

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Solar District Heating for Low Energy Residential Areas

A Technical Analysis of Heat Distribution Concepts

for a

Solar Assisted District Heating System

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Gothenburg, Sweden 2019

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Cover:

Schematic of the partly decentralized system in Vallda Heberg, showing a single-family house (SFH) to the left, substation and arbitrary building(s) with roof-mounted collectors (middle) as well as central heating plant with roof mounted collectors (right) - see *2.1 Distribution systems*.

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ABSTRACT

The integration of a solar thermal system into a district heating network can be a cost-effective solution, especially for new low-energy residential areas. Because of this, many new small solar district heating systems are built at the same time as the buildings, allowing for a more holistic approach to the design and construction. In doing so, it is possible to optimise the integration of the solar thermal system with respect to both cost and technical layout.

This thesis presents studies that aim to investigate the most energy efficient distribution concept for successful implementation of solar district heating technology. An existing solar assisted district heating system is modelled in simulation software and the distribution system is varied in order to find out whether there is a more energy efficient option. Three system concepts are investigated:

1. A Hybrid system using a combination of high-temperature, conventional steel pipe primary culvert, intermediate substations containing solar buffer stores and a low-temperature, EPSPEX secondary culvert with DHW-circulation (so-called GRUDIS).
2. A Conventional distribution system with steel pipes, higher operating temperatures and centralized solar buffer stores.
3. An All GRUDIS system, using only EPSPEX distribution with DHW-circulation, lower operating temperatures and centralized solar buffer stores.

A sensitivity analysis is performed by simulating the three different distribution system for various linear heat densities, with the added objective of detecting any range-bound limitations of the different distribution systems.

Results indicate that both the hybrid and All GRUDIS distribution concept is preferable to conventional DH distribution regardless of the network heat density. The hybrid concept seems preferable in denser district heating networks, but results are inconclusive regarding the best concept for sparser networks.

Preliminary economic considerations show that the initial investment costs may be reduced by changing from a Hybrid to an All GRUDIS distribution concept, although a more detailed analysis is needed to draw conclusions about the most economical solution.

Keywords: District heating, solar thermal, simulation, renewable energy, 4DH.

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SAMMANFATTNING

Integreringen av solvärme i ett fjärrvärmesystem kan vara en kostnadseffektiv lösning för nybyggda bostadsområden med låga energibehov. Detta är en av grunderna till att många nya små fjärrvärmesystem konstrueras samtidigt med byggnaderna, då det möjliggör en mer helhetlig tillnärmning i utformningen och konstruktionen av bostadsområdet, och optimal integrering av solvärmesystemet med hänsyn till både kostnader och teknisk gestaltning.

Denna avhandling presenterar studier som syftar på att undersöka det mest energieffektiva distributionskonceptet för en lyckad tillämpning av solfjärrvärmeteknik. Ett existerande solfjärrvärmesystem modelleras i ett simuleringsprogram och distributionssystemet byts ut för att undersöka om det finns ett mer energieffektivt alternativ än det som redan används. Tre olika systemlösningar undersöks:

1. Ett Hybrid system, bestående av en kombination av högtemperatur primärkulvert med konventionella stålrör, mellanliggande undercentraler innehållande ackumulatortank för solvärme och lågtemperatur sekundärkulvert med EPSPEX och VV-cirkulering (benämnd GRUDIS).
2. Ett konventionellt stålrörssystem med högre driftstemperaturer och centraliserade ackumulatortankar för solvärme.
3. Ett rent av GRUDIS system, bestående av bara EPSPEX kulvert med VV-cirkulering, lägre driftstemperaturer och centraliserade ackumulatortankar för solvärme.

En sensitivitetsanalys är utförd vid simulering av dem tre distributionssystemen för olika värden av värmedensitet, med målet att upptäcka potentiella begränsningar i användningen av olika distributionskoncept för mer eller mindre glesbyggda områden.

Resultaten visar att både Hybrid systemet och det rena GRUDIS systemet är att föredra framför ett konventionellt stålrörssystem oavhängig av systemets värmedensitet. Hybrid konceptet verkar att vara bättre i mer tätbyggda områden, men resultaten ger ingen klara indikationer på vilket koncept som är bättre i glesbyggda områden.

Preliminära ekonomiska utvärderingar visar att den initiala investeringskostnaden kan reduceras vid användning av ett rent GRUDIS system framför ett Hybrid system, men en mer detaljerad analys är nödvändig för att kunna nå slutsatser om den mest ekonomiska lösningen.

Nyckelord: Fjärrvärme, solvärme, simulering, förnybar energi, 4DH.

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List of papers

This licentiate thesis is based on the following papers:

Paper I Perez-Mora, N., Bava, F., Andersen, M. et al., Solar district heating and cooling: A review. Int J Energy Res. 2017, 1 – 23. <https://doi.org/10.1002/er.3888>

The author wrote the section on block-heating and case-study as well as contributed to the sections introduction and conclusions.

Paper II Andersen, M., Bales, C., Dalenbäck, J-O., Techno-economic Analysis of Solar Options for a Block Heating System, in proceedings of Eurosun 2016, Palma de Mallorca, Illes Balears, October 2016. doi:10.18086/eurosun.2016.05.12

The author continued the work of another researcher based on a subsystem simulation model calibrated against real measurement data. Planning of the modelling approach was a collaborative effort with Dr. Chris Bales, while the author carried out simulations. The author did the analysis of simulation results and wrote most of the paper, with support from Dr. Chris Bales and Dr. Jan-Olof Dalenbäck.

Paper III Andersen, M., Bales, C., Dalenbäck, J-O., Technical Study on Heat Distribution Concepts for a small Solar District Heating System, submitted to the Journal of Applied Energy, September 2019.

The author planned the modelling approach and made the simulation model, collected engineering standards on the design of heat distribution networks and carried out all design calculations for the network pipe sizes. The author carried out the simulations, analysed simulation results, did error assessments on the model accuracy and wrote most of the paper. Dr. Chris Bales supported in planning of modelling approach and the application of standards during the design of heat distribution networks and together with Dr. Jan-Olof Dalenbäck evaluated results and supported in the writing of the paper.

Only the first 11 pages of the Paper I are included, as this part is the most relevant for the thesis. Paper II and Paper III follow in full text.

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Nomenclature

CHP	Combined heat and power
CW	Cold water
DH	District heat(ing)
DHW	Domestic hot water
DN	Nominal diameter
EPS	Extruded polystyrene
EPSPEX	EPS encased PEX pipes
ETC	Evacuated tube collector(s)
FPC	Flat plate collector(s)
GRUDIS	Swedish acronym for "Gruppcentraldistributionssystem"
HDD	Heating degree day(s)
HP	Heating plant
LA	Large array
LD	Line heat density
LOA	Leftover array
LTDH	Low temperature district heating
PC	Primary culvert
PEX	Cross-linked polyethylene
PSF	Primary scale factor
SC	secondary culvert
SDH	Solar district heating
SEK	Swedish krone(s)
SF	Solar fraction
SFH	single-family house
SH	Space heating
SS	substation
SSF	Secondary scale factor
ST	Solar thermal
TMY	Typical meteorological year

1. Introduction

1.1 Background

District heating (DH) has been used as an efficient method to generate and distribute heat commercially for many years now. The world's oldest operational DH system is located in Chaudes-Aigues, France. It was put in operation in the 14th century, utilizing geothermally heated water. However, the first commercial system was developed in Lockport (USA) in 1877, utilizing steam as a heat carrier [1]. The first DH systems in Europe and Russia were installed during the 1920s and '30s, all with the aim of reducing the fuel demand and delivering heat more efficiently. This aim was further emphasized by including DH in the new national energy policies adopted by many countries during the oil crises in the '70s [2]. Nowadays, 6 – 7% of the global heat demand [3] and 9% total heating needs in Europe are supplied by community and district heating systems [4].

Fundamentally, the underlying principles of the DH concept is to recycle heat that would otherwise go to waste and to enable a more efficient use of primary energy and hence, natural resources. For these reasons, countries (e.g. Sweden and Germany) that have energy-intensive industries based on processes like metallurgy, petroleum and paper production have traditionally had strong ties to DH. Likewise, countries (e.g. Denmark and Finland) that traditionally have been dependent on fossil-fuel imports have developed equally strong bonds with DH. Geographically, DH systems are most widespread in the northern hemisphere, predominantly (descending order) in Europe (northern and eastern part), Russia, China and North America. Countries like Denmark, Sweden, Finland together with Poland and the Baltic states have the largest market shares (>40%). Eastern European countries generally have many systems, due to the influence of the former Soviet Union, where DH was under development early as part of the planned economies [5].

The resource availability and ruling energy technologies over the course of history has been dictating the heat carrier employed and maybe more importantly, the applied operating temperatures. The first generation of DH technology employed steam as a heat carrier and was characterized by high operating temperatures and distribution heat losses, leading to low overall system efficiency. As the technology evolved, operating temperatures were reduced and pipe insulation practices improved, progressing towards the third generation DH of today. The future, fourth generation DH, continues this trend and further aims to include renewable sources of heat, which are particularly well suited for low-temperature applications like space heating (SH) and domestic hot water (DHW).

However, district heating has always required a certain line heat density in order to be economically feasible, which has favoured its use in urban environments and limited its employment in rural and suburban areas. As low-energy building codes are increasingly implemented around the world [3], aiming to reduce energy demand, the heat demand density of DH networks is reduced and distribution heat losses become an increasingly larger part of the network energy use. This is contradictory to the fundamental principles of DH and further undermines its future implementation in suburban areas due to reduced competitiveness versus other heating methods. Thus, research efforts are needed to identify the most efficient distribution options available, in order to establish the potential role of DH in the future sustainable energy system [6].

District heating has a long history in Sweden and early research efforts made into small district heating systems for suburban residential areas indicated that plastic pipe systems held the potential of being a cost efficient way of extending the urban DH networks [7,8]. An own research project about sparse district heating concluded that using plastic pipes were one way to make low heat density areas more profitable [9], especially if used in a secondary network, adjunct to a conventional steel pipe system [10]. This view was further endorsed in an official research report conducted by the International Energy Agency (IEA), advising that cross-linked polyethylene (PEX) pipes in an evacuated polystyrene (EPS) casing (so called EPSPEX culvert) are suitable for areas of low heat demand density and have the lowest operation costs [10]. Another IEA report went on to recommend the EPSPEX culvert for use in low temperature district heating (LTDH) as envisioned in 4th generation DH [11], a view recently reiterated as an essential improvement in future DH systems [12].

EKSTA Bostads AB is a municipal housing company located in the south-west of Sweden, known for investments in building and operating new residential areas with the requirement of 100% renewable heat supply, the first ones from the 1980s. This is usually done using small district heating systems with bio-mass boilers and roof integrated solar collectors. The building stock is often of the low-energy or passive house standard and various attempts have been made to lower the distribution heat losses and increase solar fractions. In one system, Vallda Heberg, a hybrid distribution concept combines third and fourth generation DH technology by employing both high temperature steel culverts and low-temperature plastic pipes. In light of the promising experiences from this system, the novel distribution concept has been used as a best-case example of renewable DH [13] and may represent a new solar district heating standard for newly built residential areas. Due to this, it is therefore of interest to determine any potential improvements to the system by moving towards a 4th generation system design. This is the premise of this thesis.

1.2 Literature review on solar district heating

Paper I provided a full review of SDH, where one section went into the details of SDH integration concepts and treated a case study on a small SDH system. This section provides the most relevant parts to this thesis.

1.2.1 System typologies

There are three parts to consider when including ST into a system:

1. the solar circuit itself (collector, piping, pump, valves and expansion vessel),
2. the integration of the solar circuit into the overall system and
3. the flow control in the solar circuit and the control of the rest of the DH system.

The solar circuit itself can, in principle, have the same design for all types of system typology for DH, but practical details vary depending on whether the collector is ground or roof mounted. The main differences between typologies are in system integration, and the flow control in the collector circuit is dependent on this system integration. Primarily, two strategies are used in practice: constant, normally high flow rate to maximize solar gain and matched flow, so that the collector field supplies a desired temperature.

If the ST system will only supply a small part of the DH demand, then the system integration is relatively simple, no matter what the system typology is. With very low solar fraction (>50% of

summer demand), no storage is needed other than the network itself [14]. With higher solar fractions, storage is required somewhere in the system. The choice is centralized or distributed storage, leading to different system typologies and a need for an overall plan for the whole DH network.

The various types of system typologies in solar district heating (SDH) are shown in Figure 1:

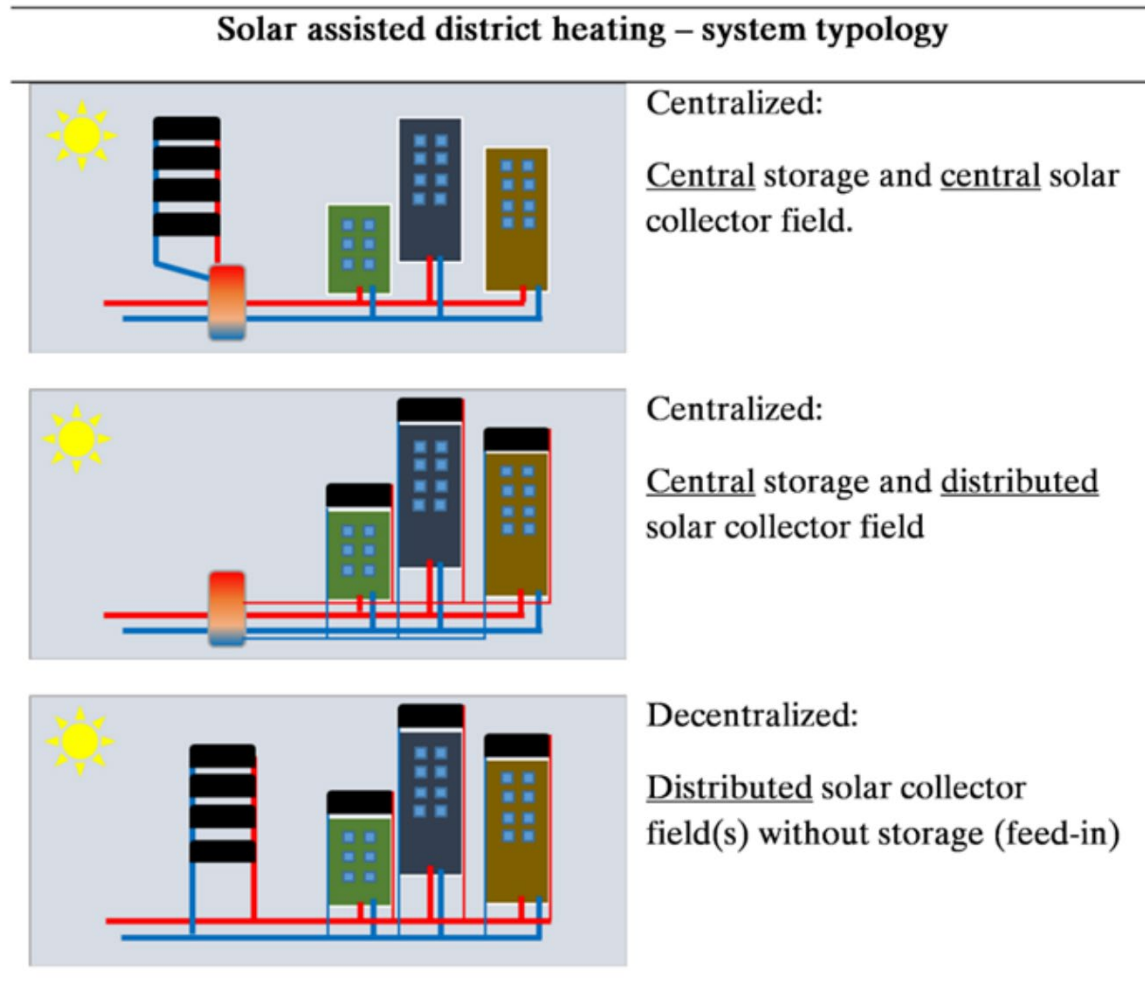


Figure 1 System typologies – overview of the most common system typologies in SDH systems.

In addition to the typologies shown in Figure 1, decentralized systems featuring distributed storage and distributed solar collector fields also exist, but are less common.

In centralized SDH systems, the solar collector field is usually installed close to the main DH plant, which hosts the auxiliary energy system. From a technical point of view, solar heat can be combined with all other fuels for DH, but the auxiliary energy system often relies on natural gas (CHP plants or boilers) or biomass [15–17], and is turned on when solar energy cannot completely cover the heat demand. The solar collector field is usually installed in parallel with the auxiliary energy system. In case of high solar radiation, the collector field often provides the entire temperature rise required by the DH network. If the solar radiation is not sufficient, the auxiliary energy system supplies additional energy to increase the fluid temperature to the DH supply temperature. The heating plant is equipped with a storage, which can store heat from the auxiliary energy system and the solar collector field. The size of the storage plays an important

role in the solar fraction that the system can achieve and short term storage, normally in the form of steel tank(s), makes it possible to increase the solar fraction of the system up to 15 – 20% [18,19]. Higher solar fractions (up to 90%) are proven to be achievable through a seasonal thermal storage [20]. The storage is charged in summer, when excess solar heat is produced, and discharged whenever it is hotter than the operation temperature of the DH network and the collectors do not produce enough heat.

A ST system that is connected to a DH network outside the main heating plant is classified as a decentralized system, even when the distance from the feed-in point to the main pumps in the DH system is only some meters [21]. The collector field is normally roof-mounted, but systems with ground-mounted collectors also exist. Nearly all decentralized ST systems are connected to existing DH networks. Unlike centralized system, decentralized plants are often, but not necessarily, located where there is a load and thus an existing DH substation. Decentralized systems are not relevant to this thesis and will therefore not be treated in more detail.

1.2.2 Block heating

Block heating systems are smaller DH systems. Networks supplying residential areas up to 100 single-family house or urban city blocks of up to 400 dwellings can be found [19]. The integration of a ST system into a block heating network can be a cost-effective solution, especially for new low-energy residential areas. This is why nearly all solar block heating systems are built at the same time as the buildings. Solar assisted block heating systems have been built for more than 30 years [22] and research studies have mainly focused on lowering the heat losses, increasing the efficiency and solar fraction of the ST system, while decreasing the costs.

1.2.3 Solar thermal system integration

The solar integration varies with system concept and may consist of different typologies: centralized storage and collector field, centralized storage and distributed collector field or mixed typologies, where there can be both centralized and distributed collector fields and storage.

Normally, systems with diurnal storage have a design solar fraction of around 20%, delivering 80%-100% of the DHW load in the summer months. Higher solar fractions may be achieved using seasonal storages [23], which is generally thought to be reasonable for networks supplying > 100 dwellings [24].

However, one block heating system supplying 52 houses was built in Canada based on energy simulations, employing ST flat plate collectors and seasonal borehole storage in a low-temperature plastic pipe network. The system has reported solar fractions >90% after five years of operation [20]. A similar system of 50 houses was built in Sweden, and although it didn't achieve the same performance for various operational reasons, it still had an estimated solar fraction around 60% [25]. In both of these systems, individual DHW preparation in combination with roof installed solar collectors on the houses was thought to be the *most* cost effective solution, which is contrary to earlier studies showing local DHW storage to be the *least* cost effective solution[8]. The main reason for this is probably that the heating networks are of the low-temperature kind, whereas DHW preparation requires elevated temperatures. The DHW demand is a large part of the total heating demand in low-energy housing and that may favour local DHW preparation with local storages supplied by solar thermal in combination with an electrical heating element for peak demand.

Increasing the solar fraction for systems with smaller storage units has been proved successful in some Swedish systems supplying low-energy housing, although by employing central DHW preparation in a so called GRUDIS distribution system [26]. These systems represent a low-temperature alternative to networks with local DHW preparation, in that they avoid deployment of comprehensive house substations that allow for DHW-preparation, while keeping the benefits related to lower operating temperatures. This type of system is used in Vallda Heberg, which is used as a case study in **Paper II** as well as being the basis for the study in **Paper III**.

1.2.4 GRUDIS

The acronym GRUDIS is short for the Swedish term GRUppcentralDIstributionsSystem. The GRUDIS system was developed during the 1980s with the intention to offer a low-cost distribution alternative to residential areas where traditional steel pipe culverts would be too expensive due to low network heat demand densities. Despite the long history of GRUDIS, it is treated as a 4th generation DH technology in this thesis, due to the fact that the technology was developed as an alternative to the 3rd generation DH system technology and that the characteristics largely correspond to those considered desirable in future DH systems [11,12].

Main characteristics of the GRUDIS technology:

- Plastic pipe (PEX) culvert.
- DHW employed as heat carrier and drawn off directly from the pipe without hydraulic separation.

Fundamental properties of GRUDIS (and plastic pipe systems in general):

- Simple and flexible installation.
- Long pipes (up to 200 m), meaning no splices.
- No welding works.
- Limitations in working temperatures and pressures.

The technology received a great deal of attention from construction companies and property entrepreneurs, but was largely disregarded by the district heating sector. In addition to restrictions in applicable working temperatures and pressures, limited availability of larger pipe sizes (> DN80) led the distribution concept to be considered suitable primarily for isolated heating networks in smaller residential areas or villages.

Despite this, based on a range of operational evaluations and years of system experiences, the Swedish district heating association has concluded that the GRUDIS technology may indeed be suitable when used in a secondary network, adjunct to a primary network with higher temperatures and pressures [10]. This was the basis for the hybrid distribution system of Vallda Heberg, which is described in the next section.

1.2.5 Case study: Vallda Heberg

The Vallda Heberg area, built by the housing company Eksta in Sweden, consists of 26 single-family buildings, four multifamily buildings (4 apartments per building), 6 terrace houses with in total 22 dwellings and also a nursing home for elderly people with 64 apartments (see Figure 2). The total heated floor area is about 14000 m² and the estimated yearly heat demand is 621 MWh [27], although measurements have shown demands of 722 MWh [28]. All buildings are designed as passive houses with mechanical ventilation heat recovery, and thus the heat demand is low. In the houses, heat is supplied by floor heating in the bathrooms and an additional water/air heat exchanger in the supply air to the building.

Figure 2 shows a schematic of the Vallda Heberg district heating system with colour coded distribution pipelines and intermediate substations (SS) connected to roof-integrated collector areas:

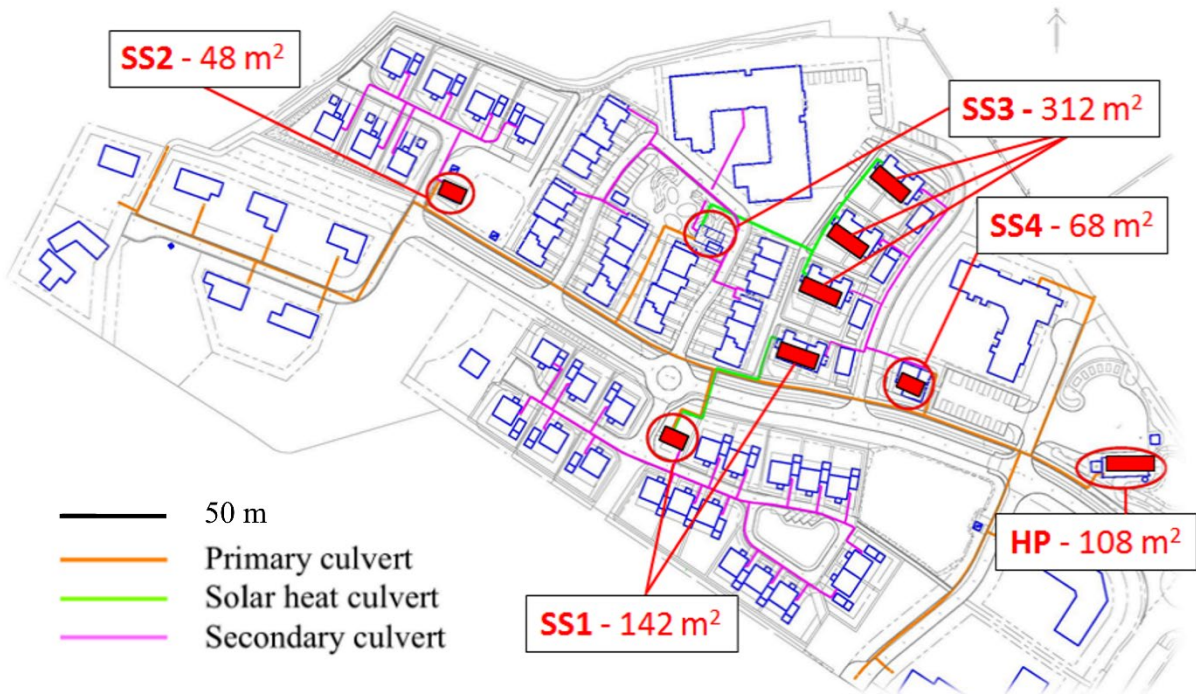


Figure 2: Schematic of the Vallda Heberg district heating system with denoted substations (SS) and the respective roof-integrated collector areas connected to these, together with colour coded distribution pipelines.

The local DH system comprises a central heating plant with a 300 kW wood pellet boiler, supplying four intermediate substations through a steel pipe primary culvert (PC). Each intermediate substation is connected to its own collector array (see Figure 4) and supplies a housing area through a secondary culvert (SC), comprised of cross-linked polyethylene (PEX) pipes insulated by evacuated polystyrene (EPS). In the central heating plant (HP) and in each intermediate substation there are buffer storage tanks. There are 108 m² evacuated tube solar collectors on the heating plant and 570 m² flat plate roof-integrated solar collectors in connection to the substations. The distribution network from the four intermediate substations to the dwellings are of GRUDIS type [10], which essentially is a DHW circulation loop with direct connection to the houses. The DHW is prepared in the intermediate substation by preheating incoming cold water in the buffer storage tank when solar heat is available and

providing auxiliary heating with the PC, when needed. The floor heating in the houses is a part of the DHW circulation loop and to avoid risk of legionella, the entire loop is maintained between 50 °C and 60 °C. For this reason, there is no flow control in the floor heating loop. This results in a very simple and cost-effective heating system, as well as a simple distribution network with plastic pipes. However, as the buildings are passive houses, the energy density of the network is low, which means that the distribution heat losses are a large part of the overall energy use in the system (see Figure 3).

Figure 3 shows the monthly energy balance in 2015 for the Vallda Heberg system as simulated in *Paper II*. Percent values show relative shares of the energy turnover in energy supply/demand.

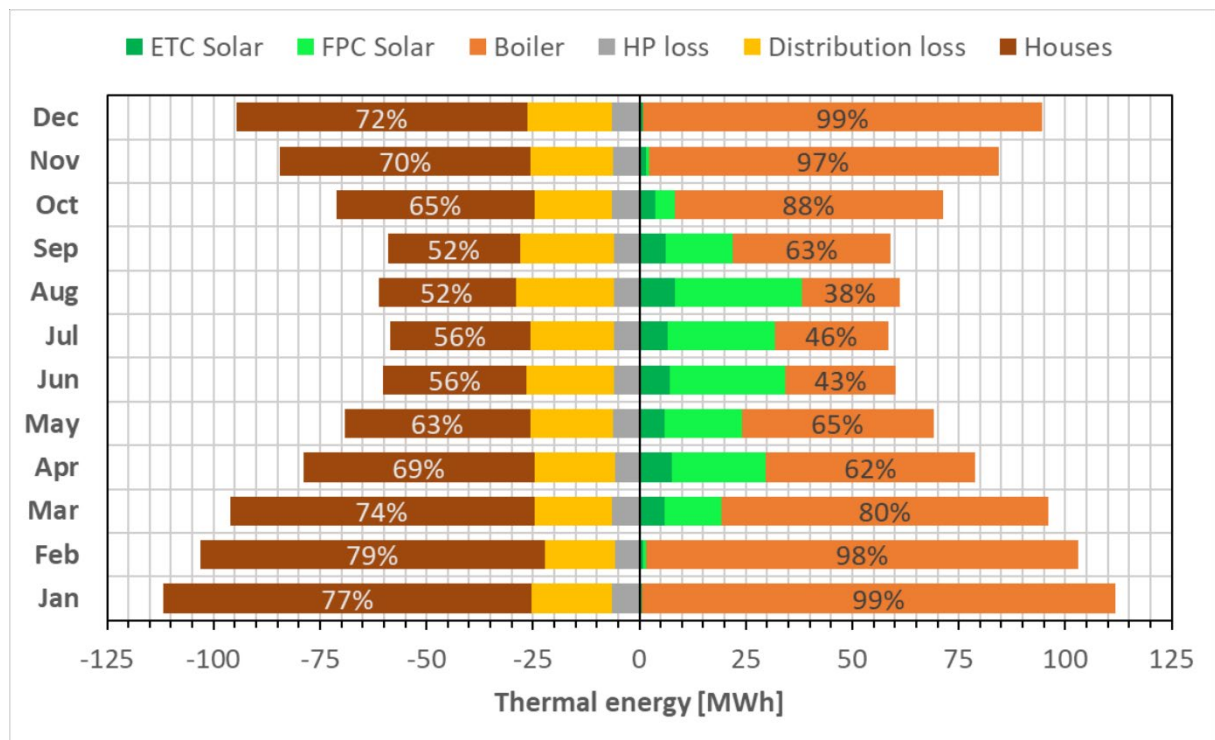


Figure 3: Monthly energy balance in 2015 for the Vallda Heberg district heating system as simulated in *Paper II*. Percent values show relative share of energy supply/demand.

1.3 Research objectives

The research presented in this thesis aims to investigate how the energetic performance of a solar assisted district heating system may be improved by changing the distribution concept altogether. By performing a review of various methods of solar energy system integration (*Paper I*), a hybrid distribution concept is identified as a promising solution for small low-density networks. This concept is comprised of a combination of 3rd and 4th generation DH technology and is compared to a 4th generation (*Paper II*) and 3rd generation distribution concept (*Paper III*), in an attempt to determine the most suitable concept for new DH systems. The main focus of this comparison is on the boiler supplied energy, solar fraction and overall system performance.

A secondary objective is to look at the suitable line heat density range for employment of the different technologies, aiming to reveal any range bound limitations related to their use (*Paper II* and *Paper III*).

Another important, but less detailed part, is related to the cost implications of using various technologies (*Paper II*), as economic conditions are of major significance for their employment.

The research is part of a larger European project on integration of solar heat in heating networks, and therefore attempts to make the results quite general, although simulations are based on Northern European climate conditions.

1.4 Delimitations

The primary focus of the technical analysis conducted in the papers comprising this thesis is on the heat losses of the pipe network and distribution units in various distribution systems, and how this affects the solar contribution. The solar collector type, size and placement (tilt/azimuth) is not varied.

Pressure considerations are not taken into account when modelling, although they are made indirectly during the sizing of the pipe network. In the pipe network, bends and tees are not included, neither are valves and other balancing components. As such, the results presented are supposed to be taken as indicative, rather than definite.

However, despite the heat losses (and costs) of the omitted hydraulic parts potentially being substantial, it is assumed that the impact of neglecting them is more or less the same for all three distribution systems and that the difference in results therefore is representable for the real differences.

2. Method

2.1 Distribution systems

Paper II focused on the case study of the Vallda Heberg residential area, which employed a hybrid distribution concept comprised of high-temperature, steel pipe distribution as customary in the 3rd generation DH and low-temperature, plastic pipe distribution as envisioned in the 4th generation DH. The paper further evaluated the use of an alternative distribution concept named All GRUDIS, which featured the use of only low-temperature, plastic pipe distribution. **Paper III** continued this research by extending the scope to include a more conventional distribution concept, consisting of only high temperature, steel pipe distribution. With a wider scope, it was possible to provide a comparison of both historic, novel present and possible future DH technology performance.

2.1.1 Hybrid distribution system (Vallda Heberg)

Figure 4 shows a schematic illustration of the hybrid heat distribution system at Vallda Heberg, with the heating plant to the right, substation in the middle and a passive single-family house to the left. Hot tap water is prepared by supply of cold water to the substation, where it is heated and distributed through the secondary culvert to the load.

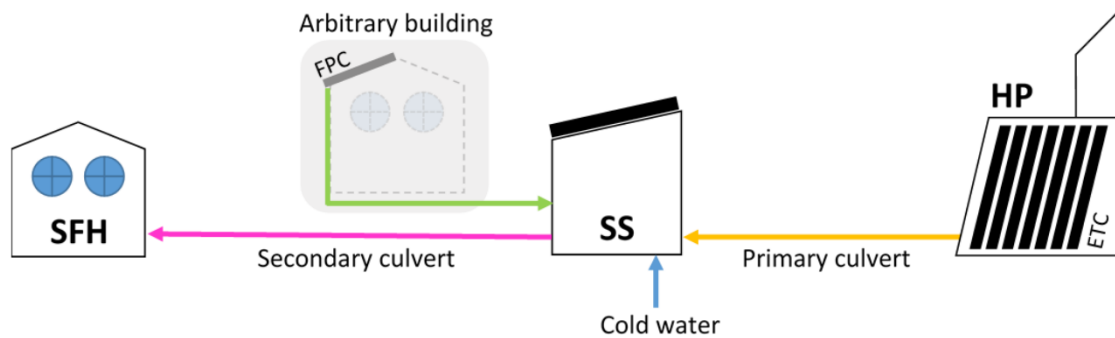


Figure 4: Schematic of the partly decentralized system in Vallda Heberg, showing a single-family house (SFH) to the left, substation and arbitrary building(s) with roof-mounted collectors (middle) as well as central heating plant with roof mounted collectors (right).

2.1.2 Alternative distribution systems

Two alternative system designs have been investigated in the papers comprising this thesis:

1. **All GRUDIS:** EPSPEX culvert and central DHW preparation in heating plant.
2. **Conventional DH:** Pre-insulated steel-pipe distribution and local DHW preparation.

The main similarity between these two system designs is the lack of intermediate substations. This involves a modified HP and extra steel distribution pipes between FPC installation location and the HP. Both system designs feature a similar configuration in that solar heat is harvested on rooftops of buildings attached to the network and stored in buffer storage units in the central HP (see Figure 5). The HP thus includes one buffer storage for the boiler in combination with evacuated tube collectors (ETC) and one buffer storage for the flat-plate collectors (FPC). The main differences are the distribution pipes (steel- vs. plastic pipes) and the location of the DHW preparation.

Figure 5 shows a schematic of a centralized solar district heating system, where cold water (CW) enters the HP as in the All GRUDIS system or the single family house (SFH) as in conventional DH:

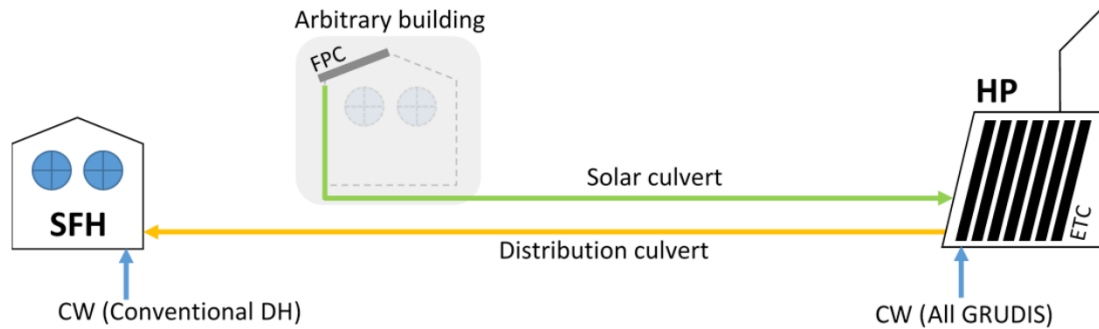


Figure 5: Schematic of the centralized system alternatives to the hybrid distribution system, showing a single-family house (SFH) to the left and arbitrary building(s) with roof-mounted flat plate collectors (FPC) in the middle as well central heating plant with roof mounted evacuated tube collectors (ETC) to the right.

In the All GRUDIS distribution, cold water is supplied to the HP intended for DHW preparation and subsequent distribution to the load. The FPC buffer storage in the heating plant provides (pre-) heating of the cold water and the DHW-circulation flow in the culvert, with additional heat provided by the boiler and ETC buffer storage, when needed.

In the conventional DH system, the DHW is prepared in the house substation, and so the FPC buffer storage is used for preheating of circulation flow only.

2.2 Software tools

2.2.1 TRNSYS

The TRNSYS [29] user interface consists of a drag-and-drop Simulation Studio, where component models are hauled from a number of application specific libraries included in the program and dropped onto a project workspace. The user can combine these components to make system models of desired complexity. The mathematical foundation of the various components is provided in a mathematical reference following the software library structure. Components can be edited or added according to the user's needs, allowing for tailored mathematical approaches and formulae. However, creating components requires programming knowledge in FORTRAN, which may not be readily acquired.

TRNSYS has been one of the standard dynamic simulation programs for (thermal) energy systems since its inception. The reason for this has largely been attributed to the available level of detail in modelling, which gives the possibility of high modelling accuracy. The software is dynamic and can solve systems of equations with a large set of independent variables by iterative calculations, for a user specified convergence tolerance and time step. It is usually accepted that the solution diverges (no solution is found) for a small number of the time steps that make out the entire simulation, but this requires checking of an energy balance for the simulated system to make sure energy is conserved. TRNSYS is highly applicable for modelling energy flux, but is limited in its use for detailed modelling of certain natural phenomenon like hydraulic effects. This, in conjunction with the high requirement on programming skills to include new

components, has led to a number of other software being adapted for simulating energy systems [30].

Some tools used for modelling SDH systems are Polysun, Modelica (Dymola) and Matlab (Simulink), to mention a few. Out of these, Polysun can be considered to be equivalent to TRNSYS in the level of model detail, although studies have shown to yield unsatisfactory accuracy when compared to TRNSYS in simulations of SDH [31]. Modelica, on the other hand, has shown some promise as it allows for a higher degree of detail when compared to TRNSYS, although with a significantly higher computational (time) cost [30]. Matlab has also been used successfully for modelling SDH [32], but as Modelica also requires significant time investments for model development and in addition does not allow for building simulations [33].

2.2.2 DHWcalc

The DHWcalc software is developed based on research on statistic distribution of water consumption in the residential sector and is currently in its second generation. The user interface consists of a number of boxes for input parameters related to DHW draw-offs, as well as a few buttons for navigation. The main features are modelling of tap categories, seasonal variations, holiday periods and variation of profile time step.

The household type (single-family or multi-family house) is taken as input, as well as the number of households (for multi-family house) and average daily water consumption (l/day). The relative share of daily draw-offs can be specified according to time of day and relative monthly share of draw-off volume specified according to peak day of the year. Four tap categories may be defined in order to realistically model the tap modes in a house, making the generated DHW-profile more diverse. Further, a series of draw-off profiles may be generated, with slight variation of the daily draw-off volume, so as to allow for modelling a collection of individual houses in detail [34].

2.3 System model development

In Paper II, a system model was made based on a simplified version of the Vallda Heberg residential area, using technical drawings of the distribution system for sizing the pipe networks and measurement data for calibration of the system heat losses.

In Paper III, a more generalized system model was made based on the simplified version of the Vallda Heberg residential area (*Paper II*), using a systematic method to first size and then model the piping networks and catalogue data for calibration of pipe heat losses.

2.3.1 Simplified system model

In Paper II, a simplified model of the Vallda Heberg district heating area was made by assuming that all dwellings were single family houses and that all housing areas were supplied by identical substations. The piping network was modelled based on technical drawings of the real system and the simplified system was simulated in TRNSYS. The model was calibrated towards measurement data with regard to boiler supplied energy and solar collector yield by adjusting distribution and storage heat losses. Calibration of distribution losses was achieved by changing the thermal conductivity of the insulation in the distribution pipe models, which was done for plastic and steel pipes individually. This calibrated model was further used to simulate an all GRUDIS distribution system using only plastic distribution pipes, meaning to represent 4th

generation DH technology. The conclusions of the study showed some promise of changing the distribution system from a hybrid of 3rd/4th generation DH to a 4th generation system. However, due to large measurement uncertainties, the calibrated model could only be made accurate to within 10% of the measured values on a yearly basis, which was generally considered unsatisfactory. Furthermore, due to large discrepancies on a monthly basis, particularly for the heat losses, some concern arose that the model was inadequate for further simulations where a 3rd generation distribution system would be modelled.

2.3.2 Generalized system model

In Paper III, new computer models were constructed for three different distribution concepts in order to devise a research setup that would allow for more general results, enabling a more just comparison. The residential area was assumed the same as in the simplified model, consisting of only single-family houses and supplied by identical substations. However, the approach used for sizing the piping network was changed from using technical drawings to systematically calculating the size based on loads in the system. In contrast to the process behind the technical drawings, which was largely unknown and therefore brought about a sense of uncertainty, this aimed to make the sizing process more transparent and logical.

Furthermore, by using established standards and guidelines to size the network distribution pipes, before calibrating the specific pipe heat losses toward manufacturer catalogue values, any uncertainties imposed by measurement data could be ruled out. The logic behind this choice of approach was that, despite potential lack of correspondence between simulation results and real system performance, the relative differences between the performances of various distribution concepts would be representative of those that could be found in reality.

Three system models were made based on the distribution system alternatives described in Ch. *2.1 Distribution*.

2.4 System model description

2.4.1 Boundary conditions

The main boundary conditions of importance to the simulations presented in this thesis are the used input data and the control card settings. The input data comprises weather data and the DHW consumption profile, whereas the relevant control card settings are those differing from the program default.

In both **Paper II** and **Paper III**, the simulation time step employed was 3 minutes and number of messages allowed before listing the ERROR statement was 1000. Except for these, all other settings were at default.

In Paper II, the weather data was downloaded from the Swedish Meteorological Institute (SMHI) data archive on the internet [35]. Data for temperatures, relative humidity and wind was taken from the station at Landvetter (57.6764 N, 12.2919 E) whereas solar radiation data was extracted using the STRÅNG tool [36] for the location Vallda Heberg (57.466 N, 11.991 E).

The employed DHW profile was generated using the DHWcalc software, using the hourly distribution of DHW volumes found in measured data (2015) for one housing area in the Vallda Heberg residential area. The total daily DHW volume was derived by scaling the measured

average consumption per single-family house in the housing area by the total number of houses modelled.

In Paper III the weather data was derived using the Meteonorm software for location Kungsbacka (57.28 N, 11.59 E). The synthetic hourly data generated is interpolated from the three nearest measurement stations. Solar data is usually corrected with satellite data if there are data points missing or large discrepancies between measurement stations. Solar irradiation data was from two stations in Gothenburg, Sweden and one station at Skagen Fyr, Denmark, with a satellite data share of 49%. Temperature data was from the same two stations as solar irradiation data in Gothenburg, Sweden, in addition to one station in Nidingen, Sweden.

The DHW profile was calculated using the DHWcalc software, using default values for the relative distribution of hourly DHW volumes. The total daily DHW volume was calculated by using guidelines from the Swedish National Board of Housing, Building and Planning for the average daily DHW consumption of one person and assuming three persons per household modelled.

2.4.2 Common subsystem models

In all system models developed, there is a set of common subsystem models employed:

Building and house substation model, comprised of a two-zone building model based on real drawings of the house. One zone is heated by a mechanical ventilation system with auxiliary water-air heat exchanger and heat recovery, while the other zone uses floor heating. The model takes into account air infiltration, shading and windows.

Heating plant model, including the boiler, evacuated tube solar collectors and buffer storage connected to a heat exchanger that supplies the DH network. Internal connection pipes are included to account for heat losses. The boiler is controlled to maintain a part of the buffer storage hot at all times, a third during the summer (maximize solar heat) and two thirds during the winter (solar preheating).

2.4.3 Distribution pipe model

The distribution pipe model is a buried horizontal twin-pipe which allows for specification of the pipe and trench dimensions, as well as the thermal conductivity of pipe material, insulation, trench gap and ground. The model is restricted to cylindrical coordinates, so all layers are essentially concentric layers around the model centre, indicating a circular trench.

In Paper II, the steel pipes were modelled by replacing trench gap thickness by EPS insulation thickness, as the pre-insulated twin-steel pipes in the Vallda Heberg system had an additional EPS casing. Plastic pipes were modelled without a trench gap due to having no other casing than that of the EPS insulation.

In Paper III, the steel pipes were modelled as regular, pre-insulated twin-steel pipes, without any additional EPS insulation. This was done by replacing trench gap thickness with the thickness of the polyethylene (PE) casing normally enclosing pre-insulated pipes.

In order to reduce overall simulation time and model complexity, the different types of distribution pipes were lumped together in segments (see Figure 6). The length of each segment

corresponded to the total pipe length of all pipes within the segment. For more information on this, see the respective model descriptions.

2.4.4 Hybrid system model

Overall modelling approach

The hybrid system has been modelled by the use of five subsystem models in TRNSYS:

- 1) Building and house substation model (SH load multiplied by secondary scale factor to represent average housing area).
- 2) Lumped pipe model for the GRUDIS distribution between intermediate substation and building(s).
- 3) Intermediate substation model (multiplied by primary scale factor to represent total system load) with ST system.
- 4) Lumped pipe model for the conventional primary distribution between heating plant and substation(s).
- 5) Heating plant model.

In order to reduce the modelling efforts, the overall system was modelled as consisting of a HP supplying an average substation, in turn supplying a load corresponding to a hypothetical average housing area represented by identical houses. The house SH load is scaled (multiplied) by equations to achieve the total load of an average housing area on the average substation. To achieve the total load on the HP, the substation load was scaled (multiplied) by equations to give the total load of the system. This load was then used to calculate the required flow rates in the PC given the simulated supply- and return temperatures, thus simulating a realistic load on the PC.

Figure 6 shows the overall model structure of the hybrid system model including the subsystem models:

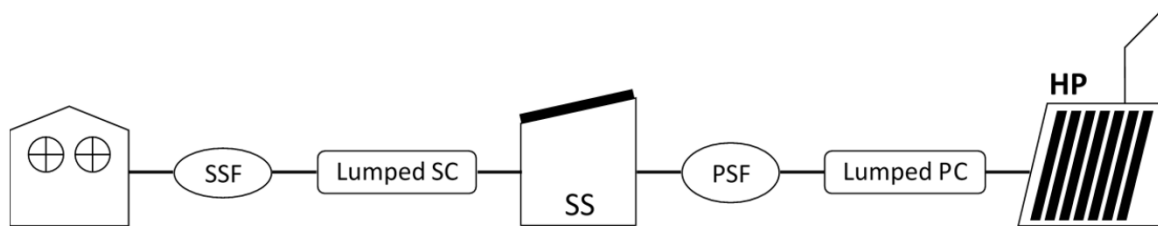


Figure 6: Hybrid model structure – Schematic showing the hybrid system model structure, including subsystem models.

The appropriate primary scaling factor (PSF) was found by calculating the relative share of flat plate collector area in the whole system to that connected to the substation (SS). The secondary scaling factor (SSF) was equal to the number of houses in the hypothetical average housing area, which was calculated by dividing the total number of houses by the PSF. This implies a substation model with a housing area that has the same solar energy contribution per house as that of the system average.

In Paper II the PSF was exactly four, while the SSF was 24.6.

In Paper III, the PSF was approximately 3.9 and the SSF was 25.4.

Intermediate substation model

The intermediate substation model was based on substation 1 in the Vallda Heberg DH (described in *Paper II*) system and was modelled as consisting of a solar buffer storage, circulation pumps and internal piping, in addition to a solar loop comprised of two solar collector arrays supplied by a solar culvert and collector connection pipes. t

In Paper II, the solar arrays were assumed to be of the same size as those connected to substation 1 in the Vallda Heberg system, where one large array was located on the roof of a nearby multi-family house and one smaller array was located on the roof of the substation. Only single pipe ducts were employed to represent the solar culvert, without modelling of insulation thermal conductivity, requiring overall UA-values as input. The pipes were thus modelled as being above ground instead of ground buried pipes.

In Paper III, the solar loop model was improved by employment of single pipe ducts that modelled insulation conductivity separately, to represent above ground connection pipes, while using a buried twin-pipe to represent the solar culvert. The solar arrays were modelled by collecting the total collector area located on substations in one array and the collector area located on arbitrary buildings (see Figure 4) in another.

Lumped pipe segments

In Paper II, the SC was modelled as one segment and the dimensions were calculated based on the weighted average diameter of all distribution pipes in the secondary network of one housing area. The diameter happened to correspond well to that of a standard DN50 pipe and thus the standard dimensions of that pipe were used. The length of the SC was estimated by using the secondary network length of said housing area and measuring the secondary network length of remaining housing areas in satellite images of the Vallda Heberg area.

The PC was modelled with certain simplifications with regard to the range of sizes considered, using four segments of standard pipe sizes (2 DN65, 1 DN80 and 1 DN100). The length of the pipe segments was taken from a previous study [37]. These four segments were connected in series, modelling one pipe connected to the load (substation) at the far end.

The solar culvert was modelled by using single pipe ducts, where supply and return was modelled by one pipe each. Two arrays were connected to the intermediate substation model, whereby one was located on a nearby roof and one on the roof of the substation. One pair of pipes were used to for the array on the nearby building and one pair was used for the collective flow of both arrays. The inner diameter of the pipes connecting the arrays corresponded to a DN40 and DN50 steel pipe, respectively. The total solar culvert length in the system was distributed between the pipe pairs so that, when scaling was employed, the modelled length was correct.

In Paper III, the SC was modelled as one segment and the PC modelled as two segments connected in series, one accounting for main pipes and one accounting for the branch pipes serving the substations. The solar culvert comprised one segment, connected to the roof-mounted collectors of the arbitrary building(s) (see Figure 4). The dimensions of each respective segment were derived by adjusting pipe diameter and scaling the related pipe dimensions (wall thickness and pipe spacing) in order to match the simulated network heat loss with the heat loss calculated based on catalogue values. This resulted in non-standard pipe sizes with custom

dimensions not commonly found in pipe catalogues, but heat losses calibrated to weighted average of heat losses given in product catalogues.

The length of the pipe segments used were estimated by measuring the various parts of the distribution system in technical drawings of the Vallda Heberg system and converting the measurements from drawing scale to a scale of 1:1. For the SC, the network length per house was found for one housing area and scaled up by the number of houses in the entire system. For the PC, the network length only included the branch pipes serving substations and the main pipes between the heating plant and most distant substation in the system. The solar culvert length was and included all buried solar pipes in the system, but was scaled down according to the primary scaling factor (PSF), so that when scaling was employed the modelled length was correct.

2.4.5 All GRUDIS model

Differences to the hybrid model

The specifics of the all GRUDIS model are:

- No intermediate substation.
- **HP**; Intermediate substation integrated with heating plant. Large solar buffer store with internal heat exchangers for central DHW preparation.
- **Pipe segments**; Different solar culvert dimensions, PEX pipe segments.

Overall modelling approach

In **Paper II**, the All GRUDIS system was modelled by using the Hybrid model, but reducing the PC length to zero so as to *imitate* that the intermediate substation model and heating plant model were one unit. This means that the intermediate substation model from the Hybrid system model was *still used*, but the simulated heat losses were included in the HP loss. Otherwise, the SSF and PSF (see Figure 6) was set to 99 and 1, respectively, in order to simulate the total system load without scaling. The FPC solar energy system thus comprised two arrays, one large and one small, connected to one large solar buffer tank. The volume of the solar buffer tank corresponded to the total volume of all solar buffer tanks in the Hybrid system and the dimensions were chosen so as to maintain the surface-area-to-volume ratio of the solar buffer tank in the intermediate substation model of the hybrid system. However, the UA values were *not* scaled according to the increase in surface area, which was a major simplification, although the influence on available solar energy due to this was assumed small (see 4.2.2 *Storage UA-values and stored solar energy*).

In terms of distribution pipes, the SC length was increased to account for the total network length (SC + PC), but the solar culvert length was assumed to be one third of the original PC length plus the original length from the Hybrid model. The pipe sizes were scaled up by calculating the necessary inner diameter of pipes to account for the increased flow when modelling the total system load, while maintaining the fluid velocity of the flow in the original substation model. This resulted in non-standard pipe sizes with custom dimensions not commonly found in pipe catalogues and in the twin-pipe model representing the SC, the pipe spacing was maintained constant during the scale-up.

In Paper III, the All GRUDIS system was modelled by integrating the intermediate substation model into the heating plant model. The major difference between this approach and the one used in *Paper II*, was that the hydraulic separation (heat exchanger) between the primary and secondary networks was omitted. The primary culvert pipe segment(s) were thus connected directly to the HP and there was no scaling employed. Hence, the DHW profile of the entire system was used as input to the heating plant model and the buffer storage used for preheating was modelled in full size. As in *Paper II*, the dimensions of the storage were chosen so as to maintain the surface-area-to-volume ratio of the solar buffer tank in the intermediate substation model of the hybrid system. However, the UA values *were* scaled according to the increase in surface area when increasing storage size from that in the intermediate substation model to that of the total system storage volume. Furthermore, the fact that no scaling was employed implied also modelling the FPC solar arrays in full size and connecting these directly to the large buffer store in the HP. This was in contrast to the hybrid model, where these were connected to the intermediate substation. Modelling the arrays in full size was done by simply collecting the arrays previously mounted on substations in the hybrid system in a leftover array (LOA) and the remaining collector area in another large array (LA).

In terms of distribution pipes, these were modelled using two segments – one for the main pipes and one for the remaining pipes. The lengths of these pipe segments corresponded to those of the PC and SC, in the hybrid model, respectively. The solar culvert was extended to include in total three segments of buried twin steel pipes, one branch pipe for each of the two FPC arrays and one main pipe for connecting these to the heating plant. The lengths of the solar culvert segments were chosen by assuming that the large array (LA) consisted of four arrays in the same location as the multi-family houses in the original Vallda Heberg, whereas the leftover array (LOA) was assumed to be located at a location closer to the heating plant, assuming that the arrays were placed quite close to the substation.

2.4.6 Conventional DH model

Differences to the hybrid model

The specifics of the conventional DH model are:

- No intermediate substation.
- **HP**; Large solar buffer store for circulation flow heating.
- **House substation**; DHW heat exchanger added. Floor heating supplied by SH heat exchanger.
- **Pipe segments**; Different solar culvert dimensions, twin-steel pipe segments.

Overall modelling approach

In Paper III, the conventional DH system was modelled. The overall modelling approach was quite similar to that for the All GRUDIS model, although with some differences in the use of the central solar buffer store and in DHW preparation. The solar buffer store in the HP was only used for preheating of circulation flow in the culvert and the DHW was prepared in the house substation by a dedicated heat exchanger. The DHW profile for the whole system was used as input to the house substation model, scaling down the draw-off volumes by a factor equal to the total number of modelled houses (99).

The floor heating system in the building model was connected to the SH loop of the house substation model and supplied by the SH heat exchanger. This was different to the hybrid and All GRUDIS system, where the floor heating loop was connected to the DHW circulation return. In order to maintain the passive heating function that was a part of the floor heating concept in the hybrid and All GRUDIS system, the pump was modelled as always running with fixed flow rate. This approach was thought to ease the comparison of results between systems.

Regarding distribution pipes, the only difference to the all GRUDIS model is that the pipes are modelled as twin-steel pipes instead of PEX pipes. The same two segments are employed, using one for main pipes and one for remaining pipes, although naturally the dimensions are different. The solar culvert is exactly the same.

2.4.7 Model calibration

In Paper II, the calibration was done separately for the hybrid subsystem models (described in section 2.4.4 Hybrid system model).

Building and house substation model

The building and house substation model was calibrated against measured SH demand by changing the house UA-value and the heating system set point temperature.

Lumped secondary culvert and intermediate substation model

The FPC solar gains/yield and solar culvert losses were regarded as one during the calibration towards measured data on solar heat transferred to substation, which means that the collector gains and culvert heat losses may not be entirely realistic. However, the solar heat transferred to substation was calibrated by mainly adjusting the solar culvert UA-values, while fine tuning with the collector efficiency. The solar energy transferred to storage was calibrated by adjusting the UA-value of a connection pipe between the solar heat exchanger hot side outlet and the buffer storage. Because this adjustment increased the transferred energy to substation, the calibration was an iterative process as changes in one component led to changes in another.

Due to bad quality of data on measured energy leaving the substation, the SC heat losses were calibrated together with the heat losses in the intermediate substation. The SC losses were calibrated by adjusting the thermal conductivity (UA-value) of the pipe model, while the substation losses were modelled by using a set of internal pipes, where the UA-values could be adjusted, as well as solar buffer storage losses. Storage losses were modelled by using theoretical UA-values that were calculated based on information about the storage in Vallda Heberg. The buffer storage was connected to the solar heat exchanger by a connection pipe and this was used for calibration of the solar energy transferred to the substation. The heat losses from the connection pipe and storage were used as the basis for the calibration of substation loss, and the losses not accounted for by these were achieved by changing the UA-values of the internal pipes in the substation so that the energy to the substation from the PC matched the measured amount.

The calibration of secondary distribution losses was based on measurement data from substation 1 in the Vallda Heberg DH system (see Figure 2) and the houses connected to this. These data were somewhat uncertain due to the small difference between supply and return temperature in the SC, which gave high heat meter uncertainty. Nonetheless, on background of the measured data, the SC losses were assumed around 10% higher than the theoretical (catalogue) losses for

a DN50 pipe, while the internal substation losses were assumed to be $\leq 10\%$ of the supplied energy from the PC and FPC. The total losses in the secondary distribution was assumed to be roughly 30% (see Table 12).

Lumped primary culvert and heating plant model

The heat losses of the PC were calibrated together with those of the HP, as no separate measurement of heat leaving the HP existed. The heat losses in the HP were calibrated by making an assumption on the relative loss of boiler supplied energy in the HP and adjusting the UA values of internal pipes to achieve this. The remaining heat losses attributed to the PC were calibrated by adjusting the thermal conductivity of the pipe insulation. It was possible to achieve satisfactory ($<3\%$ deviation) calibration for ETC solar energy yield and heat losses, but unsatisfactory ($\sim 9\%$ deviation) for boiler energy.

Because of the large uncertainty in the measured boiler energy, it was difficult to achieve a good match between the delivered energy and the PC and HP heat loss. This was considered to make the calibration too unreliable to model a third distribution system using only steel pipes, leading to a change in modelling approach for *Paper III*.

In *Paper III*, the calibration process was limited to the pipe losses, but had to be done for each distribution concept individually. For the remaining parts of the system, the calibrated subsystem models from *Paper II* were also used in the generalized system model. However, minor differences had to be made.

Pipe heat loss calibration

The specific heat loss (in W/m) of standard (catalogue) pipe sizes was simulated in TRNSYS for various pipe types (steel, PEX and copper). The specific boundary conditions employed in the simulations were taken from the product catalogue of a pipe manufacturer of each pipe type, so that the boundary conditions for catalogue and simulated values were the same. Despite using the same boundary conditions, the simulated specific heat loss differed from the catalogue values by 3 – 29% for steel pipes, 3 – 13% for PEX pipes and 0 – 5% for copper pipes. However, the stated range of deviation was for the entire range of pipe sizes, many of which were not used in the modelled heating network. In particular, the largest deviations were seen for the largest pipe sizes and these were not employed in any of the modelled distribution networks.

Due to the deviations between simulated and catalogue values of specific heat loss, the size of the lumped pipe segment that would represent the network of distribution pipes in the different system simulation models was varied to calibrate the losses properly to catalogue values. In the sizing process, the pipe diameter was adjusted so that the simulated network heat loss matched the design network heat loss, which had been calculated from catalogue data. This allowed for a realistic simulation of heat losses when pipes were subjected to user specified (ground) temperature conditions in subsequent simulations.

Changes to the building and house substation model

In the conventional DH model, the house substation model was slightly different from that of the other system models, due to the connection of the floor heating loop to the space heating loop (see 2.4.6 Conventional DH model). Because of this, the floor heating loop in the building had to be re-calibrated to supply 100W of average power on an annual basis, by changing the floor UA-value.

Scaling of solar buffer storage

The solar buffer storage employed in the simplified system model (*Paper II*) was modelled according to technical drawings and storage heat losses were calibrated towards measured data. This calibration was valid for the specific dimensions of the storage tank, in particular regarding the ratio of surface area to storage volume. When the storage volume was changed in the generalized model (*Paper III*), the dimensions of the storage were adjusted in order to maintain the same ratio of surface area to storage volume, as in the simplified model. This was also done when scaling up the storage for use in the HP model of the conventional DH and All GRUDIS system. In changing storage dimensions, the UA-values were changed also, proportionally to the change in active surface area of the tank. The logic behind this approach was to employ a systematic method to the choice of storage dimensions and to ensure correct modelling of heat losses by using the dimensions of a calibrated model.

2.5 Simple economics

In *Paper II*, a simple economic analysis was presented in the discussion section, comparing differences in installation costs for two distribution concepts. The analysis made use of three different costs:

- 1600 SEK/m (trench).
- 1150 SEK/m (twin steel pipes).
- 650 SEK/m (EPSPEX – plastic pipe culvert).

The pipe costs were average costs for all sizes used in the Vallda Heberg system and included all welding and connections. Bends, tees, valves and other balancing components were not included. The cost data for trench and steel pipes were supplied by the consulting firm that designed Vallda Heberg, whereas the data for the plastic pipes were supplied by the pipe manufacturer, who also was the installer.

In the work with *Paper III*, new and updated costs have been collected for the pipes used in the different distribution concepts. For steel pipes, prices were supplied by pipe manufacturer Powerpipe AB (Table 1) and for the EPSPEX culvert prices were supplied by culvert manufacturer Elgocell AB (Table 2).

These costs were supplied directly from manufacturer, and excludes the cost of connections, welding and VAT. This thesis makes use of these data for presentation of a new simplified analysis, to be compared to the initial one (*Paper II*). In the new analysis, the trench costs are assumed to be the same as in *Paper II*, but that only 30% (480 SEK/m) of the regular trench cost applies for buried solar pipes in parallel with the PC (double trench).

The distribution of pipe lengths sorted by nominal diameter can be found in *Paper II* and *Paper III*. The new analysis will present the total costs from these systems only and no intermediate calculations.

Table 1 shows the 2019 prices for pre-insulated steel twin pipes from manufacturer Powerpipe [38]:

Table 1: Prices (ex. VAT) on series 1 pre-insulated twin steel pipes from manufacturer Powerpipe [38].

Pipe dimension	DN80	DN65	DN50	DN40	DN32	DN25	DN20
Price [SEK/m]	704	629	535	392	382	343	343

Table 2 shows the 2019 prices for EPSPEX culvert from manufacturer Elgocell [39]:

Table 2: Prices (ex. VAT) on EPSPEX culvert from manufacturer Elgocell [39].

Pipe dimension	DN110	DN90	DN63	DN50	DN40	DN32	DN25
Price [SEK/m]	1282	1006	626	500	421	317	295

2.6 Key figures

The key figures used for evaluating system performance are:

Performance ratio (PR):	Ratio of house energy demand to boiler energy supply.
Solar fraction (SF):	Ratio of stored solar energy to total energy demand.
Energy balance:	Energy budget for energy supply and demand in the DH system.
ETC Solar:	Stored solar energy from evacuated tube collectors.
FPC Solar:	Stored solar energy from flat plate collectors.
Boiler energy	Energy supplied from boiler to flow stream, excluding losses.
HP loss:	Losses from solar buffer storage(s) and internal connection pipes.
Distribution loss:	Losses from ground buried pipes and any intermediate substation(s).
(Demand in) Houses:	Total SH and DHW demand of the houses in the DH network.
HDD:	Heating degree days.

3. Results

3.1 Energy balance

3.1.1 Overall results

Figure 7 shows the energy balances from *Paper II* and *Paper III*, respectively:

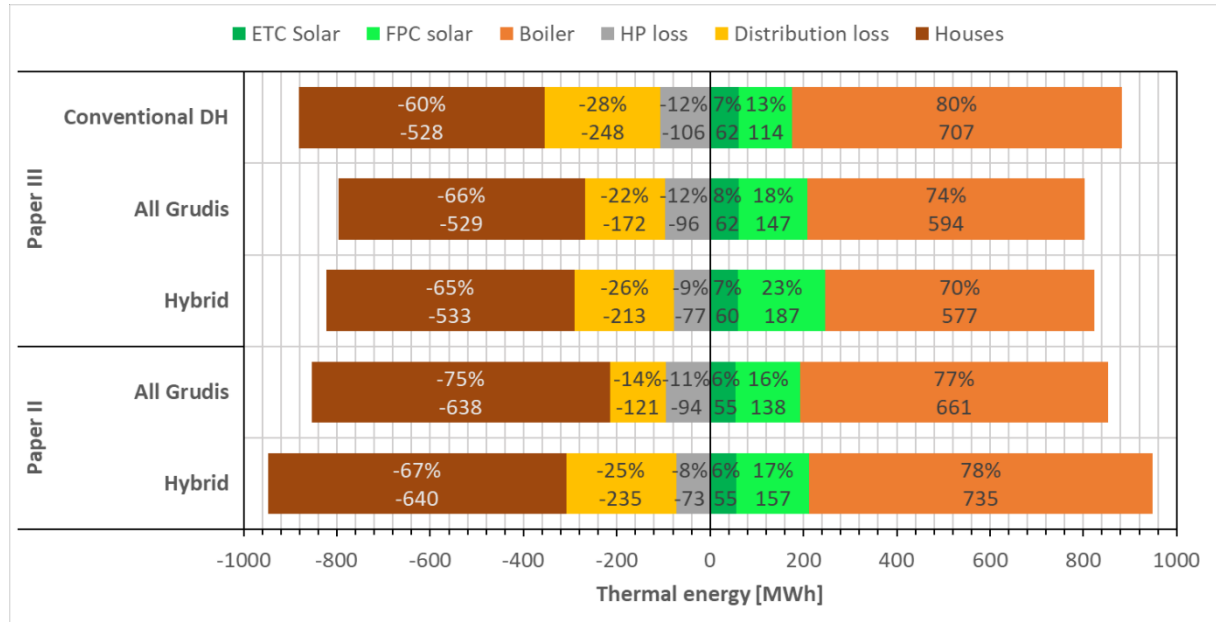


Figure 7: Comparison of simulated energy balance for the different distribution concepts investigated in Paper II (right) and Paper III (left). The relative share of the energy supply/demand is shown in percent.

According to the **Paper II** energy balance, the All GRUDIS system uses 853 MWh in total to supply the house energy demand, which gives a performance ratio (PR) of 75%. This is superior to the Hybrid (original VH) system, where 948 MWh is used to supply the same demand, giving a PR of 67%. However, the solar fraction of both distribution concepts was more or less the same, in the low 20% range. Based on these results, it seemed that the All GRUDIS distribution was preferable from an energy perspective, due to significantly lower pipe heat losses and thus less boiler fuel consumption. Notwithstanding, these results changed in *Paper III*.

In the **Paper III** energy balance, the difference in boiler-supplied energy is 17 MWh ($< 3\%$), with a PR of 65% and 67% for the Hybrid and All GRUDIS system, respectively. Due to this, the results are not conclusive as to which of these systems is better from an energy perspective. Despite this, one particular result is quite apparent; the conventional DH concept performs worse than any of the available system alternatives.

However, most (66%) of the distribution losses in the Hybrid system are related to the secondary distribution, out of which 9%-points (18 MWh) are related to the intermediate substation and most of this (15 MWh) is lost from the solar buffer storage. If the intermediate substation losses in the hybrid system are added to the HP loss, the HP losses in the hybrid system are more or less the same as those in the All GRUDIS system. This indicates that the integration of the substation in the HP gives equivalent heat losses to having an intermediate substation, not counting pipe losses.

If the substation losses are subtracted from the hybrid system distribution losses, the pipe distribution losses are still 195 MWh, or 13% higher than in the All GRUDIS system. This is assumed to be due to the use of steel pipes in the PC. The solar fraction was slightly higher for the Hybrid system (30%) than in the All GRUDIS system (26%) and, assuming the difference in pipe heat losses was covered entirely by solar energy, the amount of stored solar energy was still 15 MWh higher in the Hybrid system. This is nearly the same as the difference (17 MWh) in boiler supplied energy between the two systems. Thus, the higher amount of stored solar energy implies that the Hybrid solution may be preferable from an energy perspective, due to less boiler fuel consumption.

3.1.2 Observed differences in simulation results

Generalized model gives more similar results

The obvious implication of the differences between energy balances when moving from a specific model based on measured data, to a more general model based on theoretical data, is that the results become more similar for the Hybrid and All GRUDIS system. This is assumed to be a result of both the modelling approach and the model calibration. The simulation results are sensitive to the assumptions made when trying to calibrate simulated data in the Hybrid model against measured data in the Vallda Heberg system. In the simplified system model of *Paper II*, the All GRUDIS system was modelled by relatively small alterations in the Hybrid model. Therefore, the simulated performance of the All GRUDIS system in *Paper II* is also sensitive to the assumptions made during calibration. In the generalized system model, the modelling approach is more systematic and the same for all systems, while the calibration process is done individually for each system. Comparison of the simulated performance is therefore less sensitive to potentially erroneous assumptions as there is less error propagation.

House energy demand different

The most notable difference between the results attained in the two papers is the size of the energy quantities. Firstly, the simulated house energy demand was roughly 20% higher using the simplified system model (*Paper II*) that was calibrated against measured data from 2015, than it was in the generalized system model (*Paper III*). This naturally led the simulated boiler energy to become higher as well. However, the boiler energy supplied also depends on the distribution losses, which leads to a second notable difference, discussed in the next section.

Contradictory results due to modelling approach

Whereas the Hybrid system required the most boiler energy in *Paper II*, the All GRUDIS system required the most in *Paper III*. The distribution loss in the All GRUDIS system in *Paper II* is lower than it is in *Paper III*, both in absolute and relative terms. The differences in modelling approach that led to the differences in distribution heat loss are primarily assumed due to differences in applied pipe lengths and the model calibration, with minor influence from weather data. This is discussed in detail in Ch. 4.1 *Influence of weather data on energy balance(s)*.

3.2 Sensitivity analysis

The initial line heat density of the DH systems simulated was 0.3 MWh/m, a and 0.2 MWh/m, a for *Paper II* and *Paper III*, respectively.

The sensitivity analysis was made by simulating the different distribution systems for three values of line heat density (LD). The methodology employed was to change the pipe network length to 0.5 and 2 times the initial value, corresponding to 0.5 and 2 times the initial LD. The energy balance for all simulations were normalized to the energy balance of the Hybrid system at 1LD (see Figure 7).

Figure 8 shows a comparison of the sensitivity analysis based on linear heat density (LD) in *Paper II* and *Paper III*:

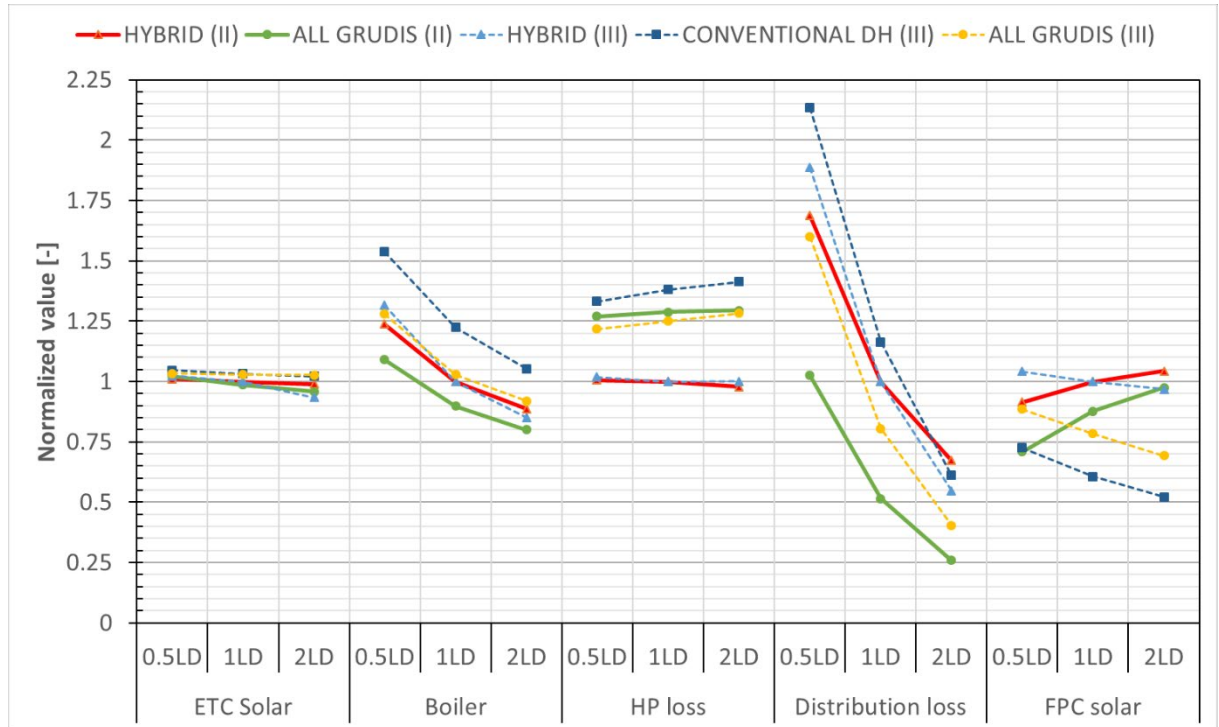


Figure 8: Comparison of the sensitivity analysis based on line heat density (LD) in Paper II and Paper III. The simulated absolute values at 0.5LD and 2LD are normalized to those at 1LD for the Hybrid system for both papers individually.

Note that the simulated absolute values are normalized to those at 1LD and that this is done for each paper individually. As the energy turnover in *Paper II* is larger than in *Paper III*, this means that the relative differences between papers shown in the figure aren't analogue to the absolute differences. Thus, despite that for example, the boiler supplied energy in the All GRUDIS system in *Paper II* seems to be lower than that in *Paper III*, the absolute amount in *Paper II* is actually higher than in *Paper III*.

3.2.1 Similarities between papers

The variation in ETC solar energy, boiler supplied energy and HP heat loss is more or less the same in *Paper II* and *Paper III*. There are minor differences in the slope of the curves with those in *Paper II* generally smaller than those in *Paper III*. This indicates that the variation in LD has a smaller effect on the losses in *Paper II* than in *Paper III*, which is supported by the variation in

distribution loss. Aside from this, the similarities indicate that the systems react similarly to changes in LD.

When considering the distribution loss further, the relative changes in the All GRUDIS system correspond well between *Paper II* and *Paper III*, while there are smaller differences for the Hybrid system. This is assumed to be due to the fact that specific heat losses of the SC and PC are similar in the Hybrid system of both papers. Simulating the All GRUDIS system by using PEX pipes of similar specific heat loss means that the curves will develop similarly with changes in the LD, because the losses are proportional to the culvert length only and the relative change in LD (length) is the same for both systems. On the other hand, when simulating the Hybrid system, the combination of steel and PEX pipes with different lengths and different specific heat losses means that the curves develop slightly different on changes in LD. However, the general trends are the same between *Paper II* and *Paper III*, in that the distribution heat losses are reduced slightly more in the Hybrid system at 2LD due to benefits in reducing the length of steel culvert, while the exact opposite is true at 0.5 LD.

3.2.2 Observed differences

The most obvious differences between the results in the two papers is found in the variation of FPC solar energy with LD. In *Paper II*, the supplied solar energy increases with increasing LD, which is opposite of the trend in *Paper III*. Once again, the modelling approach may be the reason, as the solar culvert length varies with LD in *Paper II* and is kept constant in *Paper III*. This indicates that when the LD decreases in the simplified system model of *Paper II*, the solar culvert losses become higher and therefore the supplied solar energy decreases and vice versa.

There is a noticeable relative difference in boiler supplied energy for the Hybrid and All GRUDIS system in *Paper II*, which corresponds to the large relative differences in distribution loss of these systems in the energy balance. These are related to the assumptions on the relative heat losses in the system during calibration and too high UA-values for the PC in the Hybrid system of *Paper II* (see 4.3.1 Calibration assumptions and total heat loss). If these differences in curves are taken into account, the overall trends between curves are very small and shows the same overall development with LD for all curves. Thus, the natural result would be to reiterate the findings from *Paper III*, that the conventional system performs worst for all line heat densities and that the Hybrid is best at 2LD. At 0.5 and 1LD the results are inconclusive, and further studies are needed to conclude. The implication of these results is that the Hybrid and All GRUDIS energetic performance is similar for line heat densities ranging from 0.1 – 0.3 MWh/m, a, while the Hybrid system is better for line heat densities ranging from 0.4 MWh/m, a and upwards.

3.2.3 Summary of findings

The sensitivity analysis shows that no apparently unexplainable differences exist between the two papers when the energy balance changes with line heat density. The differences in the energy balance at 1LD and the following discussion on influence of various factors on this has shown that the energy balance in *Paper II* may be wrong and favour the All GRUDIS system. When taking into consideration this and the different modelling approach for the solar energy system, the trends are the same in both papers. Thus, the result of the sensitivity analysis is that the Hybrid system seems to be the best option from an energy perspective at 2LD, corresponding to an annual value of 0.4 MWh/a and upwards. Although the results are inconclusive at 1LD, the

result from the discussion on the energy balance (see 3.1.1 Overall results) implied that the higher solar fraction makes the Hybrid system favourable. At 0.5 LD, corresponding to 0.10 – 0.15 MWh/m, a, the findings are inconclusive as to the best system. The conventional system performs worst for all values of LD.

3.3 Simple economics

The simple economic analysis aims to compare the economic calculations from *Paper II* with new calculations based on updated data on costs from pipe manufacturers. It is important to note that the calculations are sensitive to the lengths of culvert assumed in the different papers, so it is not really possible to compare the system costs directly. Rather, the data should be used to see if the conclusions drawn in *Paper II*, regarding the potential economic benefits of the All GRUDIS system, still hold for *Paper III*.

In *Paper II*, the costs did not include the total solar culvert costs, but calculated only the cost for the difference (336 m) in solar culvert length for the solar energy system in the All GRUDIS and Hybrid system. In addition, no trench cost was applied for the extra culvert length, assuming that the culvert running from the arrays to the HP could be buried in the same trench as the PC. In this analysis, the costs of the whole culvert is included in both systems and the trench cost for the extra solar culvert length in the All GRUDIS system is assumed to be 30% of the normal trench cost. However, because detailed information on culvert sizes only exist for the Hybrid system, the cost for pipes are the same as they were in *Paper II*, for ease of comparison. Note that these costs were average values ex. VAT that included installation and welding.

In *Paper III*, the pipe distribution is well known for all systems and the pipe costs do *not* include installation and welding. The costs used are all ex. VAT, as is customary in commercial price catalogues.

Table 3 shows a cost comparison for the various distribution systems in *Paper II* and *Paper III*:

Table 3: Comparison of costs for the various distribution systems in Paper II and Paper III. All costs in 10⁶ SEK.

	Paper II		Paper III		
	Hybrid	All GRUDIS	Hybrid	All GRUDIS	Conv. DH
Network length [m]	2121	2121	2681	2681	2679
Solar culvert [m]	293	629	192	290	290
Cost pipes [M SEK]	2.2	2.1	1.1	1.3	1.2
Cost trench [M SEK]	3.9	4.0	4.6	4.7	4.7
Cost total [M SEK]	6.1	6.1	5.7	6.0	5.9

It is clear from the costs in Table 3 that the Hybrid and All GRUDIS system of *Paper II* are equivalent in terms of cost. This makes the preference of either one particularly difficult, although the fact that the boiler supplied energy is a lot larger in the Hybrid system makes the cost difficult to defend.

In *Paper III*, this is not entirely the case, although one should keep in mind that installation costs for PEX pipes tend to be lower than they are for steel pipes. Thus, the 5% savings in the cost of the Hybrid system compared to the All GRUDIS system can easily be turned into costs. This is

also valid for the conventional system, which would have to be significantly cheaper in order to make up for the poor energy performance.

Another aspect that is important when considering the system costs shown here, is that they do not include the costs for the intermediate substations in the Hybrid system or the house substations in the conventional system. Neither do they consider the added cost of a large HP with room for storage in the All GRUDIS and conventional system. If these additional costs were taken into account, the cost evaluation could be quite different.

Table 4 shows an overview of estimated system costs for the three distribution systems evaluated in *Paper III*, including potential costs for substations in the Hybrid and Conventional DH system:

Table 4: Overview of estimated system costs for the three distribution systems evaluated in Paper III.
All costs are in in 10⁶ SEK.

		Hybrid	All GRUDIS	Conv. DH
Pipe network costs	[M SEK]	5.7	6.0	5.9
Substation costs	[M SEK]	5.6	0	4.0
Total costs	[M SEK]	11.3	6.0	9.9

The costs of a single intermediate substation can amount to 1.4 million SEK [40], which if added to the costs in Table 3 would surely make the All GRUDIS system more attractive from a cost perspective. In the Hybrid system modelled in the two Papers, four intermediate substations would nearly double the system cost (11.3 M SEK), which would be hard to defend economically even when considering the Conventional DH system. On the other hand, the price of a house substation can cost about 40k SEK, which for all the houses in the system would add another 4.0 million SEK to the conventional DH system cost (9.9 M SEK), thus making the difference to the Hybrid system quite small when considering that this cost still doesn't include a larger HP. Hence, the All GRUDIS system should be favourable if the costs of a large HP doesn't exceed the costs of four substations, although more details are needed to conclude on this. Nevertheless, this short analysis gives some very important indications, as a large part of the overall distribution system cost is attributable to other components than the pipes and trenches.

The costs of the distribution system is an aspect which is of great importance to the choice of system design, as it can be decisive for the approach employed to meet the demand. The long forespoken advantage of PEX pipes has been their low cost compared to conventional steel piping, although according to the prices shown in Table 1 and Table 2 (see Ch. 2.5 *Simple economics*), this advantage exists no more. Aside from lower installation costs, then the pipes are actually cheaper than their steel counterparts only for very small pipes (DN25 and DN30), although when considering pressure and temperature restrictions, there is an obvious mismatch. For large pipes, the pipe cost is significantly larger. Instead, the manufacturers advertise the low specific heat losses as a main benefit of PEX pipes, which in conjunction with low operating temperatures (as in 4th generation DH) can result in even lower distribution losses compared to conventional piping. The low heat losses are naturally tied to an expectation of lower operating costs, which in resources corresponds to lower fuel demand in boilers. Therefore, detailed calculations of fuel use are necessary to get a broader picture of the actual economic advantages of using plastic pipes instead of conventional pipes. Further, the additional insulation with EPS is another aspect which deserves more attention, as it holds the promise of combining the

advantages of steel pipes with those of PEX pipes, namely high pressures and temperatures in combination with low heat losses.

In summary, the simplified economic analysis presented here shows that the use of EPSPEX only (All GRUDIS) in a heating system has a hard time meeting the competition from the Hybrid system, if only the pipe costs are considered. This would be in line with previous results indicating that an EPSPEX system is best used as a secondary system [10]. However, if additional costs are taken into account, such as those for intermediate substations in the Hybrid system or those for house substations in the Conventional DH system, the All GRUDIS system will probably require significantly lower investment costs. The conclusion is thus far that the All GRUDIS system seems to be preferable economically, although more detailed calculations are needed to support this.

4. Discussion

4.1 Influence of weather data on energy balance(s)

4.1.1 House heat demand

One obvious difference between the results of the two simulation studies is the heat demand of the houses. The heat demand is 110 MWh (17%) lower on average in *Paper II*, than in *Paper III*, which is quite significant. A potential reason for this may be that the weather data used in the two studies are quite different, implying that the typical meteorological year used in *Paper II* could have been significantly warmer than that of the year 2015, used in *Paper III*.

Figure 9 shows an overview of average monthly temperatures and monthly global horizontal irradiation for Kungsbacka, Sweden in a typical meteorological year (TMY) and in the year 2015.

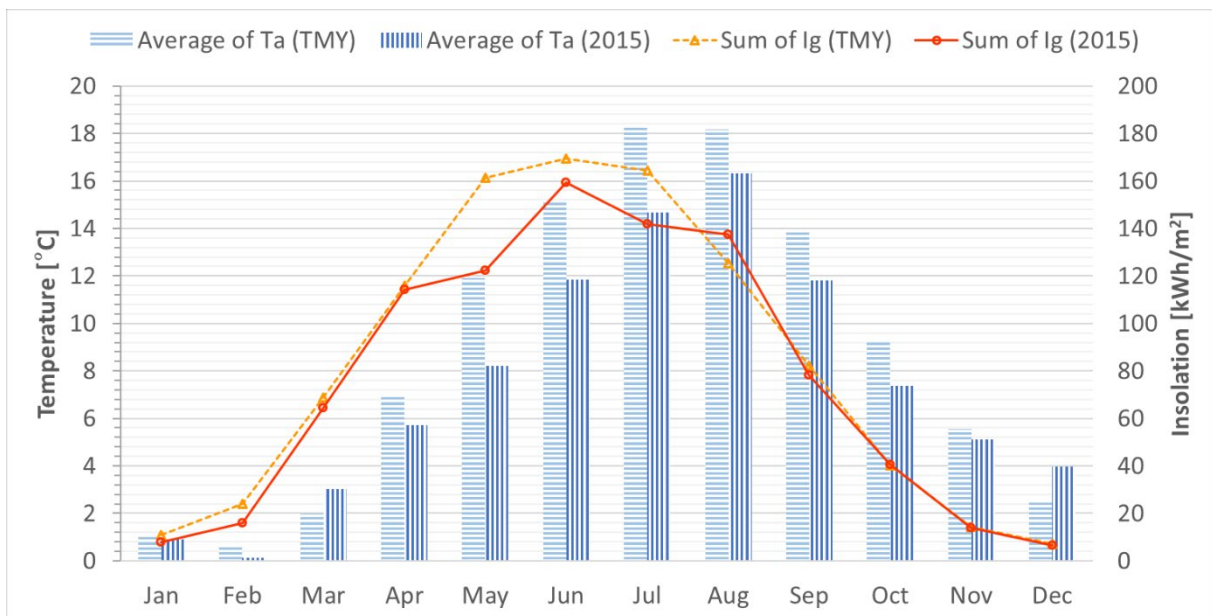


Figure 9: Overview of the average monthly temperature (Ta) and global horizontal irradiation (Ig) for Kungsbacka, Sweden in a typical meteorological year (TMY) and in the year 2015.

From the figure, it is apparent that the both temperatures and solar irradiation were lower in 2015 than in the TMY. Space heating demand is strongly correlated to ambient temperatures and the number of heating degree-days (HDD) calculated on the basis of daily mean temperatures and a baseline temperature of 15.5°C [41], is 2993 for the year 2015 and 2655 for the TMY (difference 11%). The annual irradiation is 8% lower in 2015 than in the TMY and because the building model takes into account gains from solar irradiance into the building envelope, this could further contribute to a higher heat demand. However, previous studies have

¹ For low energy houses, the balance point temperature (under which heating is required) can be much lower than the standard baseline temperature used for calculation of HDD. In this case, the daily mean temperature may exceed the balance point temperature quite often and a more detailed method based on hourly values may be needed for calculation of HDD [51]. The balance point temperature is unknown for the buildings at Vallda Heberg, so the standard baseline temperature is used as basis for discussion.

indicated little correlation between space heating demand and solar radiation [42], so this effect is difficult to evaluate without more detailed investigations. Another aspect is that space heating demand is also subject to the user behaviour of residents, so it cannot be excluded that a part of the extra demand is due to natural variation in heat consumption. Indeed, it has been documented that the measured heat demand in the Vallda Heberg residential area was 8% higher than calculated over the year September 2013 – August 2014 [43]. Hence, the combined effect of lower solar irradiation, lower temperatures and higher-than-calculated heat demands is presumably the reason for the observed differences in heat demand in *Paper II* and *Paper III*.

4.1.2 Stored solar energy

The difference in solar irradiance between datasets may also have a significant effect on the simulated amount of supplied solar energy, although it is quite difficult to determine to what extent. The solar yield for the hybrid system in *Paper II* was 16% lower than in *Paper III*, while the difference in annual global solar irradiation was 8%. According to previous studies, the relationship between global solar irradiation and total radiation on a tilted surface has been shown to be linear only during the summer months (May – August) and non-linear for the rest of the year. However, the magnitude of annual variation in total radiation on a tilted surface seems to be larger than the magnitude of annual variation in global radiation, which is assumed to be due to the radiation contribution at low solar altitudes [42]. This implies that the observed global irradiation differences between the TMY and year 2015 for the months of May – August (Table 5) should translate rather linearly to a difference in the solar yield, although this difference is likely larger than the difference in radiation.

Table 5 shows an overview of the solar irradiation for the months May – August in the TMY and year 2015 for Kungsbacka, Sweden:

Table 5: Overview of the solar irradiation for the months May – August in the TMY and year 2015 for Kungsbacka, Sweden.

		May	Jun	Jul	Aug	Subtotal	Year
Sum of I_g (2015)	[kWh/m ²]	122	159	142	137	561	903
Sum of I_g (TMY)	[kWh/m ²]	161	170	165	125	621	984
Difference	[kWh/m ²]	-39	-10	-23	12	-60	-82
Difference	[%]	-24	-6	-14	10	-10	-8

The total amount of irradiation in the period May – August makes out roughly 60% of the annual irradiation for both years. The difference in the subtotal of solar irradiation between 2015 and TMY is -60 kWh/m² (-10%), which implies a difference of roughly 6% in the annual irradiation. According to the results of previous mentioned studies, minimum this difference in solar yield must be attributable to differences in weather data, though a higher amount seems probable.

Equation 1 is known as the “Karlssons formula” for flat plate collectors, developed based on measurement data of solar collectors in Stockholm with the aim to reliably estimate the collector output for various operating temperatures [44]:

$$E = T \times A \times G - U \times B \left[\frac{kWh}{m^2} \right] \quad (1)$$

Where E is the annual energy harvested, T is the transmission (through glass cover) coefficient, A the absorption coefficient, U the heat transfer coefficient [$\text{W/m}^2 \text{ }^\circ\text{C}$], G is a constant value for global irradiation on the tilted surface found empirically ($G = 705 \text{ kWh/m}^2$) and B is an empirical constant derived from measurement data at specific collector mean temperatures ($B = 37$ at 40°C and $B = 46$ at 50°C). The equation is valid for collector tilt 45° and orientation due south.

Table 6 shows the results of a calculation using equation 1, where the global irradiation has been reduced by 8%, from 705 kWh to 649 kWh/m^2 .

Table 6: Calculation of estimated annual output for a collector with tilt 45° and orientation due south based on the “Karlsson formula”[44].

E [kWh/m^2]	T	A	G [kWh/m^2]	U [$\text{W/m}^2 \text{ }^\circ\text{C}$]	B
332	0.85	0.9	705	4.5	46
289	0.85	0.9	649	4.5	46

According to the calculations, the estimated annual yield is reduced by 13% when the irradiation value is reduced by 8%. This shows that the relationship between the irradiation and yield is non-linear and larger than the reduction in radiation, in agreement with previous studies. The operating temperatures of solar collectors vary quite a lot, while transposition is subject to soiling and absorptivity is reduced with age. Therefore, it is deemed probable that the small variation in solar irradiation could indeed lead to the observed difference in stored solar energy between papers, shown in Figure 7. However, when differences in solar culvert heat losses are accounted for, the simulated amount of stored solar energy could be very similar in both papers (see Ch. 4.2.1 *Pipe model and solar culvert length and supplied solar energy*).

4.2 Influence of modelling approach on energy balance(s)

4.2.1 Pipe model and solar culvert length and supplied solar energy

The differences in employed solar culvert length may have significant influence on the stored solar energy. The total length of solar culvert is not the same for the Hybrid system and All GRUDIS system in *Paper II* and *Paper III*, and this could naturally lead to different losses in the solar culvert. In addition to the differences in length, the type of pipe employed could further increase or decrease these differences.

The specific heat losses for *Paper III* (Table 7) are average values based on the design heat loss rate in the solar culvert, calculated from catalogue values for twin steel pipes, and using the shown pipe lengths. The number of load hours have been calculated based on the design heat loss rate and the absolute pipe loss. The load hours for the Hybrid and All GRUDIS system in *Paper III* are used as a basis for the calculation of the specific heat loss and heat loss rate of the Hybrid and All GRUDIS system in *Paper II*. These values are shown in bold face. The motivation for doing this, despite the solar energy system not necessarily operating at design conditions for the steel pipes and the weather data being different for the two papers, is to enable an analysis of the influence of model differences on the simulated heat loss.

Table 7 shows the employed pipe lengths for the solar heat culvert in the FPC solar energy system, as well as the calculated heat loss in absolute, relative and specific terms, for various distribution systems in *Paper II* and *Paper III*:

Table 7: Overview of the solar culvert length in the FPC solar energy system for various distribution systems in Paper II and Paper III, along with associated pipe heat losses calculated in absolute, relative and specific terms.

		Paper II		Paper III		
		Hybrid	All GRUDIS	Hybrid	All GRUDIS	Conventional
Collector gain	[kWh]	184333	189674	196280	165357	134087
Pipe loss	[kWh]	26950	51643	8887	18327	20427
Pipe loss	[%]	15	27	5	11	15
Spec. pipe loss	[W/m]	30.0	25.5	15.1	19.0	19.0
Pipe length	[m]	293	610	192	290	290
Loss rate	[kW]	8.8	15.5	2.9	5.5	5.5
Load hours	[h]	3065	3326	3065	3326	3707

In *Paper II*, the Hybrid model solar culvert was modelled by single pipe segments above ground, with a total solar culvert length of 293 m. In the All GRUDIS system, which was based on the Hybrid model, the solar culvert was assumed to be equal to one third of the total PC length (950 m) in addition to the solar culvert length (293 m) of the Hybrid system. The culvert heat loss in the All GRUDIS system is roughly double of that in the Hybrid system, in both absolute and relative terms, which corresponds to the difference in pipe length, indicating that the difference in lengths is the major reason for the difference in simulated heat loss in *Paper II*. This is particularly evident when considering that the collector gains are almost the same in the Hybrid and All GRUDIS system.

However, when considering the difference in heat losses between papers, the differences in culvert length seems just part of the explanation. The fact that the specific heat loss of the solar culvert is so different between the two papers and higher in *Paper II* than in *Paper III*, indicates that the UA values employed for the pipe model in *Paper II* may have been too high. As the pipes were modelled as above ground and subject to ambient temperatures in *Paper II*, it would be logical if the specific pipe losses were lower than in *Paper III*, due to the fact that the majority of solar irradiation is received in the parts of the year where the ambient temperatures are higher than the annual mean. This would have led to lower average heat losses from the over ground pipes, than for the underground pipes, as these were exposed to a similar annual mean temperature, but with lower variability over the year.

In summary, the difference in stored solar energy between systems in *Paper II* are assumed due to differences in the employed solar culvert length. On the other hand, the difference between systems in *Paper II* and *Paper III* are assumed mainly due to too high UA-values for the culvert pipes in *Paper II*, in addition to the differences in solar culvert length. This leads to the conclusion that the simulated amount of stored solar energy in *Paper II* was too low, although this does not change the overall results of that study.

4.2.2 Storage UA-values and stored solar energy

In the All GRUDIS system of *Paper II*, the intermediate substation model from the Hybrid model was used, although the volume and surface area of the solar buffer storage was increased in order to model the full system load without scaling. When doing this, the UA-values were maintained the same and so the losses of solar energy from the storage tank in the All GRUDIS model were lower than the corresponding losses in the Hybrid system. This means that the simulated heat losses were disproportional to the storage size (see Table 8).

Table 8 shows an overview of simulated solar energy supplied, stored, lost and calculated to be available after losses in *Paper II* and *Paper III*:

Table 8: Overview of simulated FPC solar energy supplied, stored, lost from store and available for use in Paper II and Paper III for the distribution options simulated.

		Paper II		Paper III		
System		Hybrid	All GRUDIS	Hybrid	All GRUDIS	Conventional DH
Supplied	[kWh]	157383	138030	187394	147029	113660
Conn. pipe	[kWh]	-5426	-4578	0	0	0
Stored	[kWh]	151957	133452	187394	147029	113660
Storage loss	[kWh]	-1547	-1142	-14836	-17448	-27217
Available	[kWh]	150410	132310	172558	129582	86443
Relative loss	[%]	-4	-4	-8	-12	-24

The connection pipe losses are a part of the modelling approach in *Paper II* and these are used in the model calibration process (see 2.4.7 *Model calibration*).

The operating strategy of the Hybrid and All GRUDIS system is the same with regard to the solar buffer storage, where cold water is preheated in the internal heat exchanger in the storage bottom, and further heated together with hot water circulation flow in the internal heat exchanger in the storage top, if storage is warm enough. The main difference between these systems is the solar culvert length, which in the All GRUDIS system not only leads to less supplied energy to the solar heat exchanger, but also lower average supply temperatures. This leads to lower heat losses in both the connection pipe and the storage, than in the Hybrid system. However, if the storage UA-values would have been scaled according to the size of the storage, the storage heat losses would probably have been larger than in the Hybrid system, in accordance with *Paper III*.

Nonetheless, even if the losses in *Paper II* were in accordance with the losses in *Paper III*, it is clear that the modelling approach leads to differences in the magnitude of the heat losses in the two papers. The larger heat losses in *Paper III* influence the overall energy balance somewhat, although the effect on the results is assumed to be very small.

In the All GRUDIS and Conventional DH system model, the storage was large and placed in the HP, so when the substation storage was scaled in volume, two simulations were run in order to see the effect of scaling the UA-values according to the storage surface area. This could be used to estimate the effects on the increase in storage loss in *Paper II* if the UA-values of the storage had been adjusted according to the surface area. The storage heat losses increases roughly 4.45 times when the UA-values are scaled according to surface area. This further leads to an increase in the stored energy of 0.86 kWh per kWh of increase in storage loss. However,

the available energy after the storage loss is actually less than in the default model. This result is quite interesting, because it shows that even though the solar fraction of the All GRUDIS system seems to be high, the truth is that most of it is used to cover losses. In light of these results and when considering the values of storage heat loss in *Paper III*, the increase in relative loss from 4 – 12% would have corresponded to an increase in stored energy of 11 MWh for the All GRUDIS system of *Paper II*. The solar fraction would thereby increase by 1% and even if the absolute losses corresponded to a direct reduction in boiler supplied energy, the reduction would still only be < 3%.

However, the losses in the Conventional DH system in *Paper III* are much larger than those in the All GRUDIS and Hybrid system and, although this does not correspond to more stored solar energy. These systems have the same solar culvert and storage model, so the differences are assumed due to different operating strategies that result in different storage temperatures. In the All GRUDIS system, preheating of cold water in the solar buffer store leads to lower temperatures in the storage than in the Conventional DH system, where only circulation flow is preheated. Solar energy is discharged in the All GRUDIS system whenever the storage is warmer than that of cold water (typically 10°C). This type of cooling is not possible in the conventional DH system and the stored solar energy is only discharged when the storage is warmer than the return flow ($\geq 45^\circ\text{C}$). Thus, a large part of the energy stored until this is possible will be lost and this amount is significantly larger than in the All GRUDIS system.

In summary, differences in scaling of UA-values may have an influence on the stored solar energy and overall energy balance, as increases in storage losses lead to increases in stored solar energy and system heat losses. However, the increase in stored solar energy does not necessarily lead to more available solar energy and the effect on reduction in boiler supplied energy is considered very small. Therefore, differences in modelling of the storage should not affect the differences between the energy balances (Figure 7) of the various systems significantly and cannot explain differences between the energy balances in the two papers any more than differences in weather data.

4.2.3 Supply temperatures and distribution pipe heat loss

The pipe model used in TRNSYS (Type 951) uses the so-called Kasuda relation [45] to derive the vertical temperature distribution below ground according to the time of year, which is based on the mean surface temperature.

The pipe heat losses are proportional to the difference between average fluid temperature in the distribution pipes and ground temperature, as shown in equation 2:

$$\Delta T = \frac{T_S + T_R}{2} - T_G \quad (2)$$

Where T_S , T_R and T_G is the supply, return and ground temperature, respectively.

Equation 2 is routinely applied to estimate the pipe heat losses of ground buried pipes in conjunction with a second factor based on the heat loss coefficients of the supply and return pipe, as described in EN13941 [46]. Because the pipe heat losses are proportional to eq. 2, the change in heat loss of pipes can be estimated by evaluating the change in ΔT for different annual mean operating temperatures.

Table 9 shows an overview of annual mean operating temperatures [$^{\circ}\text{C}$] in the hybrid system used in the design process and simulated with the weather data for the TMY and the year 2015:

Table 9: Annual mean operating temperatures [$^{\circ}\text{C}$] in the hybrid system simulated for the TMY and the year 2015.

	$T_{\text{PC S}}$	$T_{\text{PC R}}$	$T_{\text{PC avg}}$	ΔT_{PC}	$T_{\text{SC S}}$	$T_{\text{SC R}}$	$T_{\text{SC avg}}$	ΔT_{SC}
TMY	75.0	61.1	68.0	59.0	59.8	56.1	58.0	49.0
2015	70.0	59.4	64.7	55.7	57.0	55.0	56.0	47.0

The ground temperature corresponds to the average annual surface temperature and this is the same ($T_G = 9^{\circ}\text{C}$) in both *Paper II* and *Paper III*. The average annual surface temperature was taken from a 2015 temperature map in the database of the Swedish Meteorological institute (SMHI) on the internet [47].

Based on the data in Table 9, ΔT_{PC} and ΔT_{SC} is 3.3°C and 2.0°C lower in the year 2015 than in the TMY, respectively. This corresponds to a relative difference of -6% and -4%, respectively. Because the culvert lengths are different in *Paper II* and *Paper III*, the difference in ΔT should be proportional to the difference in *specific* heat loss (in W/m). Hence, based on temperatures alone, the specific heat loss of the PC and SC could be 6% and 4% *lower*, respectively, in the Hybrid system simulation using 2015 weather data.

However, it is clear that these differences are influenced by the choice of supply temperatures in the system and the values of ΔT_{PC} and ΔT_{S} are roughly 30% smaller than the differences in supply temperatures. This implies that if the supply temperatures were increased in *Paper II*, the values for ΔT_{PC} and ΔT_{S} could be even larger than in *Paper III*, which indicates that the modelled supply temperatures influences the heat losses significantly. Because the heat losses in the Hybrid system of *Paper II* are significantly larger than in *Paper III*, despite the lower temperatures, this shows that there are other modelling aspects that affect the simulation results. On the other hand, the low heat losses in the All GRUDIS system in *Paper II* may partly be due to the choice of supply temperatures, although based on the differences (4%) in ΔT_{SC} , this effect is assumed to be small.

Note that comparing the influence of ground temperature on pipe heat losses using eq. 2 is only really valid for pipes with the same heat loss coefficients, as these influence the heat losses significantly. The heat loss coefficients are a function of the thermal conductivity of the soil surrounding the pipe, the pipe insulation and the heat exchange between the supply and return pipe. Because the insulation thermal conductivity was changed in order to calibrate pipe heat losses in *Paper II*, the difference in ΔT between *Paper II* and *Paper III* does not translate linearly to a difference in heat losses, even if the supply temperatures were the same. New simulations would be necessary to investigate the influence of using the same supply temperatures on pipe heat losses in more detail, but this is considered outside the scope of this thesis.

In summary, the difference in modelled supply temperatures lead to a difference in the simulated heat losses. This indicates that other aspects of the modelling approach leads to the simulated PC heat loss, as they are higher than those in *Paper III*, despite the annual average network

temperatures being lower. The low SC losses in *Paper II*, on the other hand, may partly be due to lower temperatures, although the effect of this is assumed small.

4.2.4 Pipe model and network length and distribution heat loss

In *Paper II*, the PC pipe model was that of a standard twin steel distribution pipe, encased by additional EPS insulation. The heat losses were calibrated against measured values by changing the thermal conductivities of both the PUR and the EPS insulation, without particular priority to either.

In *Paper III*, the PC pipe model was modelled without the EPS insulation. This was due to inherent difficulties in calibrating the pipe heat losses against catalogue values, as no such values existed for pre-insulated steel pipes in combination with an EPS casing. As such, the comparison between the hybrid models of the two papers is not straightforward.

Nonetheless, when comparing the PC distribution loss of the hybrid system in the two papers, it can be seen that system specific model actually has a higher distribution heat loss than the generalized model, despite the additional EPS insulation. This is particularly noteworthy in light of the fact that the supply temperature was 70°C in the hybrid system of *Paper II*, but 75°C in *Paper III*. Recalling the model description of the hybrid model, it is evident that the observed differences may be due to the difference in employed culvert length in the two models.

Table 10 shows the culvert lengths, simulated heat loss and calculated average specific heat loss in the distribution culverts of the hybrid system model in *Paper II* and *Paper III*:

Table 10: Values for culvert lengths, simulated heat loss and calculated average specific heat loss in the hybrid model of *Paper II* and *Paper III*.

	Paper II		Paper III	
	PC	SC	PC	SC
Length [m]	950	1114	480	2201
Heat loss [MWh]	-142	-70	-73	-122
Specific heat loss [W/m]	-17.1	-7.1	-17.3	-6.3

The large specific heat loss in the PC is quite similar in size for both *Paper II* and *Paper III*, although the length of the PC in *Paper II* is roughly double that in *Paper III*. Despite the SC length in *Paper III* being roughly double that in *Paper II*, the smaller specific heat loss of the SC in *Paper III* makes the total heat loss smaller. The heat loss of the entire distribution system in *Paper II* is 24 kW, while that of *Paper III* is only 22 kW. The difference is 10%, which is about the same as the same observed difference in simulated heat loss between papers (see Figure 7), which indicates that the differences in employed culvert lengths give differences in simulated distribution loss.

However, the fact that the PC specific heat losses are so similar means that the total distribution heat losses would be very similar if the culvert length was the same in both papers. This is not what would be expected considering the lower supply temperature and higher degree of insulation in the PC of *Paper II*. This is discussed in more detail in Ch. 4.3 *Influence of model calibration method on energy balance(s)*.

On the other hand, despite that the specific heat loss of the SC in *Paper II* is 13% higher than in *Paper III*, the differences in simulated distribution heat loss for the All GRUDIS system could possibly also be attributed to the differences in pipe network length in the two papers.

Table 11 shows the calculated specific heat loss for the distribution culvert in the All GRUDIS system in *Paper II* and *Paper III*:

Table 11: Calculated average annual specific heat loss for the distribution culvert in the All GRUDIS system in Paper II and Paper III.

		Paper II	Paper III
Culvert length	[m]	2064	2681
Distribution loss	[MWh]	-121	-172
Specific heat loss	[W/m]	-6.7	-7.3

When considering the distribution loss in the All GRUDIS system, the specific pipe heat loss of the culvert in Paper II and *Paper III* becomes -6.7 W/m and -7.3 W/m, respectively. The specific heat loss value in Paper II is 9% *lower* than in *Paper III* and recalling that *Paper II* was based on 2015 weather data, the value of ΔT_{SC} was 8% *lower* in *Paper II* than in *Paper III* (see Table 9). Thus, it is possible that when taking length differences into account, the remaining difference in heat loss could be due to the differences in annual mean operating temperatures. However, because the heat loss coefficients have a large influence on pipe heat losses as well, the annual mean operating temperatures can only serve as part of the reason for the observed difference.

4.2.5 Scaling pipe size and heat loss in All GRUDIS system

One noticeable difference between the heat loss in the SC in the Hybrid system (see Table 10) and distribution culvert in the All GRUDIS system of *Paper II* (see Table 11), is that the calculated specific heat loss decreases for *Paper II* and increases for *Paper III* when changing distribution system.

When modelling the All GRUDIS system in *Paper III*, the PC pipe segment in the Hybrid system model is replaced by a PEX pipe segment. These pipes are larger in size than the pipes used in the SC in the Hybrid system, with correspondingly larger specific heat losses and hence, it is natural that the average specific heat loss of the distribution culvert increases a bit when using PEX pipes of large size. Similarly, in *Paper II*, when modelling the All GRUDIS system, the SC length is extended by the PC length in the Hybrid system and the pipe size of the SC is increased to account for the increase in flow when modelling the total system load. Thus, the specific heat loss should have been increasing in *Paper II* as well. The fact that it doesn't do this gives an unreasonable advantage to the All GRUDIS system in *Paper II*. A reasonable explanation for this may be a combination of error in modelling the pipe geometry and the lumped modelling approach.

In Paper II, the SC length the Hybrid system is divided by the PSF (equal to four) in order to model the correct secondary network length when scaling up the load of the secondary network. Thus, the effective pipe length of the SC segment is one fourth of the total SC length. When modelling the All GRUDIS system, no scaling is employed, so the distribution culvert length is increased to the total network length, corresponding to the length of both the PC and the SC network length in the Hybrid system. However, when the culvert is scaled up according to the

increase in flow, the pipe spacing between the supply and return pipe is kept constant (modelling error). Therefore, when the supply and return pipe increases in size, the larger surface area of those pipes and the small pipe spacing allows for a higher heat transfer between them. Because the casing of the twin pipe is scaled together with the supply and return pipe, the smaller pipe spacing also means more insulation between the pipes and the trench, which leads to lower losses to the surroundings. The overall effect is to reduce the pipe heat loss in the All GRUDIS system, compared to that in the Hybrid system. This would explain why the value of specific heat loss decreases.

By running TRNSYS simulations in on the SC isolated and imposing a constant supply temperature of 60°C, a circulation flow rate as in *Paper III* and a constant load of 208 kW, the difference in annual distribution pipe losses are 13% for a pipe spacing of 0.10 m and 0.15 m, respectively. This indicates that, if the pipe spacing had been scaled properly, the distribution losses in the All GRUDIS system could have been significantly higher. It is therefore considered probable that the average annual specific heat loss in *Paper II* should have been similar to that in *Paper III*, had it not been for the incorrect pipe spacing.

Thus, due to the modelling approach the SC distribution heat losses may be underestimated in the All GRUDIS system of *Paper II*. This effect is added to the effects of the assumptions made during the model calibration, which also indicate that the heat losses may be underestimated (see 2.4.7 *Model calibration*).

4.2.6 Lumped modelling and distribution heat loss

There are three types of lumped models:

1. Lumped heating load (one house to represent all houses).
2. Lumped substation model (one substation to represent all substations).
3. Lumped pipe segments (one pipe to represent a group of pipes).

Using one substation to represent all substations have the same implications as using one house to represent all houses, mostly related to simultaneity of loads. In a real system, all SH loads would occur more or less on the same time given that the SH system is automated and using ambient temperature for control. The location of these loads in the network, on the other hand, means that the temperature profile in the pipes will vary, decreasing towards network endpoints.

However, the average network temperature should never be lower than the average of the design operating temperatures. The control strategy of the DH system is to maintain a minimum circulation flow rate high enough to secure a maximum temperature decrease of 5 K between network endpoints (10 K in total). In the Hybrid system, this is valid for both the PC and SC. This is necessary to ensure a supply temperature sufficient for any arising load, but makes the average network temperature higher when no loads exist than otherwise. When DHW loads arise at various locations in the network, the flow increases and lowers the average culvert temperature, which affects heat losses a little bit, but this impact is relatively small.

In a real DH system, a larger housing area would dictate larger and more frequent DHW loads, inducing lower average pipe temperature in the culvert. Small housing areas would dictate smaller and less frequent DHW loads, inducing higher average temperatures. In the model, the entire system load is treated as one and located at the end of the culvert, inducing a lower average pipe temperature than would be the case in reality (valid for the PC only in the hybrid

system). The effect is that the pipe heat losses may be underestimated slightly for the system as a whole. Because the conventional DH system has the largest difference between supply and return temperature, and steel pipes have the largest UA values, this would affect the heat loss in that system the most. However, this is assumed not to change the results of the study, as these are dependent on relative differences between systems more than absolute values.

Nevertheless, the design operating temperatures of the conventional DH system during full load are 75°C, 45°C and 10°C for supply, return and ground temperature, respectively. In a no-load condition where the total temperature decrease should be ≤ 10 K, the supply and return temperature would be 75°C and ≥ 65 °C, respectively. Using eq. 2, $\Delta T = 50$ K during full load at design operating temperatures and $\Delta T = 60$ K at no-load conditions. Thus, the ΔT is 17% *lower* during full load than at no-load. However, this is the worst case scenario and during peak load, which usually makes out a very small part of the duration curve in a DH system.

Figure 10 shows the load duration curve and hourly average of supply and return pipe fluid temperature in the distribution culvert in the conventional DH system. The blue line shows the simulated average hourly load, the red line shows the design average temperature and the orange shows the simulated average temperatures.

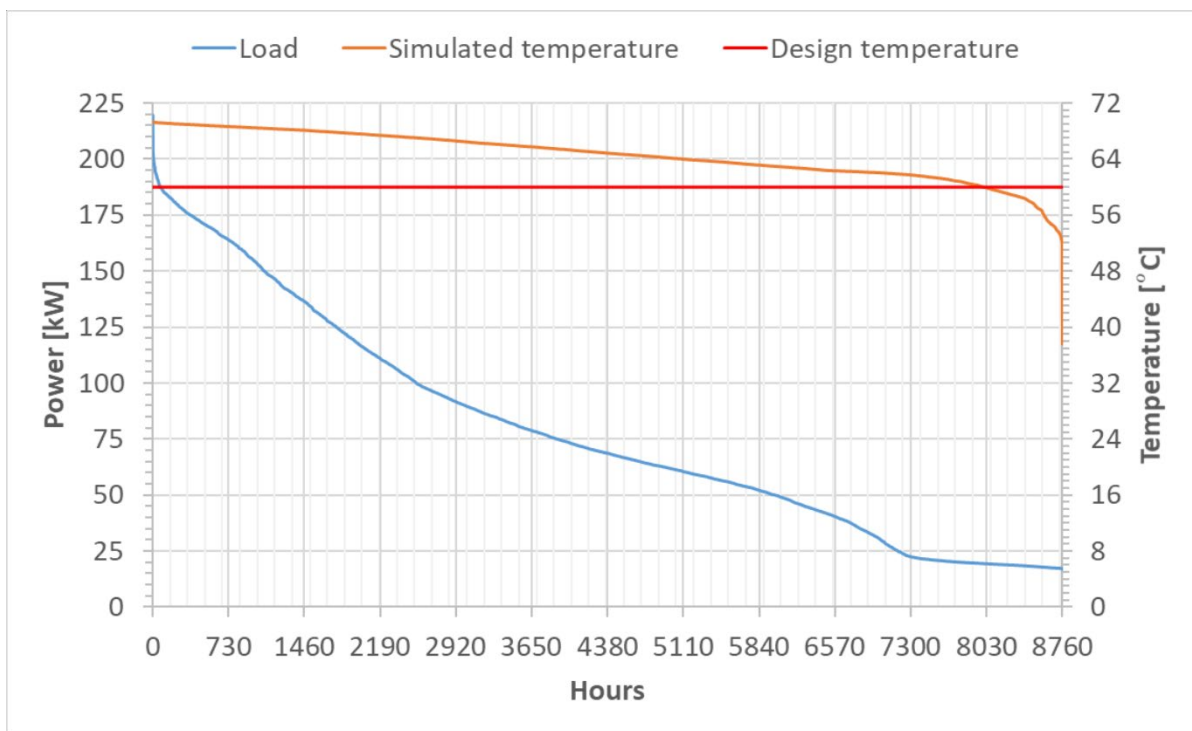


Figure 10: Hourly average of fluid temperature in supply and return pipe of the distribution culvert in the conventional DH system. Blue line shows simulated load, orange and red line shows the simulated and design average temperatures.

The maximum average hourly load encountered in the system is only 220 kW and this is due to the coincidence factor of the DHW load profile generated for the entire system. The momentaneous system load may be significantly larger than this value. The average hourly load is ≥ 200 kW in only 8 hours ($< 1\%$) of the year, which indicates that the system operates at full load very little indeed. The average hourly load is ≥ 110 kW, i.e half of peak load, in roughly one fourth of the year (26%), which implies that the average culvert temperature in the network

should be closer to the no-load temperature than the full load temperature for large parts of the year.

The simulated average temperatures are below 53°C during only 18 hours (< 1%) of the year. The few extreme values below 50°C occur before stabilization of simulation in the initial hours of running time. Further, the simulated average temperatures are higher than the design average temperature (60°C) for most (91%) of the year and only lower for roughly a month. The annual average of supply and return temperature is 65°C and roughly half (49%) of all hourly average values are > 65°C. This indicates that the system operates half the time at temperatures closer to no-load temperatures, than full load temperatures. This is less than the three fourths of the year that was implied when considering the load duration curve and therefore the pipe heat losses could be slightly underestimated. In order to get an idea of the potential error in estimation, it can be useful to revisit eq. 2, which gives $\Delta T = 60$ K at no-load and $\Delta T = 55$ K using the annual average of supply and return temperature. The no-load ΔT is 9% higher, so the heat losses would be that much higher in a system at no-load constantly, as heat losses are proportional to ΔT . However, for an annual average temperature of 68°C, then $\Delta T = 58$ K, corresponding to 3% lower heat losses than at no-load and 5% higher than at the simulated annual average.

Thus, in summary, even if the DH system operated at very high annual average temperatures, the influence of the lumped modelling approach on the simulated heat loss is small for the conventional DH system. Because the average of full load supply and return temperature is lower in the Hybrid system and a potential underestimation in heat loss only influences the PC (steel pipes) the most, the influence of lumped modelling approach on simulated heat loss is even smaller for the Hybrid system. For the All GRUDIS system, there is no difference between full load and no-load design temperatures, and although simulated temperatures vary with load, the differences are so small that the influence of the lumped modelling approach is insignificant.

4.3 Influence of model calibration method on energy balance(s)

4.3.1 Calibration assumptions and total heat loss

One aspect regarding the specific heat loss calculated for the PC (see Table 10), is that despite the lower supply temperature used in *Paper II* and the additional EPS insulation, the value in *Paper II* is not significantly lower than that calculated for *Paper III*. This is assumed due to the difference in employed calibration methods, as the heat losses in HP and PC were calibrated together, while the heat losses in the substation (SS) and the SC were calibrated together, in *Paper II*. The assumptions made in *Paper II* regarding the relative share of heat loss in the HP and SS may have been wrong and this would have had a direct effect on the specific heat loss of the distribution culverts.

According to a performance report made for the Vallda Heberg system, the measured annual loss of substation 1 (on which the substation model is based) and the SC connecting it to the houses was 36 MWh. Four of these were modelled in *Paper II*, so it would be natural to expect a heat loss of 144 MWh for all substations and the total length of the SC. Despite high uncertainties in measured heat, it was assumed that the HP losses could make out 10% of annual boiler supplied heat, corresponding to 72 MWh [28].

Table 12 shows the heat loss in various system parts and their calculated relative shares of total system loss for *Paper II* and *Paper III*. The “Report” values are based on a relative shares from a performance report for the Vallda Heberg system [28], but the total system losses in *Paper II*.

Table 12: Calculated relative shares of total system heat loss for various system parts in the Hybrid system of Paper II and Paper III. The adjusted “Report values” are based on a performance report for the Vallda Heberg system [28].

	Paper II		Paper III		Report	
	[MWh]	[%]	[MWh]	[%]	[MWh]	[%]
HP loss	-73	24	-77	27	-72	23
PC loss	-142	46	-73	25	-92	30
SS loss	-23	8	-18	6	-50	16
SC loss	-70	23	-122	42	-94	31
Total loss	-308	100	-290	100	-308	100

The assumed relative share of PC loss in *Paper II* is significantly different from the simulated relative share in *Paper III* and the values from the Report, while the HP losses are similar. It would seem natural that the PC heat loss in *Paper II* is roughly double of that in *Paper III*, because the culvert length is roughly double of that in *Paper III*. However, this neglects any reduction in heat loss due to the use of additional EPS insulation. Therefore, the PC heat loss should probably be lower, which means that the losses in other parts of the distribution system would have to increase and this is reflected in the Report values. On the other hand, the differences in SC heat loss seem logical when considering SC length in *Paper II* is roughly half of that in *Paper III*, although the relative shares of substation loss are significantly different to that of the report.

If the PC and SC loss from the Report are combined with the values of HP and SS loss from *Paper II*, the total losses become 282 MWh. This value is similar to that in *Paper III* and represents a reduction in total heat losses of 26 MWh (8%), which is roughly the same as the loss from all substations. If this corresponded to a direct reduction in boiler energy, the new value for boiler energy would be 709 MWh, although the All GRUDIS system would still be preferable. However, this is based the assumptions on the relative share of heat loss in the SC being correct, which may not at all be the case and this is treated in the next section.

4.3.2 Calibration assumptions and specific heat loss

In Table 12, the secondary distribution loss has been split between the substations (SS) and the SC in ratio 35 : 65, respectively. The influence of these assumed shares of heat loss becomes apparent if the specific heat losses of the PC and SC are calculated based on the “Report” values for heat losses in the PC and SC (Table 13).

The potential reduction in specific heat loss could be up to 80% for a standard twin steel pipe by employment of additional EPS insulation, according to a research report conducted on the Elgocell product EPS PIPE [48]. The experiments presented in the report were conducted at room temperature, so a reduction of 35% for a pipe subjected to an annual mean ground temperature of 10°C is deemed probable, considering that the heat transfer is proportional to the temperature difference between pipes and the ground. Further, according to previous research, the potential increase in thermal conductivity of EPS due to the combined effect of

ageing and moisture diffusion into the material can be as much as 44% at a material density of 33 kg/m³ [49]. The result of experiments shows potential increase of up to 43% for EPS at a material density of 30 kg/m³ due to moisture diffusion alone, although the temporary increase when the material is under water can be higher by several orders of magnitude [50]. Because of this, the potential reduction in heat loss by use of additional EPS insulation may not be as large as expected.

Table 13 shows the culvert lengths, simulated heat loss and calculated specific heat loss in the Hybrid system model based on the “Report” values in Table 12:

Table 13: Values for culvert lengths, estimated heat loss based on relative shares of system heat loss from a performance report and calculated specific heat loss in the hybrid model of Paper II.

		Report	
		PC	SC
Length	[m]	950	1114
Heat loss	[kWh]	-92	-94
Specific heat loss	[W/m]	-11.1	-9.6

When using relative shares from the performance report, the calculated average specific heat loss of -11.1 W/m and -9.6 W/m for the PC and SC, respectively. Compared to the average specific heat loss in *Paper II* (see Table 10), the PC value is *reduced* by 35%, whereas the SC value is *increased* by 36%.

The design value of average specific heat loss for the SC in *Paper II* was 6.7 W/m, calculated according to catalogue values and corrected for the difference between operating temperatures used in the Hybrid system and specified in the catalogue. The potential increase in specific heat loss due to moisture and ageing could be up to 9.6 W/m, which is exactly the calculated value (Table 13). If the heat losses in the All GRUDIS system were calculated for *Paper II* using the value of average specific heat loss in Table 13, the distribution loss would have increased to 162 MWh. If this corresponded to an increase in boiler supplied energy, the new amount of boiler energy would be 702 MWh. Thus, the Hybrid and All GRUDIS system would then be equivalent in terms of performance.

However, the calculated average specific heat loss in *Paper II* (Table 10) at 7.1 W/m was already 6% higher than the design value of 6.7 W/m. This seems a plausible value for a well-drained pipe trench, although it is possibly too low when considering moisture diffusion in EPS. Further, the specific heat loss of the SC in *Paper III* was 6.3 W/m, which was for a (dry) culvert based on catalogue data. This is closer to the simulated value in *Paper II* and, accounting for increase in heat loss due to moisture and ageing, the values could be similar. The simulated values in both papers therefore seem more realistic than the calculated value in Table 13, although the current evaluation of the calibration process has indicated that the simulated SC loss probably is too low in *Paper II*. Furthermore, this underestimation of losses implies that losses in the All GRUDIS system may be too low as well, as the distribution culvert in the All GRUDIS system was an extended version of the SC in the Hybrid system in *Paper II*. This effect comes on top of the potential underestimation of heat losses due to the modelling approach (see 4.2.5 *Scaling pipe size and heat loss in All GRUDIS system*).

In summary, the initially assumed share of PC heat loss in *Paper II* was probably wrong and far too large. Similarly, the initially assumed share of SC loss could have been too low, although it is uncertain what a reasonable value would be. The implication of these erroneous assumptions is that the simulated distribution losses of the Hybrid system in *Paper II* may be too high, while the distribution losses in the All GRUDIS system may be too low. This may explain why the All GRUDIS system was preferable from an energy perspective.

4.4 Discussion summary

Several potential factors could be responsible for the difference in results between the Hybrid and All GRUDIS system in *Paper II* and consequently the contradictory results between papers. Some of these have been discussed in this chapter and the impact of each factor on the energy balance has been evaluated.

Table 14 shows an overview of subchapters that discuss factors that influence differences in the energy balance between models. Plus and minus signs indicate an increase or decrease in the difference (Δ) between the Hybrid and All GRUDIS system for the key parameters boiler energy (BE), distribution loss (DL) and solar energy (SE).

Table 14: Overview of discussed factors that impact the difference in energy balance between models and whether they reduce (-) or increase (+) these differences. Parenthesis indicates assumed impact.

Chapter	Δ BE	Δ DL	Δ SE
4.2.1 Effects of pipe model and solar culvert length on supplied solar energy	+		++
4.2.2 Effects of storage UA-values on stored solar energy	-		-
4.2.3 Effects of supply temperatures on distribution pipe heat loss	+	+	(+)
4.2.4 Effects of pipe model and network length on distribution heat loss	+	+	(+)
4.2.5 Effects of scaling pipe size on heat loss in All GRUDIS system	+	+	(+)
4.2.6 Effects of lumped modelling on distribution heat loss	-	-	(-)
4.3.1 Effects of calibration assumptions on total heat loss	++	++	(+)
4.3.2 Effect of calibration assumptions on specific heat loss	++	++	(+)

Based on Table 14, it is possible to see that Ch. 4.2.1 discussed the effects of pipe model and solar culvert length on supplied solar energy, finding that these factors resulted in a major (++) difference in supplied solar energy (SE) between models, although the influence on boiler energy (BE) was minor (+). Similarly, Ch. 4.3.1 found that the calibration assumptions resulted in a major difference in boiler energy and distribution loss between models. Because larger distribution losses tend to increase the solar energy stored, the increasing difference in distribution loss is assumed to increase the difference in solar energy between models - this is shown in parenthesis.

The general trend is that most factors increase the difference between the models and this is in line with the observed differences in the results of *Paper II* and *Paper III*.

5. Conclusions

5.1 Method revisited

Two simulation studies have been made in TRNSYS on a small solar assisted district heating system, using different modelling approaches and calibration methods to be able to draw relevant conclusions regarding the influence of changing the distribution system. These studies are summarized in this thesis.

Three system concepts were investigated:

1. A Hybrid system using a combination of high-temperature, conventional steel pipe primary culvert, intermediate substations containing solar buffer stores and a low-temperature, EPSPEX secondary culvert with DHW-circulation (so-called GRUDIS).
2. A Conventional distribution system with steel pipes, higher operating temperatures and centralized solar buffer stores.
3. An All GRUDIS system, using only low-temperature EPSPEX distribution with DHW-circulation, lower operating temperatures and centralized solar buffer stores.

A sensitivity analysis is performed by simulating the three different distribution system for various linear heat densities, with the added objective of detecting any range-bound limitations of the different distribution systems.

5.2 Results in summary

In Paper II, technical drawings of the Vallda Heberg district heating system were used to make a simplified simulation model and this was calibrated the simulated performance of this model against measurement data. The calibrated model was used to study the change of the distribution system from a Hybrid concept to an All GRUDIS concept. The All GRUDIS system performed best and seemed to hold the promise of lower economic investments with the potential of reducing heating costs, based on the pipe costs of the distribution system. However, the measurement data used for calibration was of poor quality and satisfactory calibration could not be achieved in the Hybrid model, so the simulation results were considered too unreliable for further use and this led the model to being abandoned in favour of developing a new model.

In Paper III, technical drawings of the Vallda Heberg system were used to make a generalized simulation model for the three distribution concepts based on a theoretical approach, using sizing guidelines and technical standards to size the distribution system and system flow rates. The idea was that by using a systematic approach to build the simulation model, the differences between models would be representative for the real-world differences in performance, despite potential lack of correspondence with real world performance in the individual models. The results showed that the Hybrid system was most fuel efficient, although the All GRUDIS system performed slightly better due to lower heat losses and almost the same boiler supplied energy.

5.3 Discussion in summary

Several potential factors that could be responsible for the contradictory results between papers were investigated and some contributing factors were identified:

- The combined effect of lower solar irradiation, lower temperatures and higher-than-calculated heat demands is presumably the reason for the observed differences in heat demand between *Paper II* and *Paper III*.
- It is deemed probable that a small annual variation in solar irradiation could lead to an observed difference in stored solar energy between papers. However, when differences in solar culvert heat losses are accounted for, the simulated amount of stored solar energy could be very similar in both papers.
- The difference in stored solar energy between systems in *Paper II* are assumed due to differences in the employed solar culvert length. On the other hand, the difference between systems in *Paper II* and *Paper III* are assumed due to too high UA-values for the culvert pipes in *Paper II*. This leads to the conclusion that the simulated amount of stored solar energy in *Paper II* was too low, although this does not change the overall results of that study (that All GRUDIS performs best).
- In summary, the difference in modelled supply temperatures lead to a difference in the simulated heat losses. This indicates that other aspects of the modelling approach leads to the simulated PC heat loss, as they are higher than those in *Paper III*, despite the annual average network temperatures being lower. The low SC losses in *Paper II*, on the other hand, may partly be due to lower temperatures, although the effect of this is assumed small.
- Due to the modelling approach the distribution heat losses are probably underestimated in the All GRUDIS system of *Paper II*. This effect is added to the effects of the assumptions made during the model calibration, which also indicate that the heat losses may be underestimated.
- Even if the DH system operated at very high annual average temperatures, the influence of the lumped modelling approach on the simulated heat loss is small.

Concluding, the initially assumed share of PC heat loss in *Paper II* was probably wrong and far too large. Similarly, the initially assumed share of SC loss could have been too low, although it is uncertain what a reasonable value would be. The implication of these assumptions is that the simulated distribution losses of the Hybrid system in *Paper II* are too high, while the distribution losses in the All GRUDIS system may be too low. This may explain why the All GRUDIS system was significantly better from an energy perspective.

The sensitivity analysis shows that no apparently unexplainable differences exist between the two papers when the energy balance changes with line heat density. The differences in the energy balance at 1LD and the following discussion on influence of various factors on this has shown that the energy balance in *Paper II* may be wrong and favours the All GRUDIS system. When taking into consideration this and the different modelling approach for the solar energy system,

the trends are the same in both papers. Thus, the result of the sensitivity analysis is that the Hybrid system seems to be the best option from an energy perspective at 2LD, and although the results are inconclusive at 1LD, the result from the discussion on the energy balance (see 3.1.1 Overall results) implied that the higher solar fraction makes this system favourable. At 0.5 LD, the findings are inconclusive as to the best system. The conventional system performs worst for all values of LD.

The economic analysis shows that all three distribution systems are equivalent in investment cost, when considering the pipe network costs, but disregarding installation costs. However, the cost of intermediate substations and house substations in the Hybrid and Conventional DH system may be so high that the All GRUDIS system is most cost effective, although detailed calculations are needed conclude on this. The conclusion based on the preliminary analysis thus far is that the Hybrid system seems to be preferable economically and that the EPSPEX system is best used as a secondary system, which is in line with previous conclusions. However, more detailed economic calculations are needed in order to draw sound conclusions regarding the most cost effective solution.

Finally, in light of all the findings presented, the All GRUDIS system performs as well as the Hybrid system in sparse DH networks (0.2 – 0.3 MWh/m, a), although the estimated distribution system costs are significantly lower for the All GRUDIS system, which makes this system more attractive. For very sparse (0.10 – 0.15 MWh/m, a) networks, the systems also perform similarly and in denser (≥ 0.4 MWh/m, a) networks, the Hybrid system performs better from an energy perspective. The conventional DH system performs worst in both sparse and dense networks.

6. Future work

Despite the fact that the GRUDIS technology was developed during the expansion of the 3rd generation DH networks in the 80's, the technology has remained a peculiarity. It might be that the timing of its introduction was wrong, as it never seemed to gain the traction needed to reach large scale and international interest. However, with the transition to the 4th generation DH and low temperatures, GRUDIS seem to have a lot of characteristics which favours its implementation. Keeping in mind that one desired improvement in future DH systems was to remove recirculation flows and bypasses in order to undisturbed return temperatures [12], GRUDIS both avoids circulating water for local DHW preparation and has a low temperature difference between supply and return. That said, for low temperature DH (LTDH) the technical configuration of the system is not necessarily given and therefore, future work should focus on how it could be realized technically when annual average return temperatures are $\leq 30^{\circ}\text{C}$. Also, considering the technical limits of PEX pipes in terms of pressure, it is necessary to investigate the limits on network size when using these for entire networks.

However, future improvements in DH system are mostly relevant for new systems and, although they may also be relevant for additions to existing systems, the addition of GRUDIS as a secondary network to primary networks in suburban areas should be investigated more closely. The majority of DH systems already exists and so, the use of GRUDIS to expand DH networks into suburban areas represents an opportunity to reduce heat loss and cost already today. Whether or technical adaptations to LTDH may be utilized in these networks remains to be seen, although it is clear from the results in this study that such an expansion have important benefits that should not be disregarded. More studies are needed to demonstrate this.

Regarding economic aspects, the studies presented in this theses do not take into account the fuel use. The minimum turndown ratio of the boiler will lead to some fuel use that does not cover the demand or distribution losses, due to the different operating strategies in the Hybrid and All GRUDIS system. Therefore, more detailed studies are needed to model the additional fuel costs when regarding the minimum turndown ratio of the boiler and (the cost of) potential control strategies for mitigating this.

Other economic aspects that are relevant for future studies are related to the use of EPS, both as additional insulation for conventional steel pipes and as insulation for PEX pipes. Pre-insulated PUR pipes already exist and in contrast to the EPSPEX culvert, these are continuous and available in rolls of up to 200 m, which combines the best of both conventional steel pipes and PEX pipes in yet another way. The use of such pipes should be compared to the use of EPSPEX, in order to clarify potential reductions in cost that may result from reduced installation time and reduced heat losses due to reduced moisture diffusion into the pipe insulation. Further, the use of EPS as additional insulation for steel pipes may represent an economic alternative in LTDH, as the costs of steel pipes are lower than those of PEX and have higher pressure limits that enable higher heat transfer capacities. Thus, the cost for use of EPS as additional insulation for steel pipes should be investigated for larger LTDH networks and compared to the use of pre-insulated pipes with a higher degree of (PUR) insulation and to the use of PEX pipes.

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