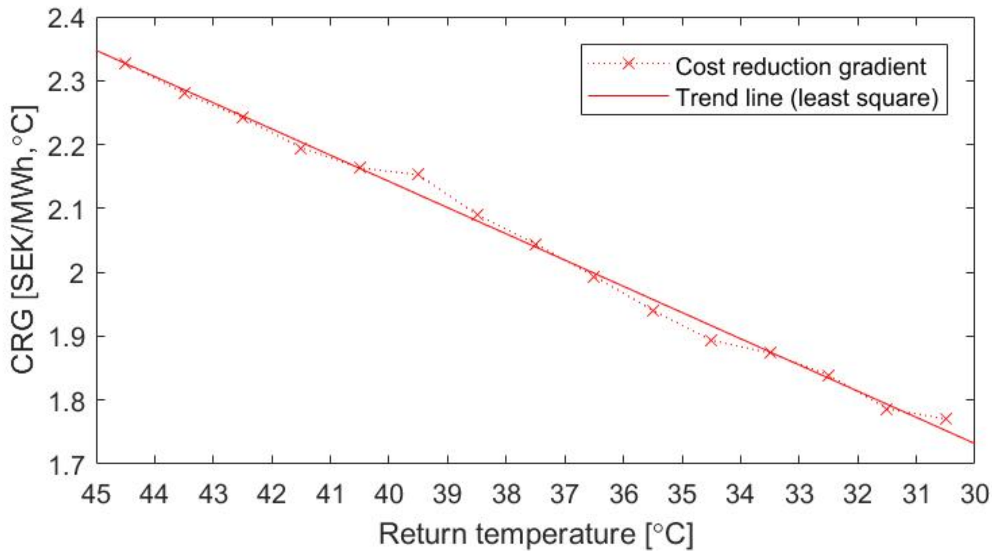


Figure 4.3: The CRG of each temperature reduction of 1 $°C$, from (90/45) towards $(75/30)°C$), plotted with a trend line showing the decreasing CRG for lower system temperatures.

Cost components

It can be seen in figure 4.4 how the electricity output from the CHP production, along with the revenue from electricity sales, is reduced as the temperature decreases. Mainly due to reduced electricity (and heat) output from Rya CHP, despite the improved α-value. Yet, the mean electricity price of the sold electricity increases, indicating that the reduced output mainly occurs at hours with low electricity prices, which is assumed to not only correlate with the overall electricity demand but also the heat load. A revenue of 120 MSEK is observed for the reference case at a production volume of almost 350 GWh electricity, at the lowest temperature the total revenue is 76 MSEK with a total electricity output of some 200 GWh.

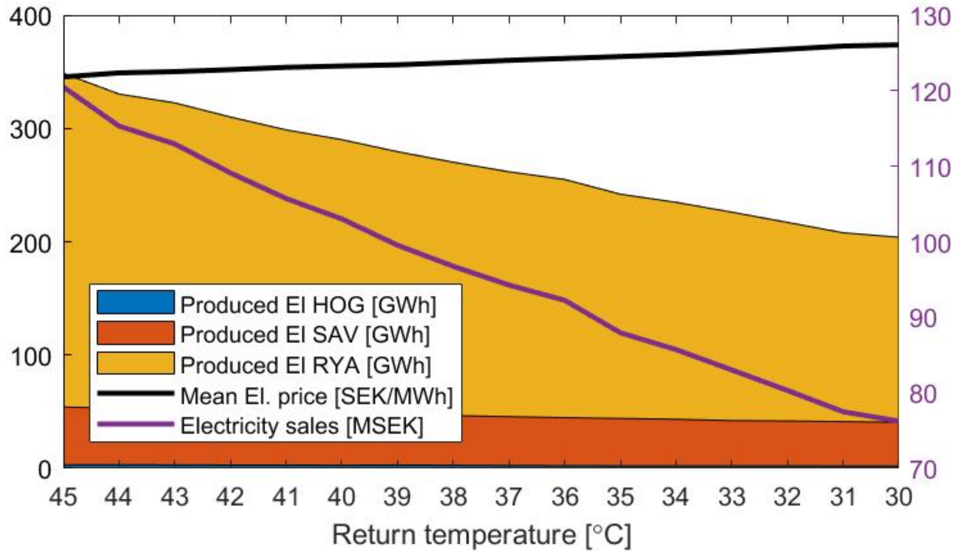


Figure 4.4: Development of electricity generation and average cost of sold electricity for lower system temperatures (left Y-axis). Also depicting the total revenue (right Y-axis).

Observing figure 4.5 the decrease in waste heat cost can be seen. The cost are reduced as the waste heat uptake actually increases, due to the reduced marginal cost of heat production which sets the price of waste heat.

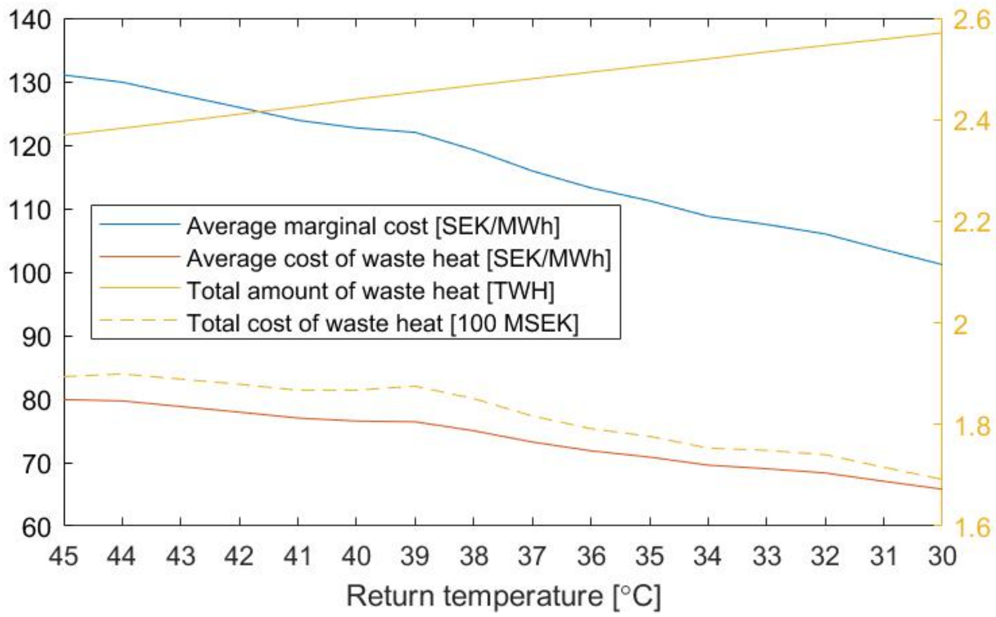


Figure 4.5: Development of waste heat cost and utilization for lower system temperature (left Y-axis), also depicting the average marginal cost of production and average cost of waste heat (right Y-axis).

Not considering the losses has no major impact of the overall trends observed for the BAU scenario. Only slightly less electricity generation and waste heat uptake can be observed for the BAU case, simply due to the lower heat load when reducing the losses.

Not including the increase in performance though has a much greater impact, as can be seen in figure 4.6. The CRG is drastically reduced (in monetary terms), only showing minor fluctuations and a small slope. Although the CRG is drastically affected by not considering the improved performance the actual operation when lowering the system temperature are not, explaining the minor CRG.

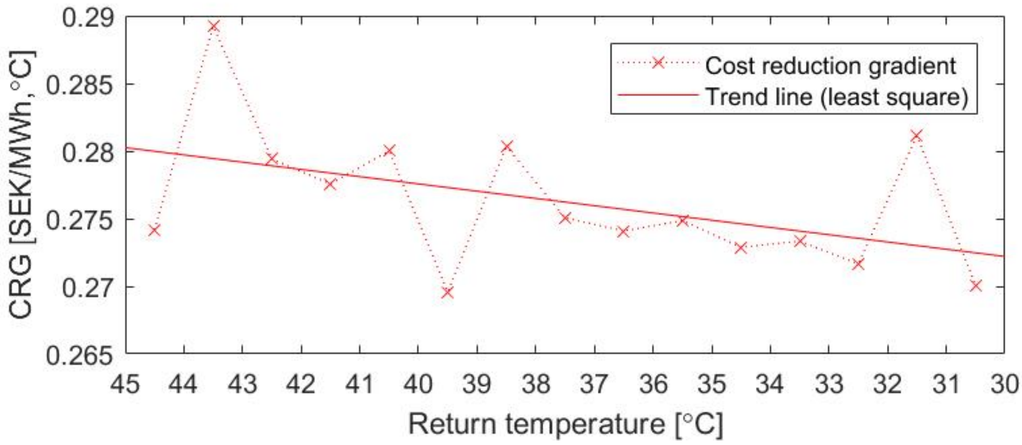


Figure 4.6: The CRG corresponding the the scenario not considering the impact of reducer performance from production units when lowering the system temperature.

In table 4.1 the different aspects investigated is compared to the BAU scenario, presenting some key figures. It might be tempting to just aggregate the two individual aspects, however, due to secondary effects when altering with one or another that's not necessarily applicable. Its however clear that the greatest benefit from reducing the system temperature originates from the improved performance of the production facilities, contributing to most of the operating cost reductions.

Table 4.1: Key figures for the BAU scenario including the two scenarios when ether the impact of distribution losses or increased performance is considered for reduced system temperatures.

Aspect Unit	**CRG** $\frac{SEK}{MWh,°C}$	**Slope** $\frac{SEK}{MWh,°C^2}$	**CRG**$_{\overline{5}}$ $\frac{SEK}{MWh,°C}$	**TC**$_{45}$ MSEK	**TC**$_{30}$ MSEK
BAU	2.33	0.041	2.24	300	198
No losses	2.05	0.033	1.98	300	209
No performance	0.28	0.0005	0.28	300	286

4.1.1 Sensitivity analysis

The sensitive analyses of this study investigates some different scenarios, including considering the impact of the EU ETS scheme, waste heat accessibility, CO_2 tax, electricity certificate, electricity and fuel prices and the different load curve of 2016. The scenarios investigated are described and further analyzed in appendix A together with elaborated results, including not only the CRG and slope as depicted in figure 4.7, but also total cost of operation, cost of waste heat and electricity revenue for the reference temperature as well as the lowest temperature.

The CRG is generally higher for more expensive scenarios, which makes sense as the potential cost reduction would be larger for a higher starting point. It can also be concluded from figure 4.7 that the CRG and slope correlates quite well, i.e. even an initially high CRG will eventually become more moderate as lower temperatures are approached.

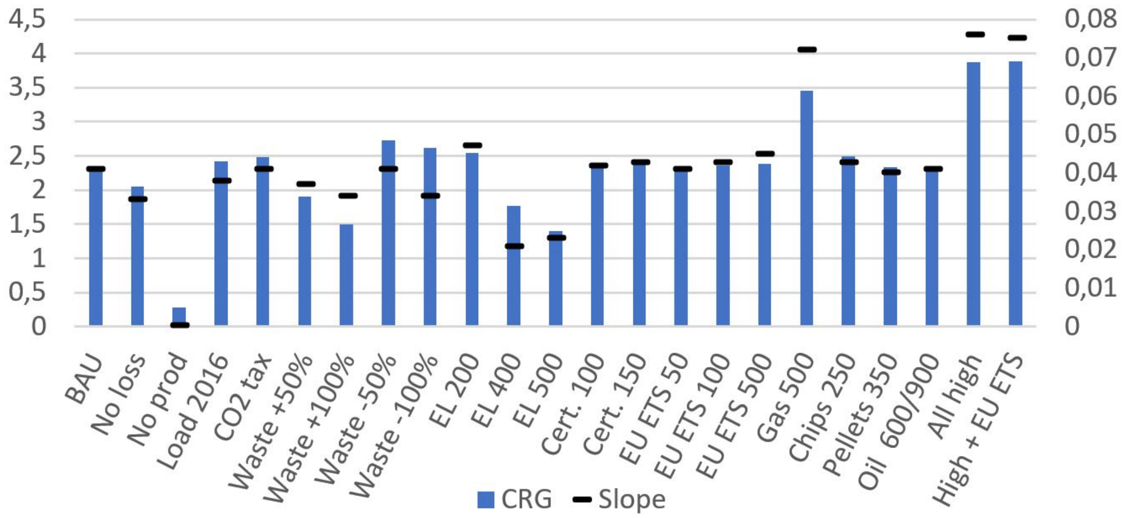


Figure 4.7: The CRG $[\frac{SEK}{MWh,°C}]$ represented on the left Y-axis and the Slope $[\frac{SEK}{MWh,°C^2}]$ on the right Y-axis for the scenarios investigated.

4.2 Evaluation of the 4GDH-3P concept

Particularly the value of the third pipe has been identified as an interesting aspect of the 4GDH concept, investigated further in this section. Also the interplay between heat losses and pump work, when burying additional pipes in the ground or decreasing the temperature difference, is investigated.

4.2.1 The value of 3P

Returning to the simulation study of [39], mentioned in the previous literature study, the cost of satisfying the heat demand of the area simulated would be 70 and 28 kSEK for the contemporary and future scenario respectively, based on the heat load from table 2.3 and an average heat cost of 79 SEK/MWh . The yearly (time averaged) return temperature reduction related to shifting from the conventional 2P to the 4GDH-3P system would correspond to 6 or 21 $°C$ respectively. With a CRG of 2.24 $SEK/MWh, °C$ ($\text{CRG}_{\overline{5}}$) the corresponding savings would be 12 and 17 kSEK, or more representative 17 and 61 %.

The energy averaged temperature reduction though corresponds to 2 and 16 $°C$ for the contemporary and future case respectively. The slightly more conservative reduction would imply savings of 4 and 13 kSEK or 6 and 47 %

Yet, observing figure 4.8, its clear that the costs of providing heat at outside temperatures over some 10 $°C$, i.e for almost half the year, is close to none. As this is when the the value of the 3P is presumably the largest, due to avoided by-pass and pollution of the return flow, the true savings might not be as high as indicated above, at least not in a waste heat dominated system like the one of Gothenburg.

In practice it is mainly at outside temperatures above the building balance temperature, with no SH demand, the 3P has a full effect. As this is at 17 $°C$ for the contemporary case and at 11 $°C$ for the future case the additional utilization is evident.

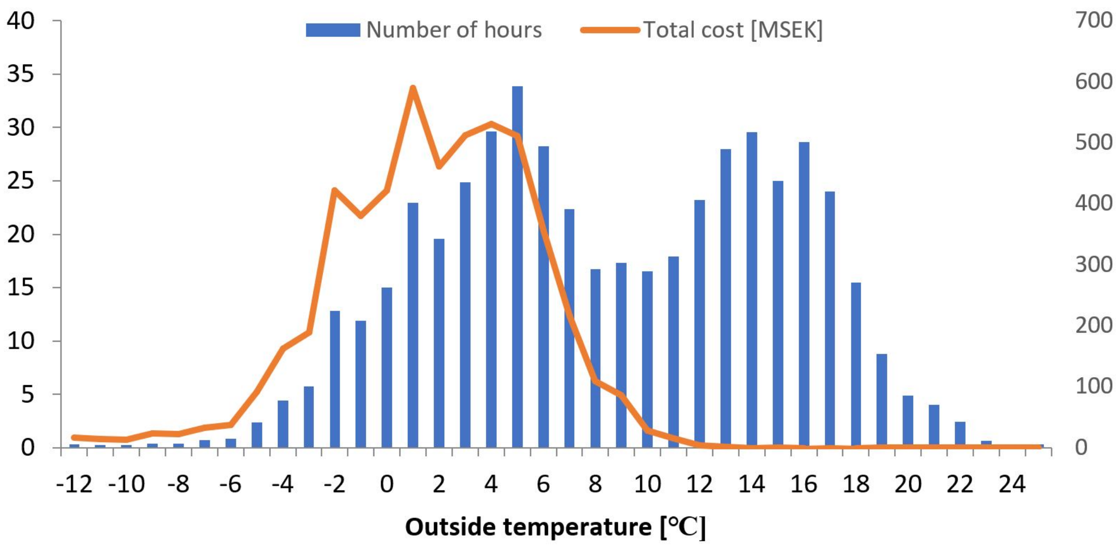


Figure 4.8: The distribution of total operating cost and number of operating hours for increasing outside temperatures. The total cost [MSEK] being depicted on the left Y-axis and the number of hours on the right. Its clear how the cost distribution is very skewed towards lower temperatures, when the heating demand is higher.

To illustrate this further the CRG is differentiated over temperature intervals specified in [39] and presented in appendix B. The corresponding loads are recalculated for the outside temperatures of 2017 in Gothenburg, which was warmer then the temperatures of the simulation study, showing a somewhat lower heat demand. However the cost savings still corresponded to 17 and 61 % when performing the calculations based on yearly time averages.

The $\text{CRG}_{\overline{5}}$ of the temperature intervals are depicted in figure 4.9, together with the average heat cost. By re-calculating the total costs and corresponding savings for each interval, also considering the varying temperature reductions, a different result is acquired. For the contemporary case the total savings are merely 0.5 %

whilst the future scenario still has total savings of 8 %. Although such savings are indeed significant, at least for the future scenario, its far from the savings calculated based yearly average temperatures. More results can be found in appendix B.

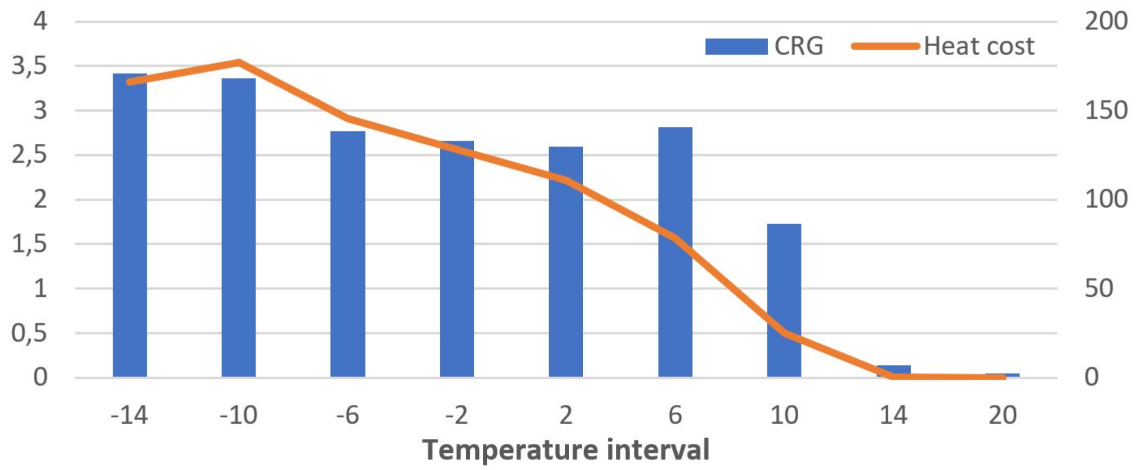


Figure 4.9: The CRG [$\frac{SEK}{MWh,°C}$] (left Y-axis) and the heat cost [SEK/MWh] (right Y-axis) presented for the temperature intervals ($\pm 2°C$) specified in [39].

Distribution losses

Using again the time averaged temperatures, the distribution losses can be calculated using equation 3.5, 3.6, 3.7 and 3.2. The friction factor (λ) is set constant to 0.025, the conductivity of the insulation (λ_i) to 0.03 W/m^2K and density and heat capacity of water to 1 kg/m^3 and 4.2 kJ/kg respectively, along with the best insulation class (3) specified in [2] used for all pipes throughout the simulations. The supply temperature is set to be 54 $°C$, ground temperature 7.5 $°C$ and time averaged 3P-temperature to 27 and 48 $°C$ for the contemporary and future case respectively, besides already established temperatures of the remaining pipes.

In the simulation study the total trench length is 1.1 km and the pipes used ranges from DN32-DN65 for the distribution network and DN25 for the service pipes, with approximately 50 % of each type. However the calculations below is preformed considering losses per meter, assuming a single load served by two or three pipes ranging from DN20-DN100. The required dimension of the 3P is set as to provide sufficient re-circulation to avoid a temperature drop of more than 0.05 $°C/m$, with a pressure losses of 100 Pa/m. DN15 is found to be a sufficient dimension for all scenarios and is therefore chosen for all investigations of the heat losses. The flow requirement and procedure for calculating it can be seen in [39], although a different approach and insulation class is used here the results are similar. The 3P flow requirements and corresponding pipe diameter for the supply and return pipe dimension can be seen in table 4.2.

Table 4.2: Recirculating (3P) flow requirements and corresponding pipe diameters, at pressure losses of 100 Pa/m, for different supply pipe dimensions.

DN	**20**	**25**	**32**	**40**	**50**	**65**	**80**	**100**
Flow 3P [l/h]	98	115	126	141	154	175	185	192
Diameter [mm]	10.8	11.5	12.0	12.6	13.0	14.0	14.2	14.9

The net heat loss is calculated as additional losses when transitioning to the 3P setup, i.e the losses from the warm 3P and cool separated return pipe, subtracting the previous losses from the the not as cool collective return pipe. Similarly the net pump work corresponds to the additional pump work required for re-circulation the same amount of water in the more narrow 3P as compared to by-passing it in the return pipe (which comes at very small losses). The pump work is calculated for the flow requirement specified in table 4.2, with the total recirculated volume specified in the simulation study assumed to be valid only for the DN32 scenario and scaled up or down proportionally to the flow requirements for the other scenarios, with corresponding re-circulation times.

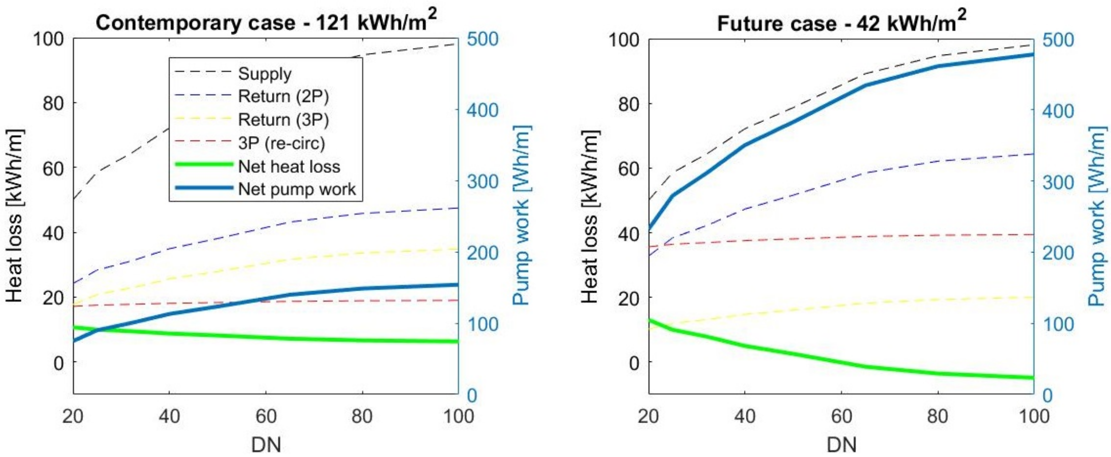


Figure 4.10: Yearly heat losses and net pump work for the contemporary and future case.

It can be seen how the net heat loses are reduced for bigger pipe dimensions for both cases, however always being positive for the contemporary scenario, approaching below zero in the future case. Not so much for the 3P though why using DN15 throughout the simulations probably would have made little difference in terms of heat losses.

Another observation is the relative small pump work required, compared to the heat losses (observe the order of magnitude), particularly for the contemporary case.

For the future case the pump work requirements increase quite drastically for the increased pipe dimensions, however the reduction in heat losses is even larger. However, for dimensions larger than DN60 the net heat losses actually goes below zero, although the pump work still is above 400 Wh/m.

Thus the main benefit from the 3P does not seem to come from the reduced losses but rather the reduced return temperatures. However with better insulation or twin-pipes, possibly burying the 3P within the the supply pipe jacket the losses might actually be reduced.

4.2.2 Temperature difference

When reducing the temperature difference, as suggested for 4GDH compared to 3GDH, the flow requirements will increase when supplying the same amount of heat according to equation 2.1. In figure 4.11 the heat losses and corresponding pump work is calculated for a 2P system delivering 100 kW in DN40-DN50 pipes and a larger system delivering 45 MW in DN400-DN500 pipes, for two insulation classes. The heat losses are calculated for the supply and return pipe individually, with temperatures decreasing linearly from (90/45) to (50/20) $°C$, consequently with a temperature difference decreasing from 50 to 30 $°C$. As the temperature difference decreases the mass flow increases accordingly, causing an increased pump work in the two pipes according to equation 3.7, why the larger dimension would be chosen.

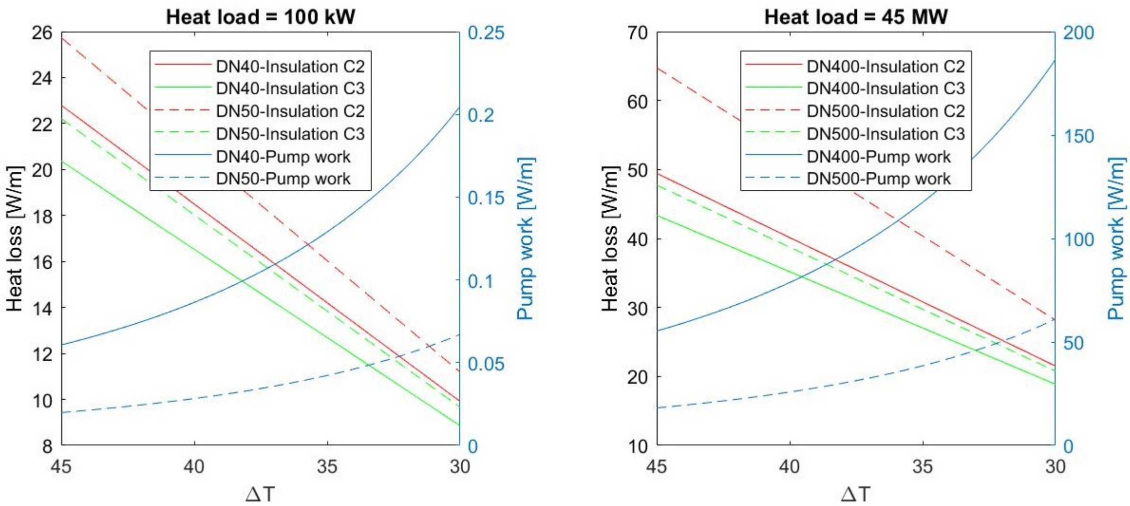


Figure 4.11: Heat losses and pump work for the small and big load with corresponding pipe diameters. The dimensions are altered slightly along with the insulation level, observing differences of both parameters.

It can be observed how the reduced temperature difference greatly influence the heat losses, much more than the very pipe size. Additionally, the increased heat losses from increasing the pipe size could to a large extent be compensated for by adding insulation. It can also be observed, for the lower heat demand, how reduced temperature differences indeed requires more pump work, yet much less than the reduced heat losses, particularly for the slightly larger dimension. If investigating the larger heat demand instead the trends are similar, however the pump work relative the heat losses are much greater and it does not seem very beneficial to reduce the temperature difference, not even for the larger pipe dimension. It should be noted that electricity (pump work) is overall more valuable than heat, why heat losses and pump work is not directly comparable[2].

In [69] different substation configurations for providing heat to a subsystem was investigated. The same report and [54], is concerned with the exergy destruction when using high temperature DH in a LTDH system, also considering the exergy destruction associated with the pump work. Matching the supplied temperature with the desired temperature is identified as an important feature in that aspect. Although little pump work is observed in the LTDH system investigated (some 3 % of the total energy input), the electricity used for the pumps has high exergy and should thus not be neglected, corresponding to half of the exergy destruction summer time and a lesser share during heating season.

As for the previous 3P example a fixed friction factor is used, which is one source of error as λ decreases for higher flows and bigger pipes, however the trend of proportionally smaller heat losses for larger pipes and increasing pump work requirements for higher flows still holds [2]. The maximum pressure losses (100 Pa/m) used when dimension the pipes, along with the choice of insulation, will also affect the results.

Based on the findings of figure 4.11 it can be said that reducing the temperature, along with the temperature differences, would be beneficial for smaller pipe dimensions, i.e. close to the costumer. However, in the main distribution system, with larger pipes and flows it would be more beneficial to maintain high temperature differences as to reduce the flow, even if it means higher overall temperatures.

[2]With a heat cost of some 100 SEK/MWh and an electricity cost of some 300 SEK/MWh the pump work could be valued as approximately twice the value of heat losses, considering the fact that most of the pump work becomes heat.

5 Discussion

The chapter will follow up questions arisen so far in this report and introduce a few new ideas. A discussion will be held regarding the modelling approach and its limitations. A discussion of the production system and units of GE will follow. The sensitivity analysis will be returned to and put into context.

5.1 The future of District Heating

The business idea of DH revolves around an efficient production system, covering the costs associated with the distribution system, in order to maintain a competitive centralized heating system, as compared to local alternatives [2]. The uptake of residual heat and other low-grade heat sources, with otherwise would have gone to waste, is another key feature concept of DH, both in terms of profitability as well as use of resources. In Gothenburg this is utilized further as residual heat is used for district cooling (in absorption HPs).

Costs of distribution include payback of capital costs and operational costs associated with pressure and heat losses [67]. LTDH could enable reduced heat loses and also lower capital costs enabling cheaper materials.

The revenue and cost of production for a DH system corresponds to the heating demand, however the distribution costs and consequently the profitability of a DH system correlates with the heat density [2].

Although new buildings with lower temperature requirements will enable better utilization of the existing distribution system and increase the heat density short term the shift towards more energy efficient NZEB-buildings will long term reduce the heat densities along with the heat demand of future cities, particularly in new areas. Thus 4GDH will not only require a more cost effective distribution system in order to be compatible, it will also require an even more efficient production system, both in terms of cost and resources.

In Sweden HPs is the main competing technology to DH , whereas natural gas remains the dominant fuel for individual heating throughout Europe [5]. The shift towards more energy efficient buildings will obviously challenge also such technologies. However the way the energy performance requirements of NZEBs is formulated DH risks being disadvantaged, as solutions utilizing locally produced heat is favoured.

Denmark is definitely a forerunner when it comes to 4GDH, for good reasons. With a power system relying heavily on intermittent wind and less access to inexpensive biomass compared to Sweden, their desire to develop their DH system towards 4GDH makes much sense. Also in Sweden it would be desirable to shift towards a DH system relying even more on low-grade heat, utilizing seasonal storage and less biomass. In combination with HPs to support the power system with thermal storage potential [5].

Furthermore a more uniform DH-technology is desirable throughout Europe, imposing increasing benefit from standardization and mass production of DH equipment, mainly individual substations [4]. There is indeed an additional cost for the installation of several smaller substations in a multi-family building than the conventional one, more so as the 4GDH substations are operating at lower temperatures. However, this would to at least some degree be compensated for by the cost reduction of mass produced equipment.

In doing so, both production costs, distribution costs and installation costs can be managed, maintaining a competitive DH system in a future sustainable energy system.

4GDH is well suited in a system with high operation costs, connecting to the method used in this report, using the CRG as a proxy for usefulness of shifting towards 4GDH, it can be said that that would apply for any kind of investment towards more efficient production and distribution.

The value of DH in a future energy system will always heavily rely on the access of residual heat, as 4GDH increases the access to such heat a transition can be motivated. However transitioning to 4GDH in order to increase market shares, requiring investments in increased production is not necessarily a good idea as the alternative HPs might have a greater value to the system, greatly depending on the surrounding energy system. For example, a HP powered by wind (and ambient heat) compared to DH powered by biomass, the HP alternative could be more beneficial in a system perspective as the biomass could be used fore something else, such as ethanol or even food.

As DH also has a value in the energy system in terms of its synergies with the DC and power system the becomes even more complex.

Although more waste heat definitely could be utilized in Gothenburg the potential to do so is already very well utilized. The same probably goes for most Swedish systems as well as in other established systems throughout northern Europe. If 4GDH could make DH a viable option in new areas though, many gas boilers could be replaced, potentially displacing substantial CO2-emissions as well as bringing additional values to the local energy system. This is probably where the greatest potential for 4GDH lies, not in large established systems like Gothenburg, but close to low-grade heat sources in a local system, in central Europe or in new areas where 3GDH had not been found profitable. Either due to expensive production or low demands, implicitly making the distribution system more expensive, due to lower heat densities

5.1.1 A potential development of 4GDH

Its likely that 4GDH, in an already established system, will develop as individual subsystems at suitable locations. Connecting single LTDH compatible buildings to the already existing network is also an option. Reaching the desired 4GDH system temperatures is not likely, mainly as the distribution system does not have enough capacity. In the case of a subsystem the conventional substation will virtually be moved from within the building to the network and be replaced by the LTDH-substation, also replacing the HWC with the third pipe.

Subsystems

With maintained system temperatures, with as low return temperatures as possible, a decent transferring capacity would be ensured. This is also shown to be the most favorable in terms of distribution losses. Individual subsystems tough, with exclusively LTDH costumers could be connected at a lower system temperature. this would also benefit the overlaying system as it would push down the return temperature. Furthermore a lager penetration of LTDH-system would be made possible by 4GDH solutions.

Such a system would show some resemblance to a typical power system, with high voltage transmission and lower voltage closer to the consumer, enabling smaller losses and high transmission capacity.

Subsystems has historically been seen in DH systems when for example transitioning from a small local neighbourhood system, with a shared boiler, to common DH connection. Such systems are known to be quite inefficient in terms of heat losses. Usually those losses are covered by the costumers as the measuring point would be at the at the substation, between the subsystem and the overlaying subsystem. If the DH operator instead would own such a system, reducing such losses would be of greater importance. In the simulation study referenced in this report, the subsystem would instead be owned and operated by the DH company, thus being more interested in reducing the distribution losses, which indeed could be done using 4GDH technology.

A benefit using an intermediate substation is the hydraulic separation, enabling lower pressure in subsystem and different pipe materials, potentially also direct connection of SH systems.

Finally, introducing a third pipe would not only imply additional heat transferring surface and potentially additional heat losses but also additional need for pump work. However, much like for the introduction of the third pipe this depends greatly on pipe dimensions and temperatures, which could be observed in the results of this thesis.

5.2 Calculating the CRG

Calculating the dispatch of the DH system of Gothenburg, a constant temperature level is assumed throughout the year, while satisfying an energy balance. This is not how the system is operated in practice, considering the control curve from figure 2.5.

For some hours, particularly in times of high demand, the distribution system can't deliver all the heat from centralized production units and local plants must be activated. Only the major ones of those distributed plants (of Rosenlund and Tynnered) are included in this study but there exist a number of minor distributed

HOBs throughout the system. These are expensive to operate but necessary to satisfy the demands of the costumers. Thus satisfying the hourly energy balance is not representative and will result in too low operation costs. However this error is present for all simulations and should not affect the CRG too much as thous units will have to operate either way.

The temperature of the DH system is neither constant throughout the year nor in space. The overall system temperature correlates to the outside temperature and congestion of the distribution system. This implies that both how the unit performance have been approximated along with how its used in this study is a source of error. Furthermore the linear approximation of the how the unit performance is affected by the system temperature is a simplification.

Not including the EU ETS scheme in the BAU case showed only a minor impact. Furthermore simplifications made in not including any minimum up- and down-times for the production units might also have affected the results, particularly the use of RYA HOBs, which in practice are not used too sporadically due to start-up costs.

Perfect foresight enables a truly optimized system, for example maximizing electricity production hours with extremely high prices. On that note it was found very beneficial to allow for a variable α-value for Rya CHP, i.e dumping heat in the river to maximize electricity production in times of high electricity prices but little heat demand. Also the operation of Högsbo CHP was very affected by this.

5.3 Production units of Gothenburg

The fact that the affected production units probably did not behave as linearly as assumed for varying temperature levels has already been disused, however their very behavior has not.

In section 2.5 the general temperature dependency of certain production units was presented and in section 3.1.2 the corresponding response for the production units was. Yet, some did not behave as expected, which is discussed below.

Rya HP's The HPs of Rya did respond to both reduced supply and return temperatures whereas the improved heat output was expected to be due to the reduced temperature lift, i.e the supply temperature. First of all the HPs are not able to deliver sufficient temperatures for parts of the year, due to design and type of refrigerant. Thus Rya HOBs are sometimes used for increasing the temperature leaving the HPs. For this reason the reduced temperature lift has limited effect on the performance of the HPs (in practice though it might reduce the need for support from Rya HOBs). Instead the lower return temperature enables sub-cooling in the condensers and consequently a larger heat uptake in the evaporator, why the reduced return temperature has an unexpected effect.

Rya CHP Reducing the supply temperature of Rya CHP is found to indeed increase the electricity output, just as expected. It turns out though that the temperature of the turbine condenser does correspond directly to the supply temperature, due to internal connections of the plant, and the effects is not as significant as it could have been if the back-pressure had been correlated stronger to the supply temperature.

Renova The waste incineration plat of Renova is the main waste heat provider in Gothenburg and an important part of the DH system. As expected their deliveries are increased for lower return temperatures. Renova constitutes an interesting case though as they have their own cooling system, consisting of absorption heat pumps, a cooling tower and cooling from a nearby creek. Thus they have the ability to set their own return temperature, crucial for the operation of their FGC and cleaning processes. Additionally all waste heat providers has redundancy for when the DH system can't take up their waste heat sufficiently. Yet, providing a lower return temperature should enable the operation and heat delivery to be improved, which it indeed is.

The refineries Both refineries shows, as expected, larger heat deliveries for lower supply temperatures but also larger deliveries for lower supply temperatures. Preem acknowledge this supply temperature dependency [70], which is actually very significant for high temperature requirements, i.e when the heat load is high and the waste heat deliveries especially valuable to both parties. Preem do have significant amounts of heat at lower temperature levels, today cooled of internally, which could have been utilized, providing investments in HEX equipment. There are bottlenecks though due to limited amounts of high temperature heat. The DH return flow enters the plant in processes operating at intermediate or low temperatures and collects as much heat as possible. In order to deliver the requested supply temperature though heat is collected from processes of higher temperatures. For higher temperature requirements tough the flow has to be reduced in order to secure such requirements and the low-grade heat has to be cooled of internally.

5.4 Sensitivity analysis

The sensitivity analysis of the CRG is described and analyzed in appendix A and the results presented in section 4.1.1. Some particularly interesting parts though is further discussed below and put into a somewhat different context.

Electricity prices The sensitivity analysis provides a good understanding of the effects of electricity prices to the merit order and overall operation. The approach of just scaling up and down the average price though is not very representative. The future electricity price is expected to be more fluctuating, resulting in even larger synergies between HPs and CHP, particularly for varying α-value [9]. Furthermore a reduced net electric output is a consequence of most analysis preformed, as the CHP production is displaced and the HP production somewhat increased.

Natural gas price As the DH production of GE will be fossil free in 2030 the very important CHP plant of Rya will have to be operated differently. The sensitivity analysis shows a large impacts to both the total cost of operation and the CRG and consequently the importance of Rya CHP to the DH system of Gothenburg. A higher natural gas price, with complete CO_2 tax exemption could correspond to scenario where Rya CHP is fueled by more expensive bio-gas.

Waste heat The sensitivity analysis preformed on increased and decreased waste heat availability only concerned with the waste heat from the refineries, Renaova was excluded. The future of Swedish waste incineration is assumed to continue, despite the fact that some of the waste incinerated today are imported from Europe [71] and that the overall goal is to reduce the material flow going towards energy recovery.

Besides showing the impact of reduced waste heat access, however likely, the scenario of increased access could be used as to represent the introduction of a seasonal storage. By increasing the share of available, inexpensive, heat throughout the year the effects of a seasonal storage is fairly represented, showing reduced total cost and CRG. The introduction of a short-term storage would also reduce the overall cost of operation by reducing the most expensive peaks, having a similar impact to the costs.

Although a seasonal storage would reduce the heat cost and CRG, thus the value of 4GDH, it would also put an increasing value on the heat during summer,increasing the value of 3P.

Another waste heat related observation has to do with the reduced waste heat cost, despite the increased uptake for most analyzed scenarios. This obviously has to to with the business model used when calculating the cost but still, illustrates an important phenomenon that have to be addressed, especially if increased uptake would require investments in the related parts of the DH system.

6 Conclusion

This thesis has dealt with the variable cost of operation and on how a shift towards 4GDH would impact such costs in the DH system of Gothenburg. It is found that the CRG of today's system, with present temperature levels of about $(90/45)°C$, would correspond to about 2.3 SEK/MWh,$°C$, decreasing linearly towards 1.7 SEK/MWh,$°C$ at $(75/30)°C$. The CRG is found to be sensitive to fuel prices and system composition and for a developing system, with probably lower costs of operation due to investments in storage and production units, the cost savings related to reducing the temperature might be reduced. The emphasis of this thesis though has not been to find an exact CRG of Gothenburg but to use it as a tool in order to evaluate parts of the 4GDH concept.

The technologies suggested when shifting towards 4GDH, namely a third distribution pipe, individual substations and longer thermal lengths has different values in a future DH system.

Longer thermal length, although coming at a cost in terms of more material intensive and increasing the pressure losses, is a necessity for enabling lower temperatures in a future DH system, particularly lower return temperatures. This is in turn made possible by the improvement in terms of energy efficiency of the future building stock moving forward.

Individual substations is also a necessity, if supply temperatures in line with the 4GDH target should be achieved without using a complementing heat source. This is mainly to reduce the risk of legionella. Also in order to reach the target of individual measuring, in accordance with the EU energy efficiency directive, for multi-family buildings.

The third pipe is mainly used off heating season, to avoid by-pass of the supply stream back to the source, polluting the cooler return flow. This is intended to reduce distribution losses and improve the efficiency of the production system, due to lower return temperatures. This phenomenon will also be more reoccurring in the future, as buildings becomes more efficient and the DHW-share of their heat load increases.

When differentiating the CRG over a year its found that the saving potential correlates with the outside temperature. Thus, the benefit of reducing the system temperature summertime is not very valuable in the DH system of Gothenburg, implying a lower value of the third pipe.

Furthermore, reducing the temperature levels, at least for smaller pipe dimensions is found to be very favourable in terms of distribution losses. However the same does not go for the larger distribution pipes, as reduced system temperatures, at least in line with the suggested levels of 4GDH, implicitly requires larger flows. For large loads the same reasoning simply doesn't hold, as the required additional pump work outweighs the reduction in heat losses.

With the conclusions above in mind, the likely full-scale introduction of 4GDH technology in Gothenburg and other established DH systems is by individual subsystems. If located close to a low grade heat sink, currently not accessible with present temperature levels, additional energy could be made useful whilst reducing distribution losses. In such a subsystem all parts of the 4GDH concept could be utilized, including the third pipe. The surrounding DH system would only be positively affected and consumers with relatively small loads could be made profitable.

A complete shift to 4GDH is not likely in an established system. In a completely new system though, perhaps in central Europe, it might be a crucial concept in order to introduce DH and open up new markets, displacing less resource efficient heating solutions.

Bibliography

[1] Our Energy System. Gothenburg Energy. Available from: https://www.goteborgenergi.se/Om_oss/Vad_vi_gor/Vart_energisystem

[2] Frederiksen S, Werner S. District heating and district cooling. 1st ed. Lund Studentlitteratur AB 2013.

[3] Connolly D, Vad Mathiesen B, Alberg Østergaard P, Möller B, Nielsen S, Lund H, et al. Heat Roadmap Europe 2050. Euroheat & Power 2012.

[4] Lund H, Werner S, Wiltshire R, Svedsen S, Thorsen JE, Hvelplund F, et al. 4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems. Energy 2014;68:1-11.

[5] Lauenburg P. Teknik och forskningsöversikt över fjärde generationens fjärrvärmeteknik. LTH 2014.

[6] GAMS. Available from: https://www.gams.com/

[7] Di Lucia L, Ericsson K. Low-carbon district heating in Sweden - Examining a successful energy transition. Energy Research & Social Science 2014;4:10-20.

[8] Tillförd energi till kraftvärme och fjärrvärmeproduktion och fjärrvärmeleveranser 2017. Energiföretagen 2017. Available from: https://www.energiforetagen.se/statistik/fjarrvarmestatistik/tillford-energi/

[9] Romanchenko D, Odenberger M, Göransson L, Johnsson F. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden. Applied Energy 2017;204:16-30.

[10] Heating and cooling facts and figures. Heat Roadmap Europe 2017.

[11] 2020 climate & energy package. European commission. Available from: https://ec.europa.eu/clima/policies/strategies/2020_en

[12] 2030 climate & energy framework. European commission. Available from: https://ec.europa.eu/clima/policies/strategies/2030_en

[13] Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. European commission 2013.

[14] Energy Efficiency Directive. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC.

[15] Energy Performance of Buildings Directive. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings.

[16] Buildings. European commission. Available from: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings

[17] Overall objectives and Swedish objectives within Europe 2020. Government Offices of Sweden. Available from: https://www.regeringen.se/sverige-i-eu/europa-2020-strategin/overgripande-mal-och-sveriges-nationella-mal/

[18] The climate policy framework. Government Offices of Sweden. Available from: https://www.regeringen.se/artiklar/2017/06/det-klimatpolitiska-ramverket/

[19] Energy in Sweden - Facts and Figures 2018. Swedish Energy Agency.

[20] Our History - Over 150 Years of Energy. Gothenburg Energy. Available from: https://www.goteborgenergi.se/Om_oss/Vilka_vi_ar/Historia

[21] The District Heating Network. Gothenburg Energy. Avalable from: https://www.goteborgenergi.se/foretag/vara-nat/fjarrvarmenat

[22] Development strategy Gothenburg 2035. Göteborg stad 2014.

[23] Färdplan Fjärrvärme 2035. Göteborg Energi 2017.

[24] Climate program for Gothenburg. City of Gothenburg 2014.

[25] Housing and premises. Swedish Energy Agency. Available from: http://www.energimyndigheten.se/statistik/bostader-och-lokaler/

[26] BEN 2. Boverkets författningssamling 2017:6.

[27] BBR 24. Boverkets författningssamling 2016:13.

[28] EU Council agrees on proposal for a revised Energy Performance of Buildings Directive. Build Up 2017. Available from: http://www.buildup.eu/en/news/eu-council-agrees-proposal-revised-energy-performance-buildings-directive-0

[29] Förslag till svensk tillämpning av nära-nollenergibyggnader. Boverket 2015:26.

[30] Petersson S, Dahlberg C. Samband mellan flödespremie och returtemperatur. Svensk Fjärrvärme AB 2013:25.

[31] FVB Sweden. Cilla Dahlberg-Larsson.

[32] Fransson A. Avkylningsarbete på Göteborg Energi AB 1995-2004. Svensk Fjärrvärme AB 2005:132.

[33] Gustafsson P. Värdet av nättemperaturen. Göteborg Energi 2014.

[34] Tekniska bestämmelser för fjärrvärmecentraler. Göteborg Energi 2016.

[35] Wollerstrand J, Lauenburg P. Fältförsök med adaptiv regelering av radiatorsystem. Svensk fjärrvärme AB 2009:19.

[36] Jangsten M. Survey of Radiator Temperatures in Buildings Supplied by District Heating. Chalmers University of Technology 2016.

[37] Lund H. 4th Generation District Heating. Presentation at Danfoss Trata in Ljubljana, Slovenien, 12-13 February 2014. Available from: http://danfoss.viidea.net/ttc3_lund_4th_generation_district_heating/

[38] Averfalk H, Werner S. Essential improvements in future district heating systems. Energy Procedia 2016;116:217-225.

[39] Averfalk H, Werner S. Novel low temperature heat distribution technology. Energy 2018;145:526-539.

[40] Kaarup Olsen P, Holm Christiansen C, Hofmeister M, Svedsen S, Dalla Rosa A, Thorsen J-E, et al. Guidelines for Low-Temperature District Heating. EUDP 2014.

[41] Energilyftet. Swedish Energy Agency 2018. Available from: http://energilyftet.learnways.com/
[42] Smart Energy Systems. Energy Plan 2019. Available from: https://www.energyplan.eu/smartenergysystems/
[43] Sandvall A. Future District Heating Interactions – Modelling Impacts of Industrial Excess Heat Utilisation and Energy Efficient Buildings. Chalmers University of Technology 2018.
[44] Nord Pool. Available from: https://www.nordpoolgroup.com/
[45] Ectogrid. Available from: http://ectogrid.com
[46] Kensby J. Smart Energy Grids Utalization of Space Heating Flexibility. Chalmers University of technology 2017.
[47] Connolly D, Hansen K, Drysdale D, Lund H, Vad Mathiesen B, Werner S, et al. Stratego WP2. Heat Roadmap Europe 2016.
[48] David A, Vad Mathiesen B, Averfalk H, Werner S. Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. Energies 2017;10:578.
[49] F:101 District Heating Substations - Design and Installation Energiföretagen 2016.
[50] Underfloor heating. Swedish Board of Housing. Available from: http://www.energimyndigheten.se/en/sustainability/households/heating-your-home/heat-distribution-and-control-systems/underfloor-heating/
[51] Arbeitsblatt W 551. DVGW 2004. Available from: https://www.dvgw-regelwerk.de/plus/#technische-regel/dokument/7b38aa
[52] Ottosson U, Wollerstrand J, Lauenberg P, Zinko H, Brand M. Nästa generations fjärrvärme. Fjärrsyn 2013:1.
[53] Fjärrvärme - resurseffektiv uppvärmning. Energiföretagen 2018. Avaliable from: https://www.energiforetagen.se/sa-fungerar-det/fjarrvarme/
[54] Li H, Svendsen S. Energy and exergy analysis of low temperature district heating network. Energy 2012;45:237-246.
[55] Is there Legionella bacteria in your water pipes? Boverket 2001.
[56] RISE. Anna Boss.
[57] Goop J. District heating in the Nordic countries – modelling development of present systems to 2050. Chalmers university of technology 2012.
[58] Utsläppsrätter. Skatteverket 2019. Available from: https://www.skatteverket.se/foretagochorganisationer/skatter/punktskatter/energiskatter/verksamhetermedlagreskatt/utslappsratter.4.121b82f011a74172e5880006846.html
[59] Kraftvärme. Skatteverket 2019. Available from: https://www.skatteverket.se/foretagochorganisationer/skatter/punktskatter/energiskatter/verksamhetermedlagreskatt/kraftvarme.4.361dc8c15312eff6fd19412.html
[60] Kvotnivåer. Energimyndigheten 2019. Available from: http://www.energimyndigheten.se/fornybart/elcertifikatsystemet/kvotpliktig/kvotnivaer/

[61] SKM Elcertificate price history (SEK). Svensk kraftmäkling 2019. Available from: http://www.skm.se/priceinfo/history/
[62] Fors J. Spillvärme från industrin till fjärrvärmenät. Svensk Fjärrvärme 2004:5.
[63] Johnsson J, Sköldberg H. Principer för värdering av spillvärme. Svensk Fjärrvärme 2005:3.
[64] Historical Market Data. Nord pool 2019. Available from: https://www.nordpoolgroup.com/historical-market-data/
[65] skattesatser på bränslen och el. Skatteverket 2019. Available from: https://www.skatteverket.se/foretagochorganisationer/skatter/punktskatter/energiskatter/skattesatserochvaxelkurser.4.77dbcb041438070e0395e96.html
[66] Averfalk H, Werner S. Framtida fjärrvärmeteknik. Energiforsk 2017:419.
[67] Persson U, Werner S. Heat distribution and the future competitiveness of district heating. Applied Energy 2011;88:568-567.
[68] HSB Living Lab. HSB 2019. Available from: https://www.hsb.se/hsblivinglab/Research/energi/fjarrvarme-i-lagtemperatursystem/
[69] Castro Flores J, Chiu J NW, Le Corre O, Lacarriére B, Martin V. Energetic and Exergetic Analysis of Alternative Low-Temperature Based District Heating Substation Arrangements. International Journal of Thermodynamics 2016;19(2):71-80.
[70] Preem. Emil Malmström.
[71] Frågor och svar om energiåtervinning ur avfall. Energiföretagan 2019. Available from: https://www.energiforetagen.se/sa-fungerar-det/fjarrvarme/fjarrvarmeproduktion/energi-fran-avfall/fragor-och-svar-om-energiatervinning-av-avfallny-sida/

A

Sensitivity analysis

Following table A.1 is a description and breif analysis of the investigated cases.

Table A.1: CRG and slope for the cases investigated, along with total cost of operation, revenue from electricitysales total cost of waste heat for the reference and lowest temperature scenario.

Case	**CRG** $\frac{SEK}{MWh,°C}$	**Slope** $\frac{SEK}{MWh,°C^2}$	$\mathbf{TC}_{45}$ MSEK	$\mathbf{TC}_{30}$ MSEK	$\mathbf{EL}_{45}$ MSEK	$\mathbf{EL}_{30}$ MSEK	$\mathbf{WH}_{45}$ MSEK	$\mathbf{WH}_{30}$ MSEK
BAU	2.33	0.041	300	198	120	76	189	169
No losses	2.05	0.033	300	209	120	80	189	175
No prod.	0.28	0.0005	300	286	120	113	189	187
Load 2016	2.42	0.038	323	213	145	100	211	187
CO2 tax	2.48	0.041	315	206	93	60	203	179
Waste +50%	1.90	0.037	219	137	85	50	200	167
Waste +100%	1.50	0.034	152	89	59	35	197	149
Waste -50%	2.73	0.041	393	271	170	111	177	164
Waste -100%	2.62	0.034	506	388	227	176	159	147
EL 200	2.54	0.047	311	201	47	27	211	182
EL 400	1.77	0.021	257	177	301	190	168	155
EL 500	1.40	0.023	169	107	530	462	135	117
Cert. 100	2.37	0.042	305	202	114	75	195	172
Cert. 150	2.41	0.043	310	204	111	75	199	175
EU ETS 50	2.33	0.041	300	198	112	73	195	172
EU ETS 100	2.36	0.043	301	199	102	67	200	176
EU ETS 500	2.39	0.045	310	207	69	36	228	199
Gas 500	3.45	0.072	380	234	22	14	289	231
Chips 250	2.49	0.043	323	215	136	81	207	186
Pellets 350	2.33	0.040	302	200	128	80	189	170
Oil 600/900	2.33	0.041	300	198	120	76	189	169
All high	3.87	0.076	450	284	105	58	318	266
High+EUETS	3.88	0.075	452	286	84	44	354	282

BAU The BAU case (including no impact on the losses and no impact on production performance) was descried thoroughly in chapter 3 and 4.

Load 2016 Corresponding calculations as for the BAU case was preformed based on the heat load, outside temperature and electricity prices of 2016, nothing else changed. The CRG of this scenario was lower, despite the higher cost of operation, which can be explained by the overall higher heating demand with more peaks. The average electricity price was slightly lower in 2016 whilst the revenue from electricity sales was larger, due a higher heat demand of some 100 GWh but also a larger share of production from Rya CHP.

CO_2 tax CO_2 tax was adjusted as to correspond to the taxes from 2018 and onward, i.e 89 % for CHP plants instead of 100 %. Mainly effecting the operation of Rya CHP the electricity revenue was drastically reduced as the plant operated for fewer hours. This also influenced the average marginal cost of heat, which can be seen observing the cost of waste heat. Consequently the CRG was increased for this scenario as the CO_2 tax appeared to be rather significant for the system operation.

Waste ± 50-100 % The amount of waste heat available from the two refineries ST1 and Preem (the waste incineration plant of Renova not affected) was increased and decreased with 50 and 100 %. The increasing performance was not adjusted accordingly for lower return temperatures, only for the -100 % scenario where it was removed completely. Again Rya CHP but also obviously the cost of waste heat is affected by the change in available heat.
For increasing access to waste heat the electricity revenue is reduced allot, however the cost of waste heat is not as much increased as might have been expected. The reduced operation of expensive units brings down the cost of waste heat, almost as much as the increased output, similarly to what is observed for the BAU case. The CRG is also reduced when increasing the waste heat availability.
For reducing the available waste heat the CRG is actually lower for the 100 % case, however this can be explained by the fact that no performance increase was coincided for this scenario. The electricity output increased whilst the cost of waste heat again was not too affected, largely due to the drastically increased overall cost of operation.

EL 200-500 The average electricity price of 2017 was close to 300 SEK/MWh. The same price profile has been scaled up and down as to correspond to a yearly average of 200, 400 and 500 SEK/MWh. It can be observed how the total cost of operation is very much increased as the electricity price increases. For some hours the CHP production of Rya even displaces some of the waste heat production as the electricity revenue leads to negative marginal costs. The CRG is affected accordingly, increased for lower electricity price and deceased for higher. The DH system of Gothenburg is apparently very benefited by increased electricity prices, despite the use of industrial HPs, du to its large CHP capacity.

Cert. 100-150 The cost of electricity certificates was adjusted to correspond to the levels observed until May in 2018 [61], along with the current quota obligation of 29.9 [60], not having a very big effect.

EU ETS 50-500 The EU ETS scheme is not included in the BAU model but the marginal impact of emitting CO_2 is coincided in this sensitivity analysis. The scheme creates a market place for trading of emission permits at a price set by the marked, which is varied over 50, 100 and 500 SEK/ton CO_2 in this analysis, corresponding to a low, intermediate and very high price. GE is assumed to be allocated sufficiently with permits, implying no direct cost from the trade. However as one can both sell and buy on the market it is indeed beneficial to save your allocated permits if the price of selling them back is sufficient. This affect is included in the optimization model by considering the cost of emission permits in the objective function, however not when presenting the total cost of operation. Thus, the scheme will impact the operation but only ad an indirect cost from altered operation. However the observable impact is quite small, both in terms of CRG and total cost.

Fuel prices The fuel prices, of natural gas, wood chips, wood pellets, fuel-oil and bio-oil has been increased. Increasing the price of natural gas the CO_2 tax was also removed, as to represent bio-gas. When increasing the price of fuel-oil the price of bio-oil was increased in accordance to 600 and 900 SEK/MWh respectively. Altering the price of pellets or oil has little affect, as the units driven by those are operated for so few hours. Yet, increasing the pellets price makes Rya CHP operate more often, thus increasing the electricity revenue. Increasing the gas price significantly has a large effect, in terms of both lost revenue form electricity production and increased marginal cost due to other production units stepping in. Increasing the price of wood chips though makes Sävenäs CHP operate less, enabling a higher utilization of Rya CHP.

High The scenarios All high and High + EU ETS incorporates the highest prices of electricity and fuel, yet not considering the electricity certificate. The resulting costs are extraordinary high, only comparable to the reduction in waste heat availability. The CRG though is even higher, as the improved performance, mainly from the waste heat providers will have an immerse affect on the resulting cost savings at such high costs. Including also the EU ETS scheme seems to have little affect on the total cost, however reducing the revenue from electricity sales and increasing the cost of waste heat.

B

CRG 3P

Table B.1: The lover interval (-18 °C) applies for all temperarures $< -16°C$, and the higher interval (20 °C) for all temperatures $\geq 16°C$. For the intervals in between ranges $\pm 2°C$ in accordance with the referenced study [39].

Interval [°C]	-18	-14	-10	-6	-2	2	6	10	14	20
Lower limit [°C]	< -16	-16	-12	-8	-4	0	4	8	12	16
Upper limit [°C]	-16	-12	-8	-4	0	4	8	12	16	> 16

Table B.2: Key figures from the simulation study of [39] and the corresponding results for DH system of Gothenburg.

Interval [°C]	Study [nr. h]	2017 [nr. h]	TC [MSEK]	Load [GWh]	CRG [$\frac{SEK}{MWh,°C}$]	Heat cost [SEk/MWh]
-18	28	0	0.00	0.0	-	-
-14	54	2	0.34	2.0	3.41	165.94
-10	127	21	4.08	23.1	3.37	177.11
-6	306	107	14.01	96.2	2.77	145.53
-2	767	692	72.17	562.3	2.66	128.35
2	1608	1594	119.54	1079.5	2.59	110.73
6	1700	1868	78.84	1006.2	2.81	78.36
10	1425	1236	10.56	422.3	1.73	25.01
14	1593	1934	0.09	370.9	0.014	0.25
20	1151	1360	-0.06	220.5	0.05	-0.26

Table B.3: Temperature, costs and savings corresponding to the contemporary case investigated.

Interval [$^{\circ}C$]	Temp R (2P) [$^{\circ}C$]	Temp R (3P) [$^{\circ}C$]	Temp 3P [$^{\circ}C$]	TC [SEK]	Savings [%]
-14	33.3	33.3	8	91	0
-10	31.7	31.7	8	903	0
-6	30	30	8	3267	0
-2	28.3	28.3	8	15 713	0
2	26.7	26.7	8	25 414	0
6	25	25	8	16 255	0
10	25	24	844	2 415	7
14	34	22	50	22	686
20	43	18	51	-7.6	-449

Table B.4: Temperature, costs and savings corresponding to the future case investigated.

Interval [$^{\circ}C$]	Temp R (2P) [$^{\circ}C$]	Temp R (3P) [$^{\circ}C$]	Temp 3P [$^{\circ}C$]	TC [SEK] [SEK]	Savings [%] [%]
-14	26.5	26.5	8	36	0
-10	25	25	8	355	0
-6	24	24	33	1 274	0
-2	25	22	448	6 049	6
2	30	20	49	2 246	23
6	36	18	50	5 952	65
10	43	15	51	833	194
14	44	11	51	211	1 885
20	44	11	51	-8.1	-593