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Obstacles for Implementation of 4th Generation District Heating for Large Scale Networks

VLADISLAV MAŠATIN

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TALLINN UNIVERSITY OF TECHNOLOGY
School of Engineering
Department of Energy Technology
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Supervisor: Senior researcher Anna Volkova, Dr.Sc.Ing.
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Co-supervisor: Professor Andres Siirde, PhD
School of Engineering
Tallinn University of Technology
Tallinn, Estonia

Opponents: Prof. Dr.-Ing. Ingo Weidlich
Infrastructural Engineering
HafenCity Universität
Hamburg, Germany

Einari Kisel, PhD
World Energy Council, Regional Manager, Europe
Senior Fellow, European Policies
Eesti Energia Ltd, Member of Supervisory Board

Defence of the thesis: 03/07/2018, Tallinn

Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree.

Vladislav Mašatin ……………………………
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List of Publications

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2. Mašatin, V.; Link, S.; Siirde, A. (2014). **The Impact of Alternative Heat Supply Options on CO2 Emission and District Heating System.** Chemical Engineering Transactions, 39, 1105−1110, 10.3303/CET1439185.
3. Mašatin, V.; Latõšov, E.; Volkova, A. (2016). **Evaluation factor for district heating network heat loss with respect to network geometry.** Energy Procedia, 95: International Sciencific Conference "Environmental and Climate Technologies - CONECT 2015". Elsevier, 279−285, 10.1016/j.egypro.2016.09.069.
4. Mašatin V.; Volkova A.; Hlebnikov A.; Latõšov E. (2017). **Improvement of district heating network energy efficiency by pipe insulation renovation with PUR foam shells.** Energy Procedia, 113: International Scientific Conference "Environmental and Climate Technologies – CONECT 2016". Elsevier, 265−269, 10.1016/j.egypro.2017.04.064.
5. Volkova, A.; Siirde, A.; Mašatin, V. (2018). **Methodology for evaluating the transition process dynamics towards 4th generation district heating systems.** Energy, 150, 253−261, 10.1016/j.energy.2018.02.123.

Author's own contribution

The contribution by the author to the papers included in the thesis was as follows:

1. Historical data collection, case study calculations, network hydraulical simulation.
2. Historical data collection, calculation of effects on DHN. Was presented in the Congress CHISA 2014 (23-27 August 2014, Prague)
3. Development and approbation of methodology. Was presented on International Scientific Conference "Environmental and Climate Technologies – CONECT 2015" (14–16 October 2015, Riga)
4. Compilation of on field experiment, data collection and analysis. Was presented on International Scientific Conference "Environmental and Climate Technologies – CONECT 2016" (12–14 October 2016, Riga)
5. Analytical data collection, methodology development and approbation. Was presented on 3rd International Conference on Smart Energy Systems and 4th Generation District Heating (12-13 September 2017, Copenhagen).

Abbreviations

4GDH(N/S)	-	4^{th} generation district heating (network/system)
AHP	-	Absorption heat pump
CHP	-	Combined heat and power
DH(N/S)	-	District heating (network/system)
DHW	-	Domestic hot water
DN	-	Diameter nominal
EU	-	European Union
HEX	-	Heat exchanger
HT	-	Heat transfer
HTC	-	Heat transfer coefficient
IEA	-	International energy agency
Rel.HL.	-	Relative heat loss
RHM	-	Remote heat metering
TEF	-	Technical evaluation factor
TES	-	Thermal energy storage
TNSB	-	Temperature night setback

Terms

Symbol	Name of quantity	Unit
c	heat media specific heat capacity	W/kg·K
C1	Fuel-based primary energy per delivered heat energy	MWh/MWh
C2	CO_2 emissions per delivered heat energy	$kgCO_2$/MWh
D_a	Network average diameter	m
d	Diameter	m
G	Degree hours	°Ch
K	Heat transfer coefficient (total/average)	$W/m^2 \cdot K$
L	Length	m
m	Mass	Kg
Q	Energy	W
Q_{dens}	Consumption density	Wh/m
Q_{hl}	Network heat losses	Wh
$Q_{hl,\%}$	Relative heat losses	%
T_1	Supply heat media temperature	°C
T_2	Return heat media temperature	°C
T_{env}	Ambient environment temperature	°C
T_{soil}	Soil temperature	°C
U	Thermal conductivity	W/m·K
$(k,M,T,G)Wh_e$	Electrical power	(k,M,T,G)Wh
$(k,M,T,G)Wh_{th}$	Thermal power	(k,M,T,G)Wh

In the future all existing currencies are abolished. The "mega-watt-hour" becomes the universal unit of exchange.
Arthur C. Clarke, *2001*

Introduction

It is important for every building to have an access to heat and provide hot water to the residents; heat energy is also often required for some industrial processes. District heating is the most efficient and environmentally friendly way of supplying cities with heat comparing with individual solutions. The global target is to reduce or completely avoid fossil fuel combustion in future energy generating systems, which makes DH even more essential. In addition to the reduction of greenhouse gas emissions, the aim is for 20% of the final energy consumption in 2020 to come from renewable energy sources, including a 10% renewable fuel share for vehicles. Additionally, the EU has set a 20% energy savings goal to be reached by 2020 (compared to the projected use of energy in 2020) [1]. Additional 30% energy efficiency target to be reached by 2030 was proposed in 2016 [2], [3].

DH is the most common and efficient heat source in countries where outdoor temperature can drop below 0ºC (author's observation). In some countries, DH is underdeveloped, despite the fact that they have everything for the popularization of DH, e.g. the United Kingdom. Although the heating and cooling sector is transitioning to clean or low-carbon energy, fossil fuels make up 75% of the fuel used (nearly half of it is natural gas) [4]. Future development and efficiency improvement of the DHS are vital factors for achieving a green, CO_2-free future, especially considering the EU goal to only use renewable energy by the year 2050 [1], [5].

In this thesis, DH is considered as a piping distribution system from a heat production source, e.g., combustion boiler to heat exchanger in house substation. Usually network is described by different numerical parameters, however, it should be noted that it is consumers who determine the DH network's dimensions, parameters and layout. When it comes to the DH network's overall efficiency and its impact on the environment, all aspects should be considered together as long as they affect each other. There is no definition of a large-scale DHN, but it can be described as a network with over 2000 houses connected to it, and with an annual heat consumption of more than 1 TWh.

Renewable energy is defined as energy derived from natural resources, such as wind, sunlight, geothermal heat and waves: resources which are naturally replenished over a short time. Household and industrial waste can be sometimes considered as renewable: most such waste can be reused or the process can be improved so that no waste remains; only unavoidable waste should be defined as renewable and used for energy production [6].

Two major challenges must be overcome for district heating systems to remain competitive in the future. The first challenge is competing with local renewable energy sources such as heat pumps, and the second deals with decreased heat demands of new and existing buildings [7].

The definition of the 4^{th} generation DH (4GDH) was proposed by Henrik Lund, Sven Werner and others in [8]. In short, it is defined as a low-temperature network, integrated with district cooling and other energy systems and utilizing renewable energy (*Figure 1*).

In recent years, the term smart district heating or smart thermal grids have also been in use. The definition smart grids is as following: a network of pipes connecting the buildings in a neighborhood, town center, or an entire city, with energy supplied by centralised plants, as well as a number of distributed heating or cooling production units, including individual contributions from the connected buildings [6]. The term refers to a network where all components are interconnected, and the connections are controlled and managed in order to maximize energy efficiency. The concept of smart energy networks came from electrical grids (country, city or single house electrical systems), as it is rather easy to route and control electrical energy, e.g. light output, electrical heating, etc. Heating, cooling and electricity systems can assist each other in order to decarbonize the energy sector: heat can also be used for district cooling systems/networks that use absorption heat pumps, and electricity can be used in heating and cooling processes. CHP and even tri-generation plants (heat, cold and electricity) will play an important role in the future from this perspective [9]–[13].

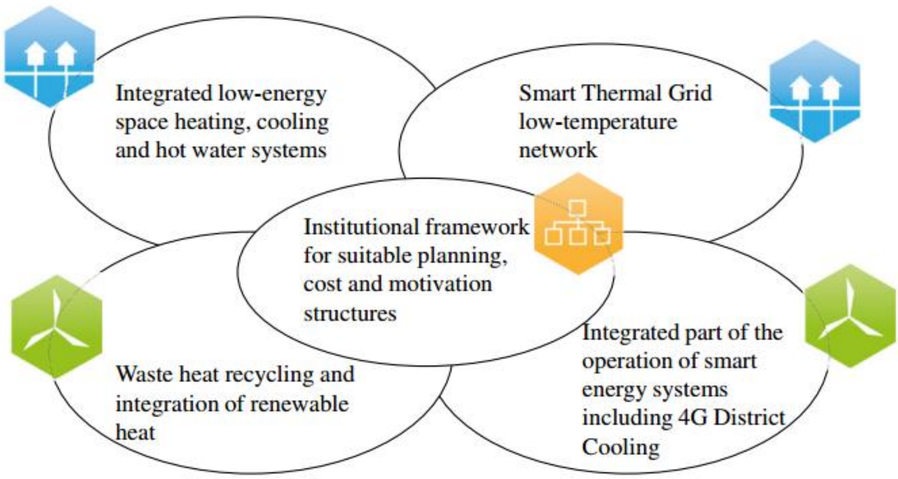

Figure 1. The concept of 4th generation District Heating and Smart networks [8].

Estonian networks were used for reference in the DH system analysis, with case studies mainly based on Tallinn's DH network. In Estonia, DH is the dominant source for space heating and domestic hot water preparation due to the relatively cold climate and a large number of multifamily residential buildings. Estonian DHNs vary widely: annual heat production numbers can range from 5000 MWh to 2 TWh. This means that different approaches could be required for different networks. The largest networks in Estonia are located in Tallinn, Tartu, Narva and Pärnu – the most populated cities in the country. The DHNs in these cities have been integrated with wood chips fired CHP plants (Narva is an exception, as there is a large oil shale fired power plant, however some amount of wood fuel is also used). DH in Estonia is regulated by local municipalities and the Ministry of Economic Affairs and Communications [14], [15]; the energy market is regulated by the Competition Authority [16], [17]. Despite the fact that this thesis is based on Estonian DH experience and case studies, the results of the research can be applied to other existing DHNs.

1.1 History and development of district heating

District heating is a heat distribution system, with heat generated in a central source and supplied for commercial and residential heating needs, such as space heating and domestic hot water preparation. The same definition can also be used for district cooling, except that “cold” is generated and distributed.

The main driving forces of DH are security of supply, flexibility, economy of scope (cogeneration, waste incineration and surplus heat utilisation is almost impossible on a small scale), economy of size (larger units cost is less than same capacity of small units), and a low environmental impact. The use of DH improves overall safety due to the absence of combustion devices for each user, it also reduces air pollutant emissions, as large combustion stations are easier to control and the environmental requirements are much more strict for them.

DH has been used for space heating for over a hundred years. The first DH system is still in operation in the town of Chaudes-Aigues, France. A real estate register from 1334 reveals that some citizens did not paid their heating fees, which means that DH is much older that it is usually expected. Geothermal water – a natural hot water source with a temperature of 82°C was used for heating, and it continues to be used today [18]. The first commercial DH system was introduced in New York in 1877; the widespread development of DH started after the World War II. Now there are thousands of district heating networks operating around the world, and the number is growing. There are about 80,000 systems in the world, and almost 600,000 km of distribution pipelines [19].

According to various EU/IEA reports, district heating currently provides around 11-12% of the EU’s heat demand via 6,000 heat networks. The amount of heat generated for DH per annum in the European Union is about 580TWh (*Figure 2*), on a global scale, the amount of energy consumed via DH is much higher, only in China annual sales turnover is over 880TWh [20], [21].

The fact is that heat consumption by existing consumers has been decreasing due to building refurbishment and installation of alternative heat supply sources, such as solar panels for hot water supply and heat pumps. The forecast for space heating demand is negative, about -17% for the year 2030 comparing to 2010 if today’s trend remain in force [20]. Despite the fact that in 2014-2016 the total final energy consumption in the residential sector was on the rise, which can be explained by overall economic growth, the amount of energy consumed on average has been declining over the last decade, with figures dropping by about 5.5TWh every year (*Figure 2*) due to several reasons including increased energy efficiency of appliances and improvement in energy performance of the building stock following the progressive implementation of the Energy Performance of Buildings Directive and minimum eco-design requirements [22]. Climate corrected annual final energy consumption has been decreasing by 0.7% on average in the last decade.

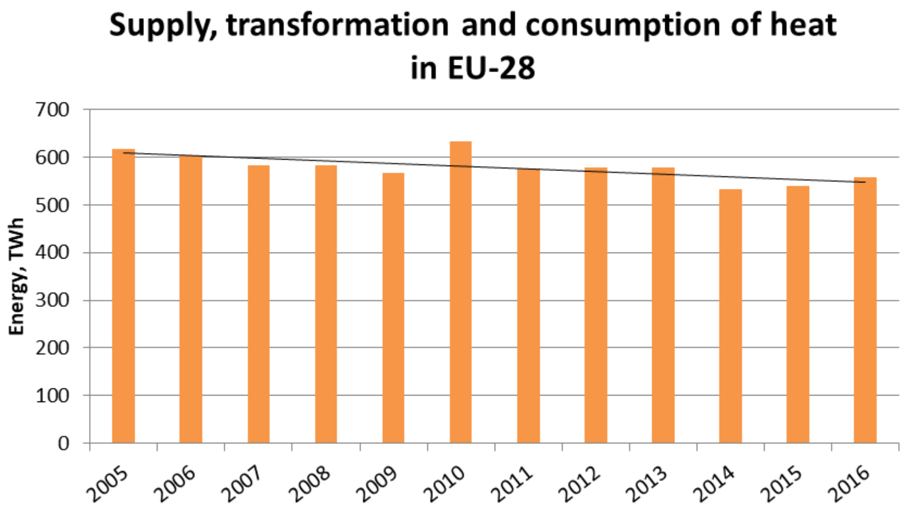

Figure 2. Heat generated for DH in EU-28 [21].

The DH potential is huge, and even the consumption reduction is significant, it only affects existing networks, which means that DH can expand its global market, many countries have share of DH below 25% (*Figure 3*). According to the Heat Roadmap Europe, if urbanisation trends continue, and appropriate investments are made, nearly half of Europe's heat demand could be supplied by district heating by 2050 [23].

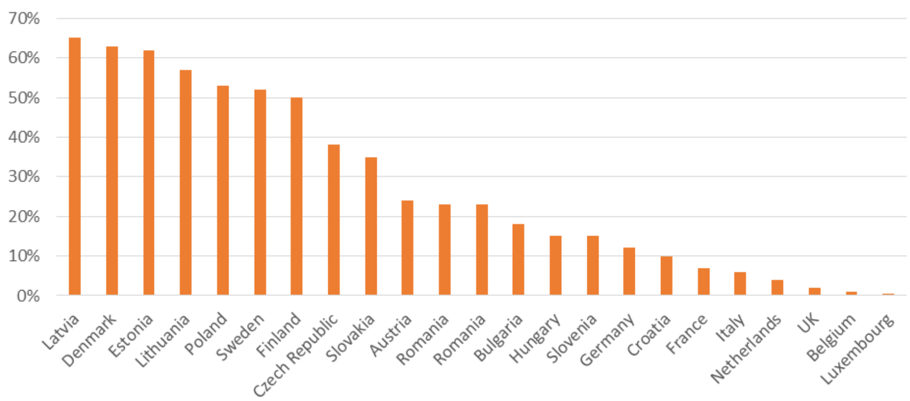

Figure 3. The share of DH in EU countries (less than 2% for others) [20], [24]–[26].

Nevertheless, DH is an essential part of energy balance. Moreover, it also plays a significant role in terms of environment: DHS helps reduce air pollution in cities due to better combustion technologies and stricter control; it is able to utilise energy sources that otherwise would be wasted; it provides a more efficient electricity production source using CHP technologies; it allows combining various energy sources. Research findings showed that connecting a house to a DHN is profitable if it consumes more than

50GJ (ca 14MWh) of energy per year, with the linear heat density of over 2GJ/m (ca 0,6MWh/m; Swedish case, but can be used for reference) [27]. For instance, this amount of energy corresponds to yearly heating needs of an average house with a floor area of 100m^2 in France or 150m^2 in Greece. Both example houses located in a quite warm climate, it means that, in theory, almost every building in Europe is profitable to connect to DH [28].

The evolution of DH consists of four generations. To put it simply, each generation can be described by a pipe system layout, heat transfer media type and temperature (*Table* 1). Today, most of the networks are characterised as a mixture of the 2nd and the 3rd generations.

Table 1. DHN simple generation division.

Generation	Media	Temperature	Piping
1st generation	Steam	140 to 180°C	Concrete channel, mineral wool.
2nd generation	Water	100-130°C	Concrete channel, mineral wool.
3rd generation	Water	70-100°C	Buried underground, polyurethane pre-insulated.
4th generation	Water	Up to 60(70)°C	Buried underground, polyurethane pre-insulated.

Today, networks are more often divided into three groups based on temperature: **high** temperature networks with a supply temperature of over 80°C; **low** temperature networks with the supply temperature ranging from 55 to 80°C, and **ultra-low** temperature networks, where the supply temperature does not exceed 55°C throughout the year.

The concept of DHS generations was proposed a couple of years ago. Along with network properties, it was also suggested that other characterisation and criteria should be used, such as heat source types and variety, network size, interconnection with electrical and district cooling networks, CHP station and storage presence, etc. (*Figure 4*). The generalisation of the concept and generation division began with electrical networks by introducing the concept of "Smart grids" [8].

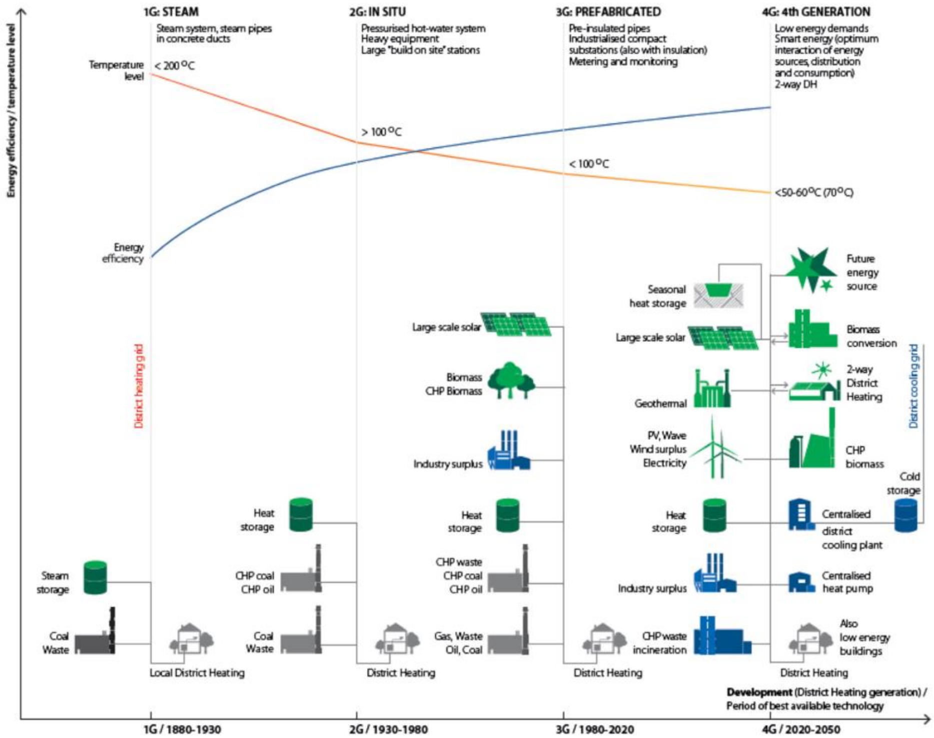

Figure 4. Comparison of DH generations[8].

Some 4th generation DHS already exist in the form of new or renovated networks, without any complaints from consumers. All of them are located in Nordic countries with developed DH infrastructures, such as Denmark and Sweden. E.g. Lystrup's (Denmark) network has a supply schedule of 60 to 80°C depending on outdoor temperatures; experimental data has shown that a supply temperature of 50°C is enough to satisfy consumers' needs [29]. Soenderby (Denmark), where all houses have underfloor heating, have an annual average supply temperature of 55°C. However, no existing large-scale networks have been identified so far that could be described as a low-temperature network or the 4th generation district heating system.

1.2 The goal of the thesis

The DH technology has been well known for over a hundred years, the operation of a DHS seems rather easy, however the more detailed the examination of every component is, the more complicated and more complex dependencies can be put on paper. Today, there often is a lack of complete understanding of all aspects, even when it comes to professionals, so complex written analyses are necessary to improve overall system efficiency. The most common reason for a non-complex approach is that the owners of each part in a DHS, from production to consumers (heat source and network owner, operation company, consumer) are only interested in their own efficiency and profitability, which is why complex ways of increasing efficiency are often neglected.

The goal of the thesis is to describe and analyse the refurbishment possibilities of large DHS in order to achieve the best possible efficiency in the transition towards the 4th generation DHS. A lot of work is already being done in this field, however almost all of the studies describe only heat distribution or production aspect of the DHS and mostly consider small networks. The author of the thesis strongly believes that the most important part of the DHS is the consumer side. During the PhD studies, a lot of time was spent on analysing the distribution side of DHS, however strong connections and dependencies between the distribution and the consumer sides were identified and further researched.

1.3 Hypothesis of the Doctoral Thesis

The only way to reach the 4th generation in large DHSs is through a simultaneous improvement of all components of the system, with the main focus on the consumer side, as it is the main obstacle in the transition process of DHS towards the 4th generation.

1.4 Tasks and methods for hypothesis

The choice of topics for this paper is based on the need to upgrade existing DHSs in order to improve their efficiency and enable them to compete with alternative single flat/house solutions like heat pumps that are inexpensive and able to provide the necessary amount of heat at a low cost.

The aim of the paper is to identify and determine how DH parts are interconnected and how they affect each other; provide an overview of renovation activities and possibilities for a large existing district heating networks in order to make them a more efficient and sustainable energy source for residents with respect to the future, saving the environment and primary energy. The 4GDH is considered as a goal for every DHS should be on track to achieve. During the research process, a lot of obstacles were identified that are slowing down large networks' transition towards the 4GDH, chapter 5 discusses possible solutions.

Most of what is written here is also valid for district cooling (DC) systems, as these systems are very similar to DH, and most methods and equations can be used for both types of systems. The connections between system parts are also comparable. However, the DC is not discussed in the research paper as an independent topic.

The following aims were defined in order to prove the hypothesis:

- Find connections between production, distribution and consumption sides of a DHS.
- Evaluate each side of DH and identify the barriers to achieving the 4GDH.
- Develop a methodology the DHN and DHS evaluation.
- Identify existing barriers, as well as possible solutions to overcome these barriers.

The following methods were used in thesis:

- Review and analysis of scientific papers, reports and other projects' outcomes.
- Experiments – on field measurements and numerical analysis.
- Analytical and statistical data analysis.
- Regression Analysis.
- Time series forecasting

- Network hydraulical and consumption simulations and optimization.
- Benchmarking – in DHN and DHS evaluation methodologies.
- System analysis, based on key performance indicators, criteria and achievement rate.

Key themes and findings used in this research paper:

- Usually, only one side component of district heating is discussed, whereas in this paper all three sides are simultaneously analysed. Each DH network is a complex system where all sides are interconnected, and even the slightest change in one of the components may lead to significant changes in others.
- Used up to date materials and numerical study cases (AHP, insulation) were used, some cases are unique and references are not found.
- On field heat loss measurements for a DN1200 pipe provided unique experimental data on replacing insulation in large pipelines (in this case, exchanging wool for PUR foam shells).
- On-site examination of the impact of night setback on DH parameters.
- Remote heat metering systems (RHM) and consumer behaviour analyses were used for a better understanding of how network parameters are changing due to consumer device characteristics.
- Parallel consumption and prosumers: how consumers that can also produce energy affect DHSs.
- Development of the DHN technical evaluation factor – a way to measure and compare technical efficiency of different DH networks, regardless of size and other parameters.
- Development of a DHS evaluation methodology – a calculation method used to track system changes during the transition process towards the 4th generation, and compare DH systems.
- Evaluation of obstacles to the DHS transition towards the 4th generation, and identification of possible solutions.

The methods and technical improvements described have mostly been approbated for the Tallinn DHS or smaller Estonian systems; the experience and numerical data of neighboring countries is also considered. The results of this study are applicable to existing large DHNs, especially in post-Soviet countries, however most results are also true for other DHNs.

2. Background

2.1 Literature review

The number of articles on DH, had been more or less the same until 2010 when approximately 40 new articles were published with "district heating" in the title, abstract or keywords, according to ScienceDirect. Since 2010, the number of articles has been growing, and by 2017 the number of published articles increased nearly tenfold, compared to 2010, reaching 390 articles (*Figure 5*) [30]. The first studies on the 4GDH were published in 2013-2014, and the first article featuring the 4th generation DH definition and description was published 2014 [8]. The 4GDHNs were described as a system that is capable of providing low-temperature heating with low transmission losses, recycling energy from renewable sources; it is integrated with other grids and is a sustainable energy system. The necessity of a new theoretical scientific understanding of the DHS was summarized in [10] by H.Lund in 2016, where the needs for cross-sectoral collaboration and scientific contribution to the technological and design aspects of DH were discussed.

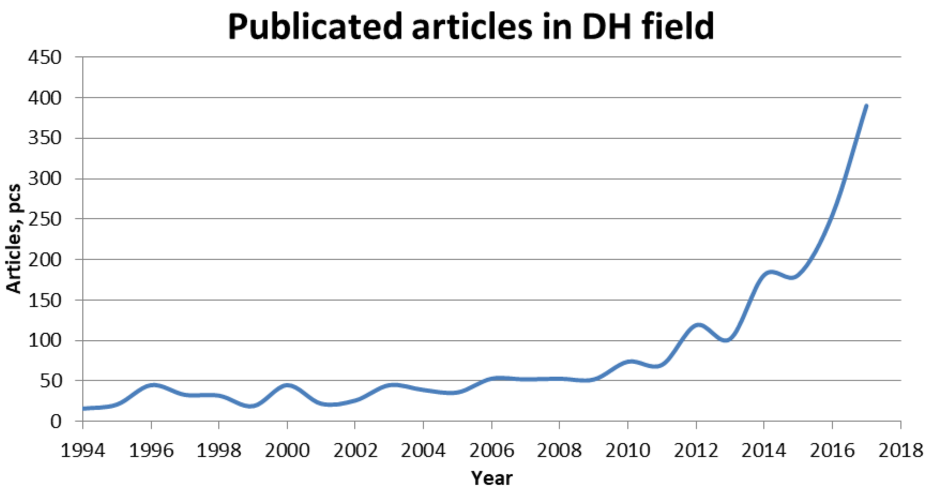

Figure 5. The number of published articles with the phrase "district heating" in the in title, abstract or keywords, according to ScienceDirect.

The summary of key articles dealing with the <u>production</u> side: the possibilities of using geothermal [31], [32] and solar energy [33]–[35] in DH were discussed and analysed for various locations. Solar-based heating is mostly considered as a local heat source for each house [36], however large-scale seasonal TES facilities where the share of solar energy is more than 50% can be found in Denmark and Germany [33], [35]. At the same time, centralised heat production is reported to be more economically viable [37]. A methodology for designing flexible multi-generation systems can be used to identify the most efficient solution was described by C.Lythcke-Jørgensen [38]. In short, modern technology is advanced enough to supply low-temperature heat to the network. Additionally, an increase in temperature can be achieved by using heat pumps for networks where it is difficult to utilise low-temperature energy.. The Absorption cycle is a better option, as it is possible to integrate it with some electricity production sources, e.g. by using Organic Rankine Cycle [39], [40].

Over the past two decades, the distribution side has been carefully examined, most analyses are conducted concerning network geometry optimisation, hydraulic network simulation methods [41], and overall parameter optimisation [42], [43]. Some optimisations are carried out with multiple heat sources in mind in order to optimise heating costs [44], [45]. Today, heating distribution is well-researched, and optimisation and simulation software is advanced enough to make precise simulations and calculations that met 4th generation requirements. There is plenty of potential in the development of insulation technologies, e.g. vacuum technologies [46], however due to high prices such technologies are not yet available.

A complex consumer-related analysis has only been described in a few articles, and all of them remarked that customer systems are not supervised properly, which leads to major problems and efficiency loss in the entire DHS [7]. In terms of the 4GDH, three main issues are indicated: small temperature differences, poor substation management, and unsuitable heat load patterns. However, in most cases, existing heating devices can be used in low-temperature DHNs without any major effects on consumer comfort [47], [48]. Using additional electrical heaters or heat pumps to reach the required DHW temperature in the 4th GDHN can be justified [49].

As for smart grids, hydrogen can be used as a link electrical and heating systems [50]. A lot of studies have examined the low-temperature DHS operation without the risk of Legionella growth and spread [42], [51], [52]. Analyses of the entire district heating systems are virtually non-existent. Fortunately understanding of the need to take all system components simultaneously is recognised more and more, and so the first studies have been published featuring all of the components [6], [53].

2.2 4th generation district heating system and barriers to reach it

The fact that energy needs in houses decrease, especially for new buildings, puts DH network development in very rigid framework: every element in network must be properly calculated, the safety factors for future development has to be realistic and minimal in order to keep network efficient. Moreover, the energy needs for houses can be even negative: some of houses already produce more energy than they need, so consumer may become a producer at certain time. Such consumers are called as prosumers: the definition came from smart electrical grids [54] but they are a reality in DH [55]. The management of such DHN can be very difficult in order to satisfy needs of every consumer in network [55].

The main idea of the 4th generation DH is high energy efficiency and high share of renewable and waste energy. The system efficiency is achieved mainly through decreasing temperature levels and network geometry optimization; energy share possibility is coming with temperature decreasing and technology development in such areas as heat pumps and solar collectors.

Lots of researches report that return water temperature is very important for all the DH networks regardless its generation: allowing the use of low-temperature energy resources, heat pump technologies, flue gas condensation type economizers on production side, optimize network size, reduce heat losses and many others [42], [56], [57]. The combination of low temperature technologies allows utilizing almost every kind of energy renewable resources effectively such as solar or geothermal.

The solar energy share in DH has grown rapidly in the last years – the primary energy is at a very low cost, the capture, storage and energy transforming technologies are becoming economically efficient enough to compete with traditional fuel burning facilities. This also applies to other surplus heat sources as ground energy, excess heat from cooling and production processes etc.

An ideal 4th generation system components may be characterized as follows:

- Production – using CO_2-free and fuel-free energy from alternative sources like solar and geothermal. As a next energy source priority waste incineration in CHP mode should be used, then biomass plants in CHP mode and last option is fossil fuels.
- Network – having as little heat losses as possible. To reach that the best available technology for pipe insulation must be used, pipe dimension correctly calculated and layout must be optimized. Heat transfer media supply temperature in the range of 55-60°C and return temperature about 20-25°C to ensure low losses.
- Consumer – is able to use low temperature heat source; is using maximum heat potential by returning heat media with as low temperature as possible; having defined consumption curve (not using DH as reserve or peak heat source).

The 4GDH can be described by characteristics with main barriers as follows:

1. *Barriers to low-temperature DH for space heating and DHW to buildings:*

A low supply temperature between 50–60°C is one of the main characteristics of 4GDH [8], [58]. In fact, there are no barriers from the production side, as it is always possible to mix the flow after the heat source with the DH to decrease the temperature to the required level [59]. The first barrier appearing from the network can be described as follows: the supply temperature is reduced while the return temperature remains at the same level or is reduced by a smaller amount, such that heat is not delivered to all consumers because of hydraulic factors [60]. It is possible to compensate for this to an extent by placing more powerful pumps; however, this requires more investments, and electricity use for pumping is increased [59].

During a building renovation process, heat consumption may decrease [61] and the supply temperature may be reduced by 5–10K without additional investments from hydraulic point as water flow will remain at same level. However, further decrease in temperature may be a challenge, as analyzed by Bolonina et al. [62]. Nevertheless, the most important barrier here is the consumer. The heating devices are often designed to operate at high temperatures, often up to 80°C, to decrease the heat exchange surface, thereby reducing the investment cost. Small heat exchange surfaces are one of the main reasons for higher return temperatures. One of the possible solutions to maintaining a high temperature difference in a space heating system is the use of a larger radiator [42]. In another vein, the analysis of possible temperature reductions in existing radiator systems has been provided [47], [48]. Jangsten et al. studied the possibility of lower operating temperatures than those of the radiator systems that were initially designed for use in multi-family houses, and concluded that it is possible to reduce the DH temperatures to an extent [47].

However, this depends on the DH system specifications and location. Østergaard and Svendsen reported, based on case-studies with single-family houses, that it is possible to heat existing single-family houses with hydraulic radiator systems, with ultra-low-temperature DH [47]. Developing this study further, the researchers analysed the possibility wherein only critical radiators are replaced by larger-sized radiators while the remaining radiators operate at a lower temperature [63].

Major source of high return temperatures is the domestic hot water circulation system in multifamily buildings, where an average temperature level in the range of 40–50°C is very common [51], [64], [65]. To avoid this factor following solution for DHW preparation is offered for multi-family houses: consumer substations for each flat, where each flat has its own completely separated DHW system (with instantaneous DHW heat exchanger and water volume in piping below 3 liters) [59]. Yang and Svendsen studied the possibilities of reducing the return temperature for DHW under ultra-low DH conditions by applying micro hot water storage tanks [66]. These solutions require additional investments from the consumer, and thus, the consumer should be strongly motivated.

Another reason for higher return temperatures, which appeared in recent years, is a heat parallel consumption, i.e., heat pumps are installed for heat recovery from ventilation and used to cover the base load [67]–[69]. Thalfeldt et al. compared the influence on return temperature of two ventilation system types with heat recovery, which is exhaust ventilation with heat recovery and exhaust ventilation with exhaust air heat pump. The results based on simulating the energy needs of a typical renovated 5-storey apartment building in Estonia showed that the return temperature with heat pump solution was between 32°C and 37°C, while the return temperature with ventilation heat recovery was 22°C [68].

Temperatures in DHW below 50°C are considered one of the factors that influence the growth of Legionella. Yang et al concluded that a decentralized substation can be an efficient solution not only to decrease the return temperature reduction but also to decrease the risk of Legionella growth [51]. Elmegaard et al. proposed supplying hot water temperature by supplementary electric heating between the DH and the hot water tank [49]. The main disadvantage of this method is that direct electric heating is economically and environmentally inefficient.

Solutions to overcome barrier for low temperature DH can be realized; however, mostly, they strongly depend on the consumer. Possible solution, aimed to increase consumer awareness about heating systems, and to stimulate installation of proper low-temperature devices, is multicomponent tariff with a bonus-malus tariff component based on the return temperature, as for example in Copenhagen, Stockholm and Saclay [70]. Local law and normative for heating system design are also good incentives to change consumer behaviuor.

2. *Barriers to the use of non-fuel renewable energy*

The global idea of DH is to recycle surplus energy: this kind of energy can be taken as non-fuel renewable energy. The most significant barrier here is the location: wind, geothermal, solar, and excess energy is highly dependent on location and/or time. There is no provision for natural heat sources in case these resources are not available. Excess energy sources can be planned by local/national government; however, it requires a precise long-term development agenda.

Ziemele et al. analyzed the possibility to integrate non-fuel renewable energy technologies, such as heat pump and solar collectors within existing DHS and concluded the main barriers to this integration: relatively low prices of fossil fuels, fossil-based heat sources that were recently installed, and high investment costs for non-fuel energy sources [71]. Continuing the research, Ziemele et al. evaluated the following policy support measures to overcome barriers: subsidies for renewable energy technologies, risk reduction instrument, and energy efficiency increasing instrument (R&D measures) [72]. Urbaneck et al. analyzed possible solution to overcome following barriers to solar heat energy integration within existing DH system: low cost of fossil fuels and the fact that DHS is designed for very high temperatures. The solution assumes complete restructuring of the heat supply, including optimization of hydraulics, operation, installation of a low temperature network , development of energy transfer station for multiple dwelling, [1]. Winterscheid et al. proposed the evaluation methodology of solar thermal energy unit integration into large CHP-based DHS that supposes solar thermal energy unit supplies heat to DH sub-network [73]. Another solution to the problem of non-controllable solar heat is seasonal TES [74]–[76].

3. *Barriers to low heat losses in network*

Reasons for network heat loss emergence can be divided into two categories: pipe properties and environment properties. Mašatin et al. proposed to specify the pipes by heat transmission coefficient (W/m^{2}K), which is influenced by network temperature level, insulation heat transmission coefficient, network average diameter and length [77]. Pre-insulated pipes provide low heat loss level [78], however pipe renovation is not always economically reasonable, because of the comparatively low lifespan of the network transmission part and long technical service life [79]. Barriers, with respect to the surrounding environment properties of pipes, cannot be influenced and, therefore, overhead pipes should be avoided as the yearly average heat loss from the same pipe in soil is about 20% - 30% less, than in air [80].

Pipe diameter is one heat loss factor. Pipe sizing can be calculated quite precisely; however the main problem is the inability to predict existing consumer consumption in the long term. Additionally, rapid consumption changes at nights lead to high consumption peaks that require larger pipe diameters than needed. However, it should be mentioned that night setback control is only suitable and profitable for buildings with high specific demands and lower energy efficiency [81]. It is important to consider both perspectives of heat demand and peak heat load reduction for existing consumers and connection of new consumers. Long-term DH network planning is possible only through cooperation between DH companies and local authorities.

4. *Barriers to CHP plant integration*

It was mentioned in the concept of 4GDH that CHP is one of the flexible technologies essential to consider in future DHS [8]. The main idea of CHP is to utilize energy that otherwise would be wasted. CHP is a best option from energy use point for supplying heat to DH; however its capacity is limited by DH heat load parameters. When CHP is considered as base-load utility, it can operate in all seasons. In case CHP has a capacity higher than for the base load, there are the following options: CHP operates only during cold seasons, when heat load is sufficient; CHP operates with partial loads; use long term heat storages; or CHP operates in condensation mode (in this case there is no benefits for DH system). It is important to choose both optimal capacity for newly installed CHP plants (e.g., see [82], [83]) and optimal operation for existing CHP plants (e.g., see [84]). One of the barriers to CHP implementation is economic feasibility of CHP operation, which is influenced by electricity and fuel prices. A solution to obtain

CHP integration can be achieved through various policy support measures (e.g. tax advantages, feed in tariffs, certificates, grants, etc.) [85].

5. *Barriers to thermal energy storage integration into DHS*

Thermal energy storage technologies allow DHS to become an integrated part of smart energy system [8]. Short-term TES is mainly used for daily peak compensation in order to load CHP plants evenly during the day avoiding the use of peak boilers [86].

Short-term TES are used together with CHP in numerous DHS. TES have been widely and successfully used in Austria and Germany [87]. Another example is Denmark, where almost all the larger CHP plants have TES units installed [88]. In 3rd generation DHS, usually short-term TES are not used together with CHP. For example there is no TES used together with CHP in Estonia [89] and Latvia [90]. This can be explained by the fact that new CHPs are often installed to provide base-load during the year, and in this case installation of TES does not lead to fast payback. Because of improvements to DHS, the interest for integrating TES to DH system has risen in recent years.

6. Barriers to intelligent metering

According to the concept of 4GDH, remote intelligent metering is an important aspect of future district heating [8]. It gives additional information about consumer behaviuor that allows, on the one hand, for a DH enterprise to manage the grid efficiently, by making precise hydraulic calculation, production, TES optimization, and finding faults in substations quickly; on the other hand, the consumer will be better informed about consumption and motivated to decrease it [91]. As the RHM technology is well developed and data transmission technologies are fast and inexpensive, there are no obstacles to installing remote intelligent metering system from the consumer side.

7. Other barriers in DH systems

Based on experience of large DH system transition process towards 4th generation, the following barriers that are specific for large networks were determined:

- Because of their large scale, it is not possible to make changes to the whole network during a brief period of time because changes require years and decades, e.g. changing pipeline for better insulation or corrected diameter. Additionally, pipe changes often have longer payback period or are unreasonable from a heat loss saving point of view.
- Hourly temperature profile optimization might be inefficient because of long delivery times. In small- and medium-size DH networks, the supply temperature can be changed hourly to compensate for consumption peaks and keep network diameters small. But to large networks, heating media delivery time from source to consumer can sometimes take up to 8 hours depending on pipe diameter and length. Consumption peaks that are compensated by quantity and diameters in network must be larger than optimal.

Legislation and attitude also might be a barrier in some cases:

- Lack of trust between large DH companies and consumers is an obstacle to introducing intelligent remote substation control.
- Insufficient cooperation between production and distribution companies doesn’t allow producing and delivering heat in a most efficient way. Sometimes it is more reasonable to produce heat from one source from a hydraulic or environmental

point of view, however the economic side will suffer. Agreements about profit sharing are necessary.

- Legislation sometimes might negatively affect system efficiency to protect consumers. E.g. it is reasonable from a technical perspective when a heat production enterprise delivers and additionally provides substation maintenance: however, in that case a monopoly situation appears. Additional regulation methods are needed here for consumer protection.

For every network it is possible to find some non-technical barriers that are hard or not possible to overcome. Geothermal, solar and wind energy is not available in every place or might be unreasonable to use. Legislation questions e.g. how to consider heat losses from TES: as network losses or as production losses and should CHP station get subsidies for electricity generation if heat was lost? How to put production and network owners to cooperation with consumer?

3. Methodologies

3.1 DHS components. Production-distribution-consumption triangle

Production, distribution and consumption are the three key elements for every DH and district cooling system, as well as for other grid systems. In DHS, these elements can be portrayed as a triangle where each element is connected to the others, and has a direct impact on the other elements, in case it is changed; a schematic view is available in *Figure 6*.

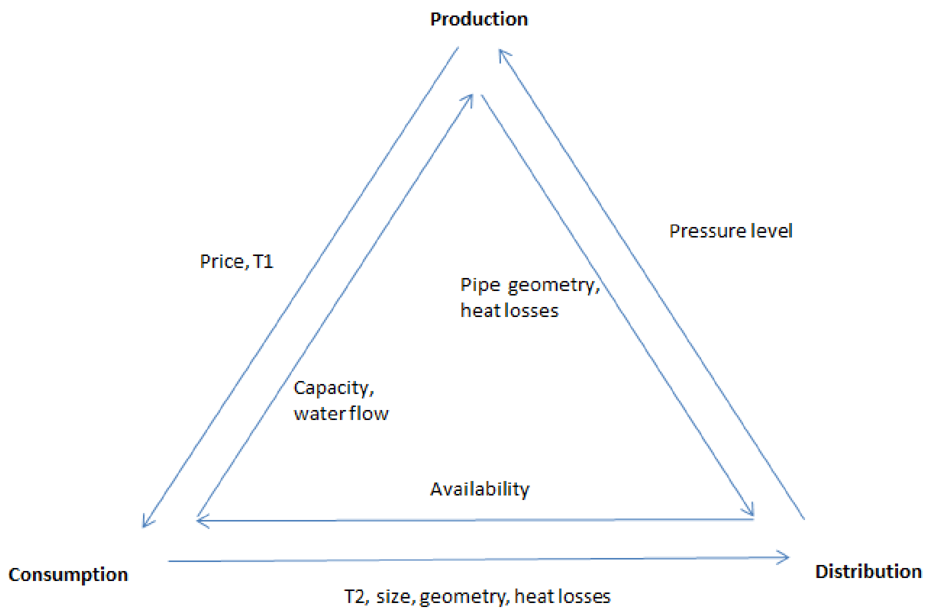

Figure 6. Production - Distribution - Consumption triangle. Vector arrows show the direction of impact.

Production affects heating prices for consumers through energy generation efficiency and fuel used; it defines substation design properties trough T_1, and determines network geometry in accordance with the designated supply temperature. Heat loss and network damage amount can be modified by reviewing the production parameters. The network affects the availability of heat (whether the house can be connected to the network from a hydraulic point of view), determines pressure levels in a heat source, as well as pump capacity. The consumers determine production volumes and the size of the network through return temperatures, which also affect heat loss and final energy prices.

At the same time, it is possible to add two vectors over the DHS elements: the direction of heat transfer and system development direction (*Figure 7*). The heat is transferred from production to consumers. Nevertheless, network development and most of the parameters are determined by consumers.

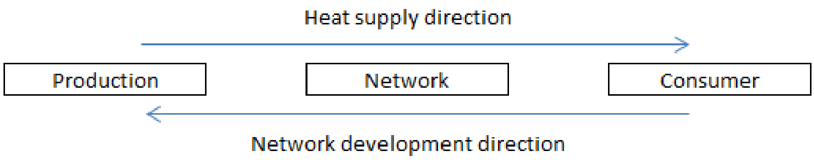

Figure 7. DHS heat transfer and network development vectors.

The elements that are using energy and causing energy loss, both electrical and/or heat can be found at each vertex of the PDC triangle. It is important to understand that losses are unavoidable, and DHSs cannot fully avoid them, but they can and should be reduced as much as possible. The most heat is lost through the walls, floor, roof and windows of a consumer's house. These losses defining DH existence: if they are very low (e.g. passive houses or nearly zero-energy houses), managing a DHS can prove to be inefficient or simply impossible from both economic and technical (e.g., very low energy consumption density will lead to higher relative heat loss) perspectives. In *Table* 2*,* the main components of each DHN are listed along with the type of energy loss and relative loss amount.

Table 2. DHS elements and energy loss.

DH side	Component	Type of loss	Relative loss amount
Production	Boilers and heat transfer components	Heat	High
Production	Boiler fan systems	Electricity	Low
Network	Pumps	Electricity	High
Network	Pipe insulation	Heat	High
Consumer	Substation insulation	Heat	Low
Consumer	Substation automation	Heat and electricity	Low
Consumer	House piping system insulation	Heat	Low
Consumer	House pumps	Electricity	Low
Consumer	Walls, floor, roof, windows	Heat	High

The greatest heat loss on production side is caused by flue gasses from the boiler; in networks the most heat is lost through pipe insulation, and consumers lose heat through the walls, windows, roof and floor of the house. The main electricity losses come from heat transfer, however the relative amount of electrical energy used for pumping is low, depending on network within the range from 5 to 10 kWh_e per $1MWh_{th}$ produced. All energy used for the pumping is spent on overcoming water friction in pipes, and it eventually is converted to heat energy due to friction.

3.2 DHS evaluation methodology (publication)

It is important to analyse the transition process towards the 4GDH. A complex multi-perspective model for the assessment of the transition process towards the 4GDH was proposed in [92]. This complex model is used for the evaluation of the DHS development scenarios and formulation of various prospects for the system in the future. This complex model also includes a system dynamics model and the results of modelling depend on the assumptions provided by all interested parties (producers, consumers, policy makers). At the same time, the general method for evaluating the transition towards the 4GDH cannot be influenced by the interested parties; it is based on the analysis of clear engineering indicators and input data, which is available for each DHS. This method should be developed based on the analysis of the main barriers encountered by the existing DHSs during the transition process. The proposed method involves the monitoring of the DH transition progress both past and present, which is essential for future DH developments and strategy formulation. The results of this evaluation can help in identifying weak links in the system that hinder the progress, a detailed description of this method is given below. The application of this method is demonstrated in Chapter 3.2.2 by the example of the Tallinn DHS evaluation.

Usually, production is described and compared using production efficiency (%), network using relative heat loss (%) or, sometimes, overall heat transmission coefficient (W/m·K), and consumers using annual energy consumption per unit area (W/m^2). The following methodology uses two types of measures to evaluate production and distribution systems: CO_2 emissions per unit of delivered energy and primary energy consumption. Consumer energy efficiency is not evaluated per se, as it is incorrect to compare old and new houses, different types of houses (multi-family residential or office), etc. The results of the calculations can be easily compared, making it possible to follow the progress of the DHS transition towards the 4GDH.

3.2.1 Theory and limits

It is clear that, based on Chapter 2.2, the DHS is in the process of becoming a CO_2- and fuel-free system. The methodology involves the use of relative CO_2 emissions and fuel used per unit of energy delivered to consumers, the numerical results are presented graphically (*Figure 8*), as it makes it easier to compare results of various systems, as well as track the progress of a single system. According to the DHS generation division, during the first stages, the heat production units are replaced by renewable fuel sources and then by fuel-free sources, so the way the generations are arranged in the picture is predetermined (*Figure 8*).

It is expected that the methodology will be used for single district heating system calculations, where consumption efficiency (building's thermal resistance) is not taken into account. The energy flow consists of the following stages: "fuel is in a plant" → "fuel transforms into heat/electricity" → "transmission" → "energy delivered to consumer's building".

Two criteria are used for the assessment of the district heating system:

1. Fuel-based primary energy per delivered heat energy, MWh/MWh
2. CO_2 emissions per delivered heat energy, kgCO_2/MWh

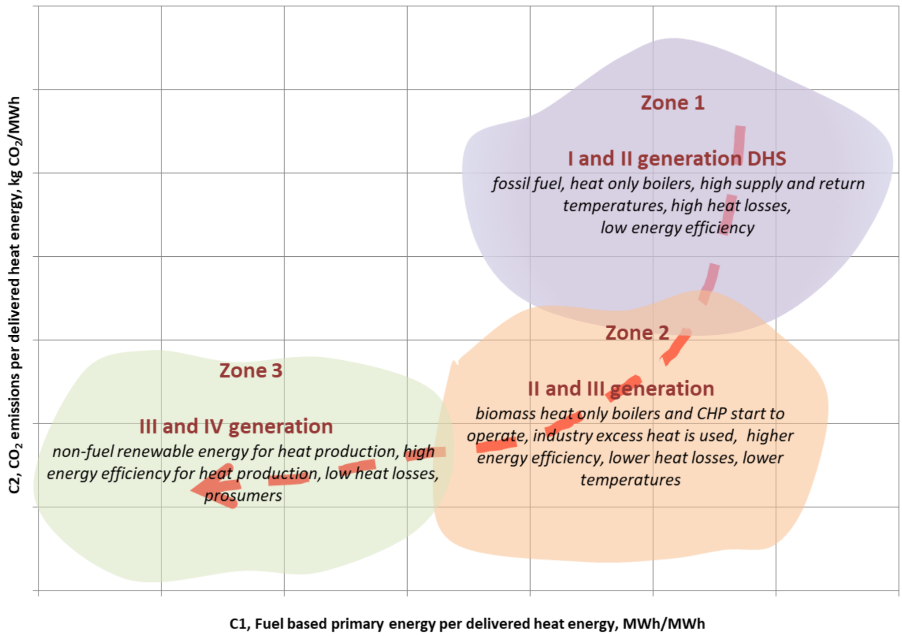

Figure 8. DHS evaluation zones based on CO2 emissions and fuel-based primary energy.

The data required for the evaluation process should be available for every DHS in service company, no additional measurements are needed. The following input data is required:

- fuel-based primary energy used for heat generation based on the type of fuel. Fuel used for electricity generation is not taken into account;
- CO_2 emissions per used fuel MWh;
- electricity used for heat production, e.g. in heat pumps (disregard in case of fuel fired power plants, as relative consumption is low and does not affect the results);
- total energy delivered to consumers.

For the CO_2 emission calculations, „power bonus method" is used, as CHP plants are preferable to heat-only plants: electricity produced in CHP mode (which is considered as "bonus") is considered as electricity not generated at other power plants, so the national average CO_2 emission per MWh_e is subtracted from the total emission for energy generation, in particular, DHS [93]. CHP plants are given priority, as they have better efficiency and they produce more valuable products than heat-only stations.

CO_2 emissions should be calculated for heat sources that are fuel-free but still use a lot of electricity, e.g., heat pumps. Average national CO_2 emissions per used MWh_e should be taken (estimated to take into account electricity use over 50kWhe/MWh_{th} which corresponds to approximately 50kgCO_2/MWh_{th}).

It should be mentioned, that biomass burning emission factors are still disputed, and in accordance with the proposal for a revised Renewable Energy Directive, CO_2 emission factor for wood chips from forest residues or poplar for a transport distance of less than 500 km (a distance of less than 75 km is typical for Estonia) is 18-32.5 kgCO_2/MWh [94].

The following assumptions were made in order to determine these parameters:

- Electricity used in heat plants is disregarded, as the amount is relatively small and it does not have a significant effect on anything. Also, some factors have a much higher uncertainty values in subsequent calculations. In case plant has high relative electricity consumption, the effect must be taken into account.
- Surplus heat (e.g. from a glass factory) is considered as CO_2 and fuel-free, it is also considered as unavoidable energy loss during the production stage of industrial products.
- Used fuel, electricity and CO_2 emissions from surplus heat are not taken into account, and it is assumed they are as unavoidable for the industrial process and this emission shall be applied to final product.

A more in-depth description of the methodology, along with a more detailed calculation description, can be found in an article, in Publication 5.

3.2.2 Case study

The proposed methodology has been tested in 15 Estonian DH networks, varying in size, fuel type and CHP presence. The results are divided into two groups based on whether a CHP station is present, and shown in *Figure 9*. Some DHSs with CHP stations achieved negative CO_2 emission per delivered MWh_{th}. Nevertheless, in all of the networks presented, the heat generation is based on fuel incineration, so the primary energy use is over 1,15MWh_f/MWh_{th} for all of the networks tested.

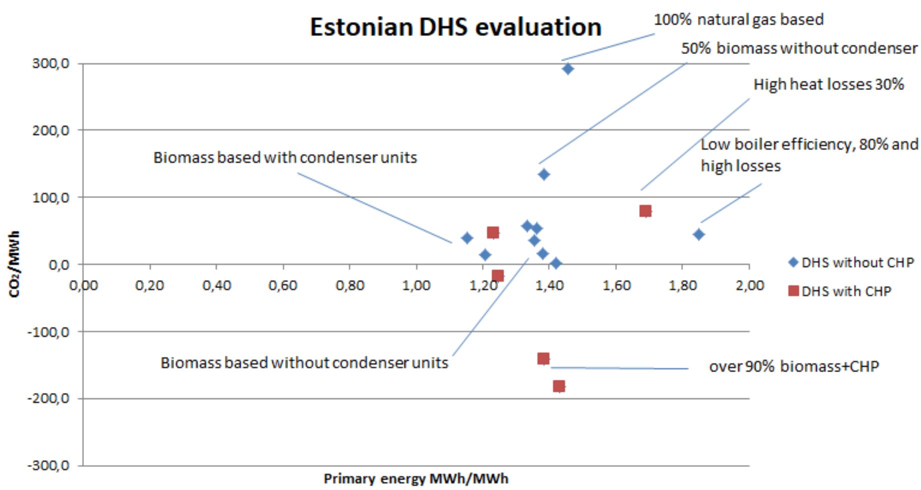

Figure 9. DHS evaluation methodology approbation in Estonian networks.

The results show that it is possible to compare the systems, and the obtained results are consistent with the expectations. The same methodology was used in order to track an achievement rate of a single DHS over some time (*Figure 10*). Theoretically possible emissions and primary energy consumption based on real possibilities was calculated for the network, based on real estimates, in order to identify a possible target for the 4th generation.

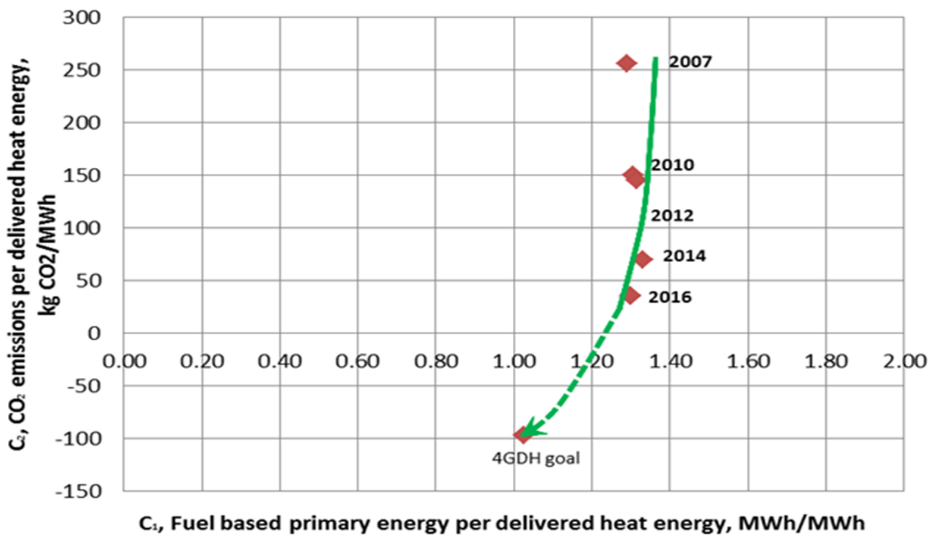

Figure 10. Tallinn DHS transition process over a 10-year period.

When analysing the results, it was found out that it is not possible to completely avoid fuel-based primary energy consumption, particularly in Tallinn network, because there is a lack of surplus or fuel-free energy sources: obtaining energy from geothermal and solar sources is highly unlikely, as large networks are located far from surplus energy sources. In other locations the situation might be different and there is known examples of very long transmission pipelines from heat source to network, e.g 35km line in Refuna, Swiss [95].

3.3 DHN evaluation methodology (publication)

The first question faced by all network providers is how to measure the effectiveness of a heat network and how to compare the networks. The following methodology makes it possible to determine a numerical description of insulation quality, and enables benchmarking between different networks. The “relative heat loss” parameter is mostly used, which may lead to a wrong impression concerning the effectiveness of the DHN, as it is not a suitable parameter for the network evaluation. The problem is that the amount of heat loss depends not only on insulation quality and temperature levels, but also on pipe diameter, pipe length, linear consumption density and other values and environmental parameters.

In order to conduct a better analysis, overall heat transfer coefficient (HTC) of the network should be considered together with the average network diameter. Pair of these parameters is giving irrefragable description of the network’s insulation quality. The HTC can be calculated (*equation 1*) for new pre-insulated pipes and for old types of pipes with mineral wool insulation or it can simply be taken from technical documentation.

$$K = Q_{hl}/(L \cdot 2\pi \cdot D_a \cdot G) \text{ [W/m}^2\text{K]} \quad (1)$$

The HTC was calculated for prefabricated polyurethane and an old type of pipes with mineral wool insulation, the result for each diameter is considered as expected limits for the DHN (*Figure 11*). Mineral wool's thermal conductivity is as assumed to be 0.06W/mK, as it is more fitting for a 20-year-old pipe.

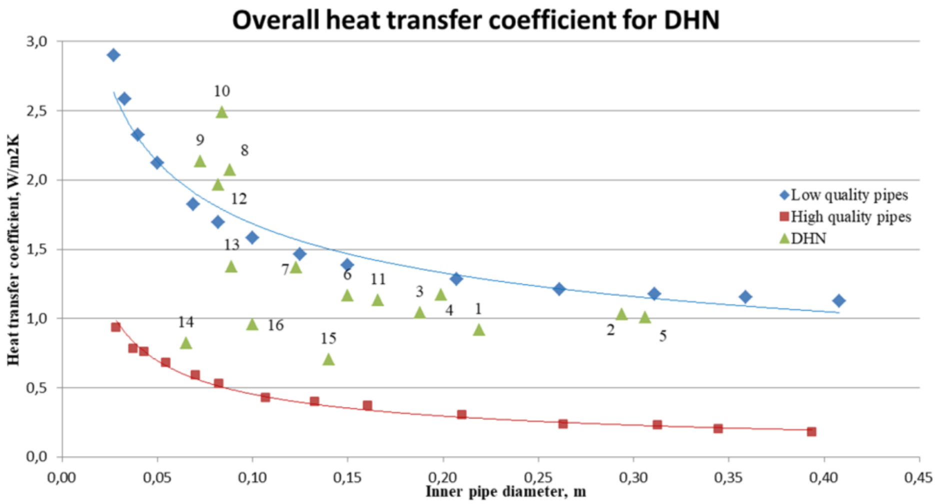

Figure 11. Overall heat transfer coefficient for high quality (pre-insulated) and low quality (old channel layout) pipes. The actual DHN results are mostly within the expected limits.

In order to better describe the renovation potential of the network, technical evaluation factor (TEF) of the network is proposed to be used, a percentage scale would come in handy here. TEF indicates HTC's relative position or DHN's renovation potential within the expected limits: when TEF equals 0%, it means that the network has no renovation potential and the network's heat transfer coefficient is the same as that for pre-insulated pipes with the same inner diameter. TEF of 100% means that the network state is the same as in a low-quality network; TEF>100% corresponds to a higher heat transfer coefficient than that in the case of low-quality pipes [96].

3.3.1 Case study

The proposed methodology was approbated in 16 networks in order to compare TEF with relative heat losses (*Figure 11*). Numeric results (*Table* 3) show a big difference in network quality, based on the comparison of relative losses and TEF, the most significant difference is seen in networks with both small (less than 100mm) and large (more than 250mm) average diameter.

Table 3. DHN heat loss comparison based on relative losses and TEF.

No.	Average diameter (m)	Heat consumption density (MWh/m)	Relative heat loss (%)	TEF (%)
1	0,224	3,59	17,0	77
2	0,294	4,16	19,0	85
3	0,188	3,50	14,2	70
4	0,199	3,79	16,1	84
5	0,306	1,93	33,8	85
6	0,150	2,62	16,1	73
7	0,123	2,86	14,3	83
8	0,088	2,17	17,4	125
9	0,073	1,78	18,0	119
10	0,084	1,68	25,3	155
11	0,166	2,09	21,0	74
12	0,082	2,36	16,0	113
13	0,089	1,74	21,4	70
14	0,065	3,18	4,8	17
15	0,140	2,90	10,0	30
16	0,100	3,33	7,8	41

Results show that there are networks with high-quality of insulation, however, due to low consumption density and oversized pipe diameter, relative heat losses are still high, e.g., network no. 5, and vice versa, relative losses can be low, but TEF indicates that the network's insulation quality is bad and additional investments are needed, e.g., networks no.8 and 12.

A detailed description of the calculation process can be found in Publication 4.

4. Barriers to the 4GDH

4.1 Consumer side

Heat consumers are the most important part of every DHS: consumers determine network growth, the parameters it has, they can affect heat losses through heat consumption density and return heating media temperature. Today DHS renovation projects must consider the changing consumption behaviuor: most houses are insulated; numerous consumers install additional equipment in order to reduce heat consumption, e.g., heat pumps integrated into ventilation units; heating systems are also changing; installation of solar collectors for hot water preparation is becoming more and more popular also as air-to-water and ground heat pumps.

The heat power transferred or distributed over the heat network is determined using the following equation:

$$Q = m \cdot c \cdot (T_1 - T_2) \text{ [W]} \tag{2}$$

Out of all parameters, only supply temperature can be modified to some extent by the heat producer, return temperature and mass flow rate depend on consumer behaviour and may be influenced by producer in very small range, moreover, it is always short-term, or it coincides with production and network efficiency loss, e.g., increased supply temperature will reduce the flow rate, at the same time increasing heat loss; whereas decreased supply temperature will quickly cause energy deficit for consumers and will require increase in electricity consumption due to pumping, as the water flow increases.

It is important to study consumer behaviour, in order to make accurate heat consumption predictions and be able to plan the use of heat sources, as well as make the right investment decisions when it comes to new plants and network expansion. Understanding of consumer behaviuor makes it possible to calculate the perfect size of TES and install it, which is one of the key factors for DHSs with multiple heat sources, especially the ones using solar and wind energy.

The importance of the DHS parameters, particularly temperature, is well-known; it has been estimated that a 1° C drop in the district heat return temperature means a reduction of about 7 percent in pumping energy and a 0.8 percent reduction in heat loss [97].

Metering and billing are often overlooked when dealing with heat consumption. Today, most DHSs have a single rate tariff billing system: consumers only pay for MWh consumed. The multiple tariff system is becoming more popular, as it offers different pricing plans for low, medium and high consumption seasons, for example, lower prices are offered during the summer in order to encourage hot water consumption, while higher prices during the winter encourage heat saving, thus avoiding the use of peak boilers and fossil fuels. In some networks, the heat producer is in charge of billing residents, however, a DH operator usually sells heat to the house substation, and from then on the building manager is in charge of further distribution. In networks where the network operator provides maintenance for house heat distribution systems, and is in charge of billing residents, the network parameters are better in terms of energy efficiency.

Other problems are discussed in the following chapters: including the behaviuor of the substation and the effects of night setback on the network, double consumption and prosumers, consumer heating devices and DHW device analysis.

4.1.1 Consumer substation, ownership and loads

Consumer substation consists of heat exchangers, pumps, valves and various smaller devices that make it possible to deliver and regulate the amount of heat needed for heating devices by regulating the building's network supply temperature and/or flow. Substations also play the role of a hydraulic separator, separating the house heating system from the network in order to maintain pressure required by the house heating system regardless of DHN, minimize the consequences of network failures.

Substation ownership and maintenance are not well covered by other researchers. For the most part, consumers own the substation due to the fact that "DH enterprises should not be allowed to regulate it, as they are interested in selling more heat than the house requires", which means that every house is responsible for its substation parameters and working order. In general, consumers are free to choose the company to provide maintenance and repair services, or decide to maintain the substation themselves. However, there are some great advantages to a DH enterprise's ownership of the substation or the enterprise's involvement in all stages of substation life cycle, from design to maintenance. The following improvements can be made to the DHS: the service is more accurate and reliable, performed with respect to the network parameters at this point of consumption, at neighbouring points of consumption and their consumption loads and variations. Most importantly, the enterprise can provide highly accurate monitoring of the DHN parameters as well as develop network geometry and production sites according to the actual needs. It is obvious that the maintenance team will be properly trained, as the DH enterprise is interested in substations operating without a hitch, that are not causing unnecessary exaggerated parameters and fluctuations in the system. The DH enterprise is also interested in building efficient DHSs.

Secondly, substation standardisation and the use of standard components could significantly reduce substation prices, especially if used in many cities, maybe even all over the country or in neighboring countries. Today, every manufacturer offers a wide range of various substations because of different requirements put forward by each DH enterprise [98]. This leads to higher market prices for substations that could be lowered with a standardized solution.

Thirdly, problems with oversized control valves that are causing over- and under-shooting of the setpoint are very common these days. This results in unstable operation of the DH and consumer devices. Moreover, the wear rate increases due to the valve's inability to stop in proper position. It is most often caused by insufficient information about network parameters in the connection point of the substation, and a lack of substation behaviuor knowledge. Mistakes in substation design are made worse by improper heating device dimensions; this is usually caused by attempt to reduce installation costs. As a result, substation parameters are far from optimal, which means that such consumers cannot be a part of the 4GDHN, because the temperature schedule cannot be strictly followed.

As far as the ownership and maintenance of a consumer substation is concerned, it is clear that substation design, installation and maintenance should be controlled. From a technical standpoint, the best solution is for the DH provider to offer all these services, however, a trusting relationship between consumers and enterprises must be established first. This could lead to a monopoly, and to hold it under control, strict regulations must be imposed.

4.1.2 Consumption data and remote heat metering

It has been determined in the previous chapter that proper and at the very least hourly metering is very important in the 4GDHN. Online metering and home energy management systems are an essential part of smart networks; these systems make it possible to understand and optimise energy consumption, conduct precise network geometry calculations, and for prosumers to produce energy via a decentralized production unit (*chapter 4.1.6*). There are still are some networks, where metering is done without any meters, using only calculation methods. Such networks can still be found in Eastern Europe. Fortunately, all known meterless networks have already started the process of installing a heat meter at every consumer substation.

The billing of residents is not discussed in this paper in detail. The simplest and most common approach is a distribution by kWh per square meter; however it does not encourage the residents' efforts to save energy. In case of installation radiator thermostats in order to save energy, the houses itself start consuming even more energy (author's observations based on Tallinn consumer-related statistics) if distribution by m^2 is used. A different billing method should be used in this case, for example, one is to install heat allocators [1], [14], [99].

Today, technology development is sufficient and inexpensive, which is why RHM is becoming a standard solution. The first remote metering systems appeared in the 1990s, but well-developed and reasonably priced systems have only become popular in the last decade, as the Internet connection and mobile technologies became inexpensive. Remote metering is now very common in electrical grids – it is quite easy to implement it there as electricity distribution companies have more possibilities because they have more consumers (the cost-per-point is lower), and data can be transmitted through power lines.

The proposed classification of RHM technologies is as follows:

1. Local radio metering (manual or attached to a vehicle) – meters are connected to low-power radio transmitters, the data can be read only if the receiver is close to the transmitter (up to 50m). This type of metering devices is used to collect consumption data by the end of month, because data processing is rather time-consuming, so daily consumption data readings could take a while, which would it impossible to read the data for all consumers in large networks.

   A slightly smarter solution is to install receivers on garbage trucks, as they are constantly moving all over the city, and they drive past every house at least once a week. Trucks have local data storage, and the data is retrieved from it at the "base". As a result, the data will be collected at least monthly, at the same time minimizing transportation and manpower costs. The downside of this metering method is that it could prove to be problematic trying to make different companies work together.
2. Radio reading meters in over the city or its part – the transmitters are either more powerful on their own or they are connected to amplifiers. The data collection system usually has local receivers installed all over the city to record measurements in a specific area and then sends it over to the main receiver via radio or upload it straight to the server using an Internet connection. In this case, data processing usually happens every 24 hours, however the data is mostly sent

as a package of hourly measurements. Instant reading of a single meter is possible with some restrictions and it takes a few minutes. The biggest downside of this system is that base stations require major investments; considering the technologies available today, it is far more reasonable to choose a different way of collecting the data.

3. Interval reading over Ethernet/GSM. – A more advanced version of the previously described technology. The main difference is the absence of intermediate receivers/transmitters in the city, the readings from the meter are uploaded directly to the server. In this case, the data is uploaded once a day as a package of hourly readings. Instant reading of a single meter is possible with minor restrictions, and a delay of up to a couple of minutes. The investments are smaller; however the reading interval is still limited to a range from one to several hours.
4. Online. The readings are uploaded directly to the server at least once an hour for the entire city. A single meter reading is possible with minimal delay, meanwhile practical data reading interval is limited to 5-15 seconds, depending on heat meter hardware. For this solution, the data can be exchanged in both directions, so it is possible to allow a heating company control and regulate the substation, as consumers can change substation parameters from any device connected to the Internet. It is also possible to conduct a detailed analysis of consumption parameters and behaviour allowing DHS optimization.

For all data reading systems, it is important to note that any data request from a meter is an energy-consuming operation, and if the data reading is planned to be performed more often than once an hour, the meter should be charged using power supply instead of batteries. It is known from experience, that a once-per-hour reading reduces battery life by about 2 years, e.g., a typical battery lifespan is 10 years without using the reading system, or 8 with the system. Usually, using power supply raises questions like “who should pay for the meter’s electricity consumption?” and “how can heat consumption be calculated in case of electricity supply disturbances?”. In reality, the energy consumption is no more than 2-3kWh per year, and the corresponding electricity bill cannot be compared with the electrical energy necessary for pumping. As an answer for a second question, the heat will not be delivered to heating devices in case of power outage, due to the fact that heating media cannot be distributed without a circulation pump, so a non-working meter won’t be an issue, and dual energy source meters are also available and are used as a standard solution in some networks.

The importance and advantages of the remote metering system can be described as follows:

- Accurate consumption statistics – households often provide consumption information on different days within a particular period, and monthly energy sales and heat loss statistics might be incorrect.
- Detailed overview of network parameters – better supply and return temperature control, installed pressure sensors enable better pressure control in the network, and as a result the network parameters can be optimized.
- Cheating detection – usually, inspectors visit substations couple times per year, and during the rest of the year some households might cheat meters. Continuous substation parameter monitoring will help in quickly identifying the cheaters, and evidence is saved for a possible trial.

- A new level of customer convenience – substation parameters and consumption can be followed in real time and from any location via the Internet; customers don't have to provide consumption data on a specific day.
- Substation's operating parameters are continuously monitored, any errors and failures can be detected in a very short time.

4.1.2.1 The advantages of remote heat metering. Study case.

To confirm the advantages of online metering, the network parameters of a medium-sized Estonian DHN – Jõgeva were analysed. There are 80 buildings connected to the network, the RHM devices were installed during the same week by two teams. Two 6 months periods from 2016/2017 and 2017/2018 (September – February) were chosen for the network parameter analysis in order to compare changes.

The supply temperature and boilerhouse heat output curves remain the same, depending on the output temperature. The results matched the expectations, as no major changes occurred during that time (*Figure 12*).

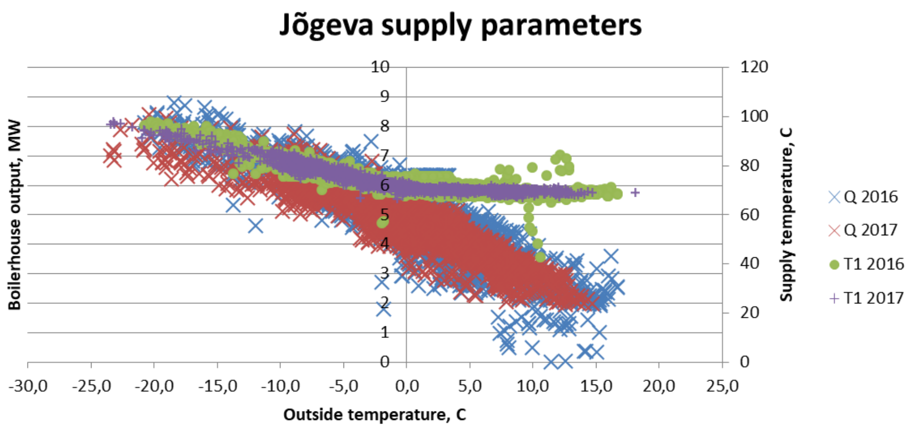

Figure 12. Jõgeva DH network: supply temperature and output during 2016 and 2017.

In fact, typical return temperature curve has been decreased by 6-8K (*Figure 13*). The decrease is explained by much stricter substation parameters control: before, an inspector visited each house twice a year, and now, the parameters are available online. A cooperation with consumers continued throughout the spring of 2017: several substations required regulation or valve changes, but most only needed minor service and change of control parameters.

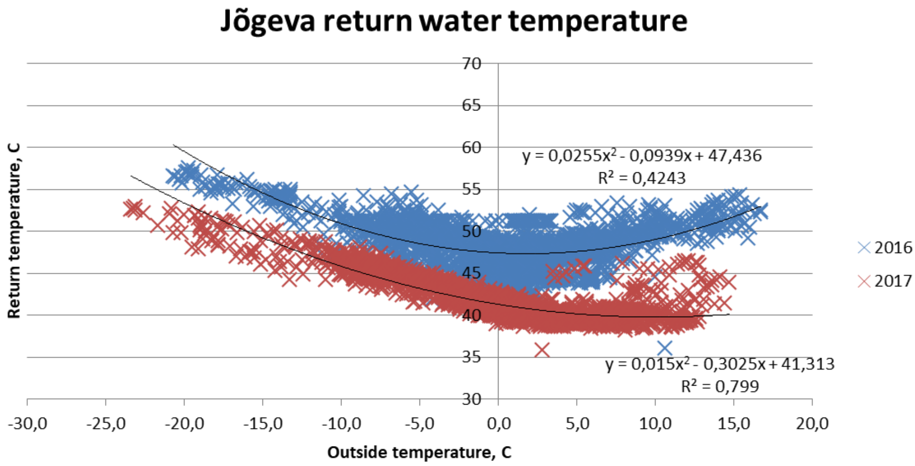

Figure 13. Jõgeva DH network: return temperatures in 2016 and 2017. Major decrease is explained by strict substation control.

Economic benefits can be calculated by considering the following indicators: the heat loss from the return pipeline is decreased; pumping power is decreased; flue gas condenser production (6MW wood chips boiler) is increased. The total annual benefit is estimated at over 20,000€ (57MWh heat loss; 5MWh electricity; 1100MWh additional production by the condenser unit).

As a result, the installation of RHM is a relatively simple, inexpensive and quick procedure that is essential for consumer parameters monitoring, as well as identifying and eliminating substation errors within a short time. Possible primary energy savings are high and the system installation costs pay off quickly.

4.1.3 Consumer substations' loads

It is evident from Chapter *4.1.2.1* that consumer loads are an important part of each system; the understanding of hourly, daily and seasonal consumption changes provides great help in system management and development. All heat loads variations can be divided into two categories based on the origin: physical and behavioural [81]. Physical variations are caused by weather conditions, such as air temperature, changes in solar and wind conditions – these changes mainly affect heating loads and are quite similar throughout all DH networks. Hot water supply load can also be affected, especially in places where open water sources are in use – during the summer the temperatures are higher than during the winter.

Behavioural variations are caused by human activity: usually, showers are taken in the morning, hands are washed after returning home, etc., and expressed mainly through a hot water load variation. Behavioural load variations affect things differently in every network, mainly depending on DHW supply based on DH network penetration. Heating loads are can be also affected: during the weekend schools and business premises are empty, and the heating load is lowered, temperature night setbacks (TNSB) are often in use, etc. [81]. Additional variations are caused by the use of electrical devices as most of electricity is converted by the end to heat energy, and personal preferences in terms of maintaining warmer or colder room temperatures;

however, the overall effect is insignificant and can be disregarded for standard multifamily houses.

Consumption variations are different for every network, and generally depend on a number of factors, including system size, consumption linear heat density, common local practices like NTSB, building materials practice, etc.

In order to provide an example of typical load changes in a large DHN, the production data of the Tallinn DH network was analysed: the data was collected on an hourly basis, grouped by similar months and presented in *Figure 14*. Significant load variations occur during the heating season (October through April), especially at the beginning and the end of the season: the outdoor temperature is constantly changing due to solar activity and causing “midday dips”. Nighttime load decrease mostly has to do with the night temperature setback (NTSB, discussed in chapter *4.1.4*). During the summer and transitional seasons (May through September), the variations are minor because a large network with a large volume, plays the role of the heat storage due to low heating media velocity in pipes. Morning and evening activity peaks are still visible due to hot water consumption.

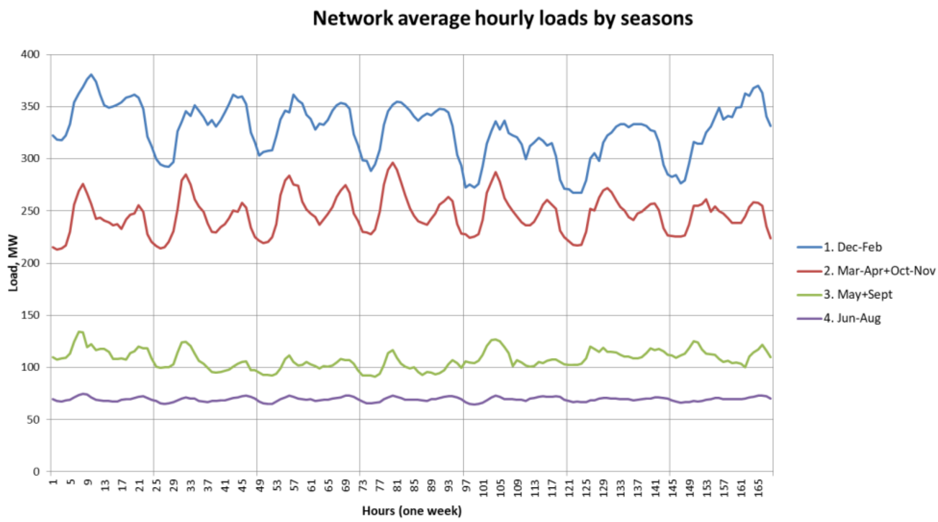

Figure 14. Average hourly loads for a large DH network based on the season (Tallinn DHN).

Load peaks in the mornings and evenings during the heating season are caused by the heating schedule, NTSB, and hot water consumption. In this case, the storage effect of network is not seen, because proportion between network volume and actual loads is small. During the midseason (March, April, October, and November) the midday dip is more profound due to increased solar radiation, daily temperature variations are more significant, with the heat load following these changes.

The difference between the days of the week is also pretty evident. It is caused by consumer behaviuor: a shorter working day on Friday, on Saturday consumption grows less rapidly, and the midday dip is smaller, and on Sunday people return to the city, and start getting ready for the week ahead and use larger amounts of hot water for cooking, dishwashing, etc.

Daily data analysis can be used for a rough network consumption estimation compared with the outdoor temperature, which, in turn, can be used for production units planning, network and consumer device sizing in a simple way with large reserve for further adjustments; the 4GDHN requires the data to be collected at least every hour in order to make precise installations. This analysis ensures that TES is accurately calculated for both production and consumption helps determine the new consumer's connecting pipe dimensions and the size of the consumer substation device. Hourly network dynamic simulation makes it possible to identify hydraulic bottlenecks during peak consumption hours.

4.1.4 Night Temperature Setback

One of the biggest problems that is causing significant load variations, and is encountered by almost every DHN is heating NTSB – the heating devices' supply temperature is reduced during the nighttime to save energy [100]. A lot of researchers have studied NTSB effect on the total heat consumption, and all of them have reported different amounts of energy saved, from 5 to 20% per annum [100]–[102]. Energy savings depend on the quality of building insulation and its thermal capacity: the more energy the building is able to store and the longer it takes to cool the house, the less energy can be saved.

Individual thermostats for radiators have become rather popular and common in new buildings (in the future are going to be obligatory also as individual heat metering), which minimize the night setback effect. The actual energy requirements for rooms are managed by room thermostats, since the room temperature setpoint remains unchanged, the load stays the same and has a linear relationship with the outdoor temperature (other minor factors are not taken into account). Besides, a lot of existing buildings have insulation added or improved, and newer houses have better insulation per se, so the building's heat storage effect is growing, while NTSB savings decreasing. As a result, in buildings with NTSB heat energy savings are minimal, but the electricity used for heat pumps is increasing, in addition, high return temperature issues are appearing due to morning peaks.

4.1.4.1 Night setback effects analysis methodology

To conduct the night setback effects analysis, it was decided that similar houses will be used, with the same heating area, similar heating systems, number of flats and weather conditions. Over the same period of at least two weeks, one building must operate with NTSB and the other without. In order to prevent object differences from affecting the results, NTSB should be reversed for both objects and measurements should be taken during the reversed NTSB status at each object.

The following parameters must be measured for the future analysis: supply and return temperature, heat consumption, water flow and outdoor temperature. Differences in heat load and water flow should be noted: significant variations for the object with NTSB and nearly linear changes in the parameters for the object without NTSB.

4.1.4.2 Experiment and results

Two similar houses were chosen in Tallinn in order to compare daily load variations and night setback effects (*Figure 15*). Both were built in 1954 using the same set of blueprints, each has 33 flats, 4 floors, only space heating by radiators (hot water is provided by individual natural gas or electrical boilers). Object 1 has lower initial heat consumption due to better renovation results – the attic floor is insulated, house façade is renovated, but not insulated – in theory, these differences should have a minor effect on the NTSB measurements. In both heating systems thermostats are installed on each radiator.

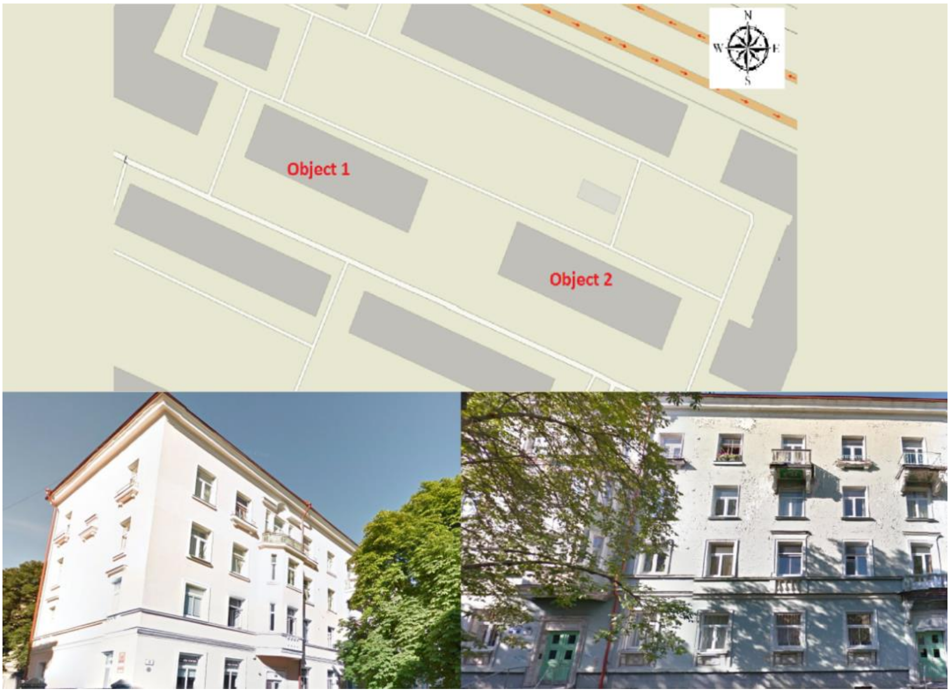

Figure 15. "Object 1" is on the left, "Object 2" - on the right.

The heat load is measured every 15 minutes in both substations during April and May; typical daily load variations are shown in *Figure 16*. A drastic load increase is observed every morning at 6 o'clock, and a dramatic decrease at 23 o'clock every evening for "Object 2". Midday dip for both objects can be explained by increased solar activity, the difference between night/day outdoor temperatures was 7 to 13K.

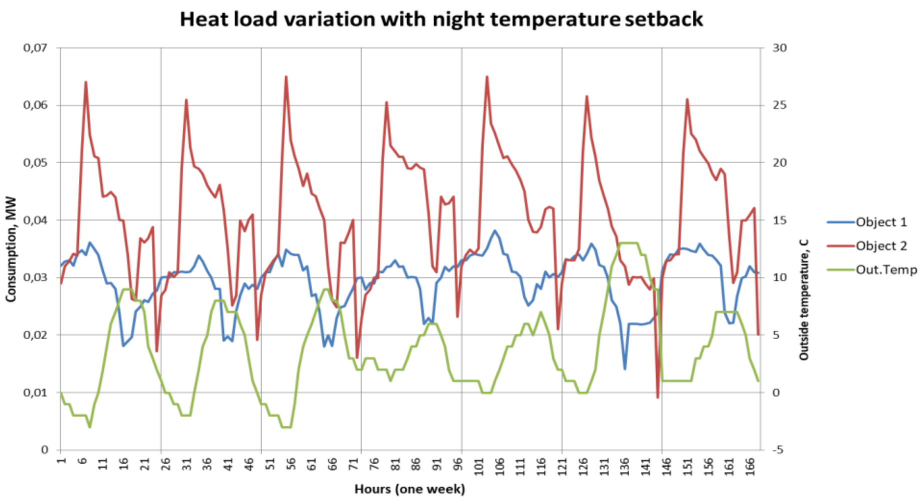

Figure 16. Heat load variation with night temperature setback (Object 2) and without (Object 1).

A rapid load and mass flow change was detected during the hours when NTSB was turned on or off for “Object 2”, and a significant change in return temperature was also registered. The following conclusion can be drawn from the initial result: NTSB has a significant effect on network parameters and causes increase in consumption and water flow peaks.

During the second part of the experiment, “Object 1” had NTSB turned on and “Object 2” had it turned off. Unfortunately, it was impossible to take measurements in reverse for “Object 2”, however obvious differences were identified based on the measurements of only one object. “Object 1” was selected for a more detailed analysis, along with two similar periods in terms of outdoor temperature (*Table 4*), each period lasted for two weeks: the first with NTSB and the second without.

Table 4. Descriptive statistics of meteorological data for Object 1.

	Period 1	**Period 2**
Mean	1,32	1,35
Median	1,40	0,72
Mode	0,30	2,81
Minimum	-4,70	-4,95
Maximum	6,10	8,21
Count	335	335

A correlation between outdoor temperature and key substation parameters was determined for the data analysis (*Table 5*) and expressed graphically (*Figure 17* and *Figure 18*). It was expected that without the night setback the correlation between outdoor temperature and substation parameters would be much higher.

Table 5. Substation parameters correlation with and without NTSB for Object 1.

	$\mathbf{T_{env}}$		$\mathbf{T_2}$		**Flow**	
NTSB status	OFF	ON	OFF	ON	OFF	ON
T_2	-0,898	0,066				
Flow	-0,599	-0,083	0,669	0,776		
Energy	-0,929	-0,127	0,97	0,539	0,624	0,5

As expected, substation parameters and outdoor temperature displayed strong correlation during the time NTSB was off, and when NTSB was on, a some kind of relationship was observed between the two, as seen in the graphs, however the deviation was far too significant to determine mathematical correlation. It can be seen that return temperature increases by about 7K during the hours NTSB is active due to a rapid increase in flow.

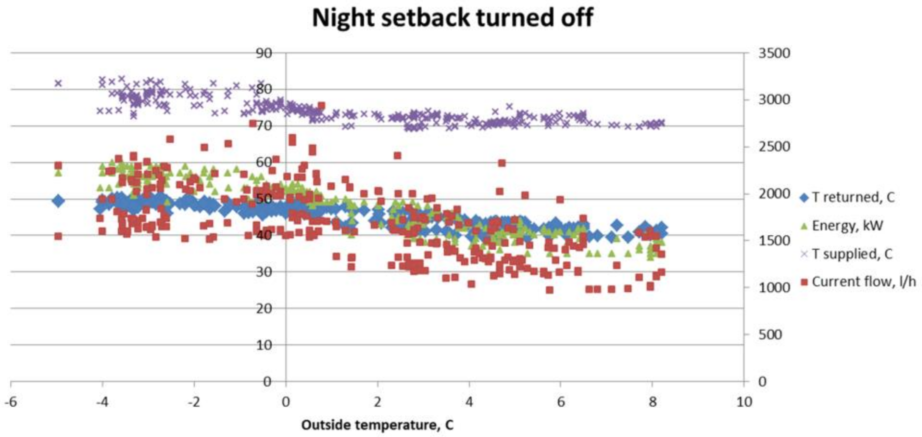

Figure 17. Substation parameters without night temperature setback.

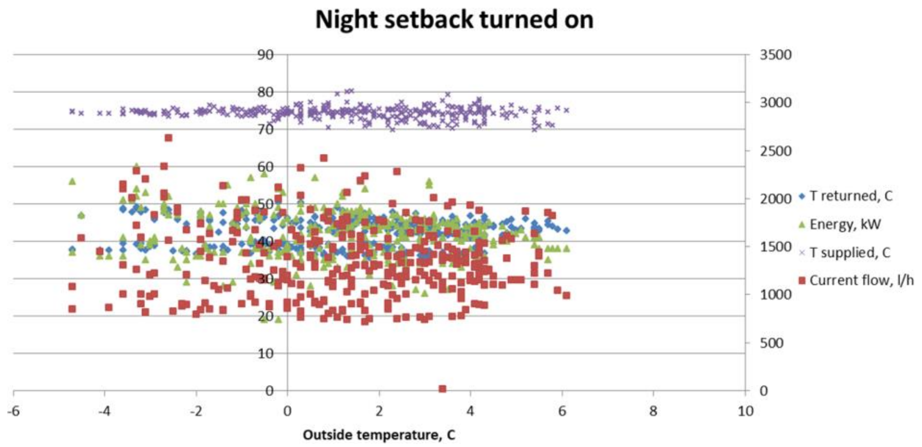

Figure 18. Substation parameters with night temperature setback.

Despite the fact that NTSB may decrease building's energy consumption, increased return temperature and non-linear flow have a negative effect on the network through increased heat losses and on production through increased pump power use and decreased production efficiency, particularly for plants with flue gas condensing economizers. Additional disadvantages may appear depending on production equipment used as boiler load change always leads to efficiency loss. In networks where hydraulic characteristics are accurately calculated, high velocity fluctuations can require to increase in supply temperature in order to overcome hydraulic problems, which is against the 4GDH philosophy.

The 4GDH should avoid NTSB as much as possible, considering that due to better insulation buildings now can store more heat and NTSB leads to very insignificant energy savings. Another solution is to use local TES, as they will also help linearize energy consumption for DHW supply (discussed in chapter 4).

4.1.5 Double consumption (publication)

In the world of market economy, it is only natural for consumers to seek less expensive, alternative energy sources, some consumers are wishing to use green energy only. But because production capacity of these kinds of sources varies greatly, relying on them to completely cover all heating needs would turn out to be rather expensive, especially during peak hours. That's why, consumers want to keep DH connection as both a reserve and peak heat source.

Double heat consumption means that the consumer has alternative heat source(s) like solar panels, heat pumps or even a small boiler (usually a gas-fired one), while remaining connected to a DHN. Usually, alternative sources are used for generating heat and covering the base load or until the price of the generated heat is lower than that of DH (e.g. heat pumps).

If we analyse this house as a closed system, as is usually done by consumers and heat generating device sellers, it is pretty obvious that the heating bill can be significantly reduced. However, if we consider the entire system, from the power plant to the consumer, it is easy to identify many drawbacks of double consumption:

- If heat pumps are used, it is necessary to compare CO_2 emissions from the power plant that generates energy for the heat pump with emissions from the DH plant [101]. In many cases, power plant emissions per delivered MWh_e are worse compared to DH.
- Because of reduced heat consumption, there is a rapid increase in relative heat losses: the network still has to be heated in order to avoid freezing, and keep the ability to deliver energy to the consumer at any time. It is one of the reasons why relative heat losses should not be used for network heat loss evaluation (see chapter 3.3), however these losses cause large increases in heating prices.
- CHP plants have the most efficient fuel-based energy production; however with decreasing heat consumption and increasing power consumption, running existing CHP plants and building new ones becomes economically inefficient, as some plants won't even operate when there is no demand for heat or they have to use cooling towers that brings primary energy loss.
- Even if there is a significant decrease in heat consumption during the base load, the peak load remains almost the same, which means that it is impossible to optimize pipelines in order to reduce consumption, and as a result have reflection on heating prices. It is also impossible to optimize production sites to reduce fixed fees.

In order to conduct a numerical analysis of CO_2 emissions, three common energy saving and double consumption options were compared with a base case scenario: DH consumer without additional devices, DH consumer with an air to water heat pump, DH consumer with heat recovery using a heat pump and DH consumer with room-based heat recovery units. The results show that in the scenario with room-based heat recovery units, total CO_2 emissions were less than those in the base case scenario; for heat pump scenarios emission increase by 24 to 55% were calculated. The results are mainly dependent on the national rate of CO_2 emissions for power generation and the fuel used for heat production in the DHS.

In addition, it was discovered that due to the installation of alternative heat sources in the existing buildings that connected to DH, the relative heat loss increased by more than twofold for some scenarios, which could lead to a drastic increase in heating prices or even put the existence of DH at risk. This topic further discussed in Publication 3.

4.1.6 Prosumers – consumers producing energy

Consumers that generate excess heat and want to sell it to a DH network are the next generation of consumers after the double-source ones (chapter 4.1.5). They are already present in DH networks and will appear even more often in the future. Prosumers have been a common in electricity networks for many years, but in DH networks hydraulics make prosumer's connection to the DHN much more complicated. This type of consumer is even more problematic for DH enterprises, especially in terms of investing in DH connection, however, due to the prospect of selling excess energy to the DHN, this could result in a symbiosis of sorts (in some cases). Prosumers are not only important stakeholders in the future of smart grids but they also may play a crucial role in peak demand management.

DHN's decentralised heat production ensures increased flexibility in terms of network parameter management, and it could also reduce construction costs as there's no need to build major pipelines all over the city in order to connect to the largest power plant. Distributed power generation also increases heat availability as network failures will affect a smaller number of consumers due to flexibility to deliver heat from other source. The drawback is that air pollution control could be far more complicated. Only sources of wasted energy are considered here, as it is reasonable to use the energy that would otherwise be wasted instead of using fuel resources. As a result, the overall use of such sources will increase energy consumption efficiency and decrease indirect pollution of the environment.

Supermarkets with large refrigeration systems are one of the best examples of consumers producing energy [103]. Typically, cooling units are connected to heat exchangers located on the roof and high temperature energy is released into the environment. In worst cases, heat consumption for space and water heating can be accompanied by excess heat release to the environment. Various production sites, such as glass mills, cement production facilities, etc., are required to be connected to a DHN, because waste energy is usually available throughout the year and it can be used to cover the base load.

Apartment buildings and stand-alone houses can also to be considered as prosumers. Solar panels and heat pumps are inexpensive and during periods of high solar activity, panel production can exceed house consumption needs. The main problem here is how to deliver this energy to the network and what parameters it will have. There are four connection schemes that could be implemented (*Figure 19*). Each scheme has its own pros and cons.

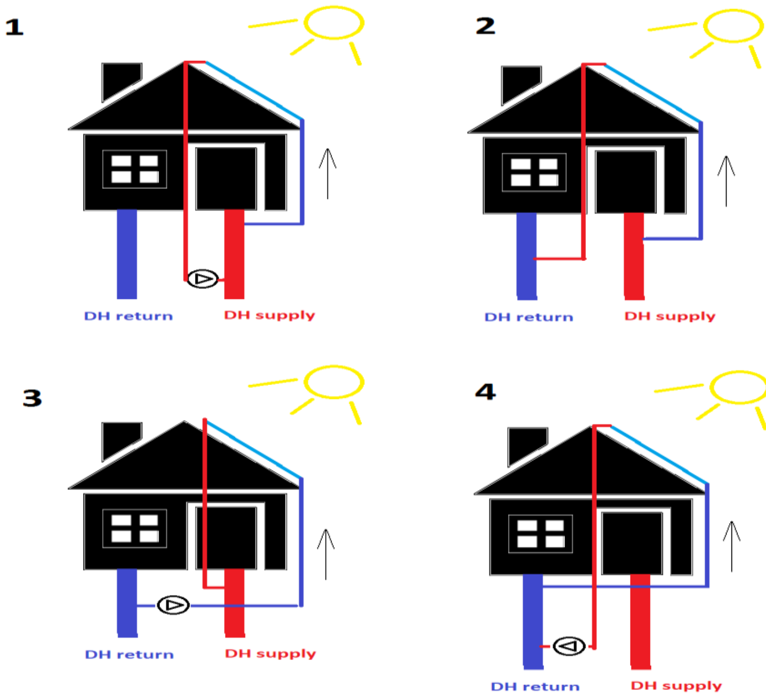

Figure 19.Options for prosumer connection to DH.

1. Heat supply from T_1 to T_1 – this option can be considered, however it requires high-temperature surplus heat. Additional heat loss from distribution pipes should be considered; also, supply temperature will be differ from network schedule and will be higher for consumers located nearby to prosumer. Energy delivery pipe must be connected to a major pipeline, otherwise energy will not be delivered due to the closed loop – and so it cannot be considered for a single consumer with long lines. Pumping costs are relatively small, only internal pressure drop must be overcome.
2. Heat supply from T_1 to T_2 – the only advantage here is that additional pumps are not needed. It has the same issues as the first option; besides, return temperature will rise, which may reduce production site's efficiency and increase water flow rate and heat loss in the network. This is the worst option from the DH enterprise's perspective, and the best from the consumers' perspective.
3. Heat supply from T_2 to T_1 – this is the best scheme for DH: it allows lower excess heat temperature, and reduces pumping energy from the producer. The drawback is that it requires high pumping capacity at the prosumer's site. Considering that supply temperature in the 4GDHN is no higher than 60°C, the connection has no significant technical impact.
4. Heat supply from T_2 to T_2 – this option has the same issues as options 1 and 2 at the same time and might be discussed it the production efficiency is not dependent from return heating media temperature.

The first and third connection options can be explored further, as they have the smallest overall impact on the DH network. Each prosumer case must be analysed individually in order to understand its impact on the other consumers and DHS. A few general ideas have already been expressed [104], [105]:

- supply temperature could decrease for neighbouring consumers, due to the fact that prosumer's (heat pump and solar panel) efficiency depends on the temperature, so the prosumer might want to supply heating media at lower temperatures than scheduled;
- despite the fact that the water flow rate from production stations is decreasing, the velocity near the prosumer will increase if supply temperatures are lower than scheduled;
- differential pressure will experience slight changes close to the production plant if prosumer's capacity is relatively small compared to heat generating plants. In general, the pressure must decrease if supply temperature is the same as scheduled, and the pressure remains the same or increases if the temperature is lower.

From the 4GDHN perspective, the excess heat from prosumers can benefit the DHN by decreasing the amount of fossil fuels used during the heating season. For the networks, where the heating demand during the low load period is already covered by non-fossil fuel, seasonal TES is crucial in utilising excess heat [55].

4.1.7 Consumer devices

All consumer devices can be divided into three groups that are quite similar to the DH network parts: substation (production), distribution (network) and heating devices (consumers). Most of the consumer devices available on the market are technologically advanced, geometrically compact and their potential for further energy loss reduction is quite low. Most problems are encountered in old buildings, where the system was built according to old standards and has not been renovated, or, what's even worse, the heating system was renovated without a project, which leads to numerous issues. Sometimes, old projects are used for renovation without considering that household consumption profiles have changed (chapter 4.1.3).

The heat exchanger is the heart of every consumer substation. It ensures hydraulic separation between the DH network and consumers based on the pressure and temperature parameters. There still are systems that use direct connection, however, they are moving fast towards heat exchanger solutions, as they are more reliable and flexible for both the consumer and DHN. There are ways to improve HEX geometry in order to reduce hydraulic resistance and increase life cycle duration. Considering the fact that the 4th generation of DH will have lower temperature differences, the HEX thermal length will increase by 2 to 5 times [59], [104].

Pumps providing heat transfer media circulation through HEX and consumer heating devices are well developed today. There still exist old systems without a pumping device, where the water flow rate is ensured by the difference in hot and cold water density, however, these systems are pretty much impossible to be used in multi-family houses, and they are not that energy efficient: it is difficult to control these systems individually, the pipe dimensions are larger than in systems with pumps, etc. Low-temperature DH is almost impossible to use with systems based on natural circulation due to low density difference. A whole-house systems approach and accurate mass flow rate calculations are necessary to achieve maximum pump efficiency. Frequency changers must be used for speed control of motors to ensure efficient heat distribution and low electricity consumption.

Various substation controllers for automatic device management are available on the market. For the most part, these controllers manage supply temperature by closing the valve on the primary side in front of the HEX, without any feedback from the return temperature. More advanced control system should be implemented for the 4GDH consumers in order to achieve the lowest possible return temperature in the network [55].

The heat distribution process from the substation to heating devices changed a long time ago when plastic pipes replaced black steel pipes. The main advantages of plastic pipes include their cost and long life expectancy, because plastic piping is not subject to corrosion. It can be concluded that the current state of piping could not be any better in terms of technology, however, piping layout and size should be determined separately for each system. Flow regulators with a thermostatic sensor are absolutely necessary to achieve low return temperatures in multi-family residential buildings [106]. It is possible to avoid using regulators if the heating devices are well designed, but even in this case, the use of regulators is still recommended.

For the renovated houses, it is important to not only renovate the heating system in accordance with new consumption needs, but also to try reducing heating devices' temperature level. Existing buildings are usually designed for supply temperatures of 70°C to 80°C during winter; however, some studies show that after the renovation, the maximum supply temperature can be 65°C or even less, depending on the level of renovation, not only in new but also in existing houses [107], [108]. Renovated houses require the supply temperature of 50°C or less for more than 95% of the year, which means that the average annual temperature meets the 4GDH requirements [7], [107].

To complete the transition to the 4GDH, all existing buildings need to adjust the existing devices to lower temperatures. Unfortunately, due to the cost level, house owners are not always willing to do that, as the process is rather expensive, and it will pay off much later but not directly, e.g., in networks with multiple tariffs, temperature reduction could lead to some decrease in cost. Temperature reduction itself does not save energy for the house, which is usually the main renovation goal; heating costs can only be reduced only if a significant number of consumers undergo such renovation.

Energy needs are often reduced due to the renovation and insulation, which means that existing devices can be used with a lowered temperature schedule [109]. If the building's energy needs have not changed, but the temperatures have to be reduced, we must increase the surface area of heating devices. The easiest way to increase the surface area of a radiator in order to reduce the temperature is to choose a deeper radiator. It will be mounted in exactly the same place, and it can be easily connected to the existing piping [108]. For new buildings, the supply temperature of no more than 40°C is needed for floor heating [110].

The technology required for the 4th GDHS exists and is already available on the market. It is important that consumers start using high-performance devices today in order to ensure the DH transition to the next generation, although, in most cases, previously installed devices can still be used in the future in low-temperature DHNs. Consumer devices must be monitored and controlled by DH companies, however, it will be difficult to accomplish if the level of consumer trust is not high enough. At the same time, consumers require additional motivation, because investments in low-temperature technologies do not pay off directly.

4.1.7.1 Domestic hot water supply

Our desire to instantly get hot water running from the tap comes from the need of comfort and water conservation philosophy. A water heating solution is very important for DHNs, even more so than space heating, because it has a major impact on network parameters, such as return temperature and flow variation, especially during the summer when the heating is turned off. The real issue here is how to ensure the required temperature setting for DHW (usually 55°C) in low-temperature DHNs.

Multi-family residential buildings, where consuming point may be far away from substation, the typical solution is an additional pipe for continuous water circulation. There are several drawbacks to this solution: the DH return water temperature increases to level 40-50°C or more, especially during the night; however, these energy losses could prove to be beneficial, because in some houses these losses are used to heat towel rails. Additional installation and maintenance costs for the circulation pipe to heat exchanger with additional inlet and circulation pump. Additional electricity consumption for pumping. Traditional solutions with hot water circulation could have an immensely negative effect on network heat losses and production site efficiency through increased return water temperature in case the system is not configured properly (*Figure 20*).

The problem of high return temperatures from consumers is especially noticeable during the summer and transitional seasons when the heating load is minimal or non-existent. In theory, cold water enters the heat exchanger at 5 to 20°C, depending on the water source, so the expected DH return water temperature should be 10 to 25°C. In reality, the return water temperature is 40-50°C. The main reason for such an increase in temperature is hot water circulation, which is a necessity in multi-family residential buildings, as it provides a continuous availability of hot water. Sometimes, high temperatures can be caused by a locked flow control valve and the reason is improper or absence of substation maintenance.

Typical summer return water temperature schedules for consumers with hot water circulation were used for the analysis (*Figure 20*). At night, when the consumption of hot water is minimal, the return water temperature typically increases by 5 to 10K compared to average daytime temperature, and for some objects it could increase by up to 25K. The reason is that when no water is consumed, the circulating water cools down by only 5-10K and the DH return water temperature is about 45-50°C. For faulty substations the return temperature can be nearly identical to the supply temperature.

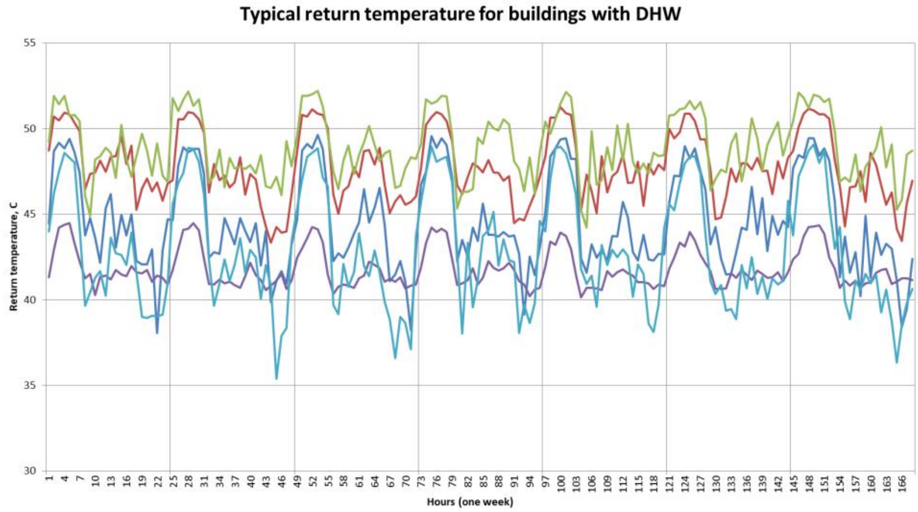

Figure 20. Typical diurnal variations in return temperature during the summer for houses with DHW consumption.

Very few consumers are shutting down hot water circulation for night time or, at least, reduce circulation temperature set point (*Figure 21*). In this case, the DH return temperature increase is avoided, however, for some flats the comfort level may decrease, as the temperature of the hot running water can be lower for a while, depending on pipeline length and diameter. At the same time, some energy is saved through heat loss reduction by circulation.

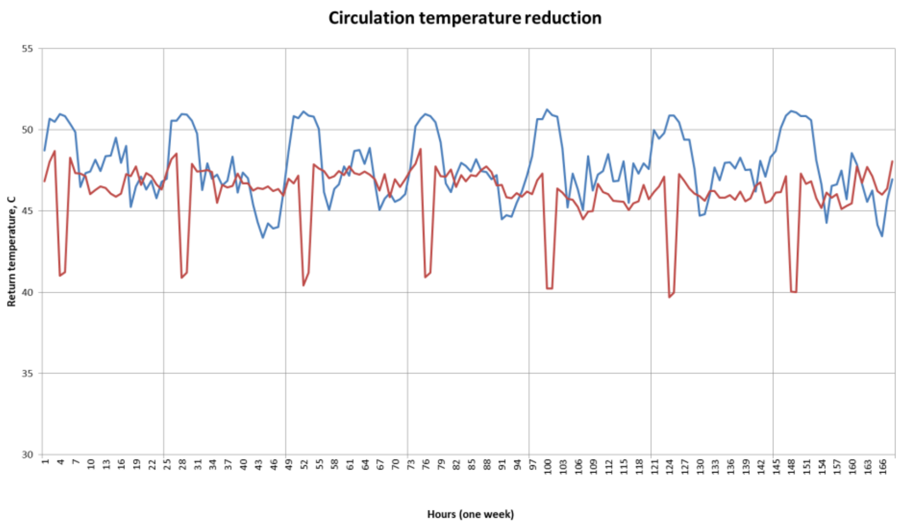

Figure 21. Return temperature for the night circulation temperature reduction (red) and typical temperature schedule (blue).

A typical schedule for service buildings shows weekend differences (*Figure 22*), diurnal temperature variation is up to 20K due to high water consumption during the day (kitchen, dishwashing, shower) and very low consumption at night and during the weekend. For this type of buildings, it is recommended to turn off the water circulation for the weekend or, at least, reduce temperature set point.

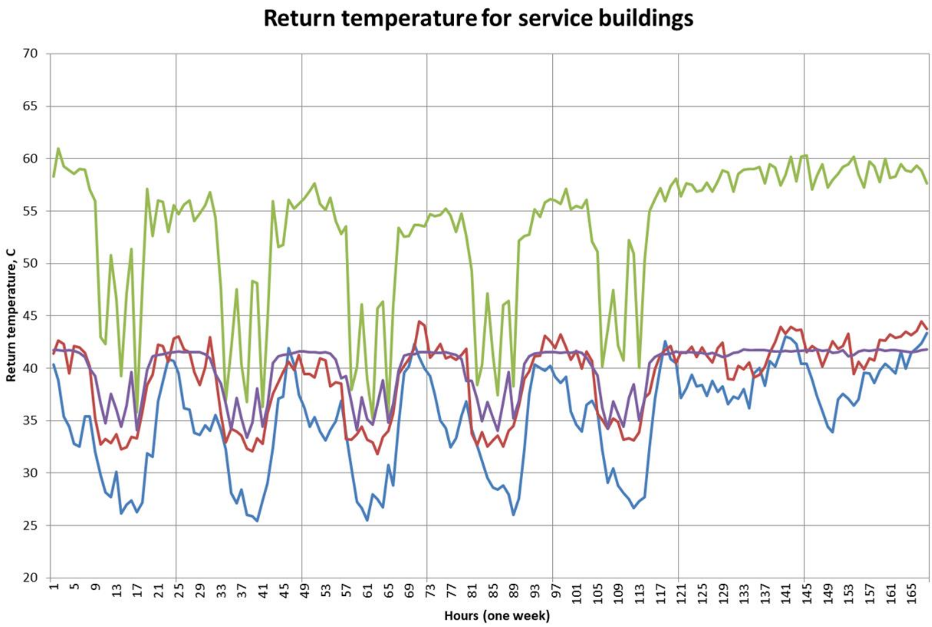

Figure 22. Typical return temperature for service buildings.

There are three solutions to avoid high return temperature: cool down the circulating water through, for example, underfloor heating in bathrooms; use hot water storage systems without constant water heating; avoid circulation and bring hot water supply to every consumer. There are drawbacks to all of the proposed solutions: underfloor heating is not always needed and it is hard to install it in existing homes. Water supply close to each consumer requires significant investments and can be hard to implement in existing buildings, especially in multi-family residential buildings, as it is nearly impossible to use DH as heat source. Hot water storage system requires investments and space for installations and also brings additional heat loss through storage walls.

For the ultra-low temperature DHN, where the supply temperature is lower than 55°C, additional electrical equipment can be used in order to achieve the required 50-55°C for DHW, such as micro heat pumps (*Figure 23*) [111]. Depending on the size of the network and consumer behaviuor, additional power consumption for DHW heating can be justified, since the amount of power consumed is smaller than the amount of heat lost from the network due to higher supply temperature. Additional heating equipment is not necessary for single-family houses, as DHW temperature can reach around 40°C without causing any inconvenience and without the risks of Legionella. For that the simultaneous tap water preparation must take place, and water pipe volume must be less than 3 liters [112].

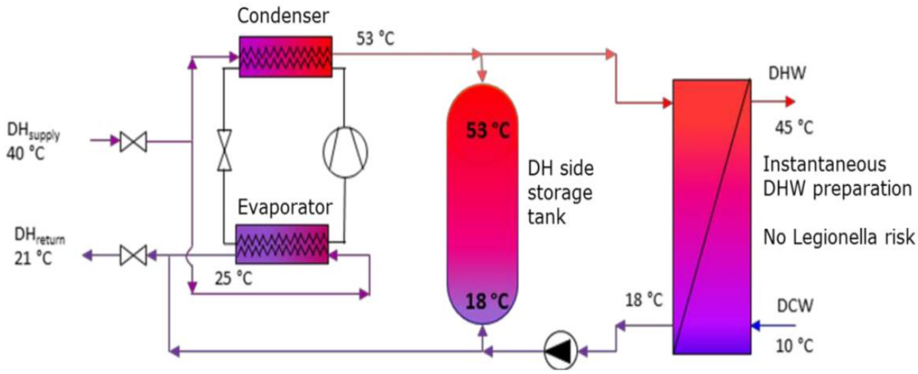

Figure 23. Micro booster application scheme [110].

In the 4GDHN, it is expected that all pipes are properly designed, so hourly and daily variations in heating media temperature and velocity must be minimized. The problem is that DHW may cause significant variations in consumption that lead to the installation of wider pipes. The problem can be solved by installing a storage tank on the primary side of the heat exchanger (*Figure 24*). The volume of the tank must be calculated individually, depending on expected (or measured in case of existing buildings) DHW consumption.

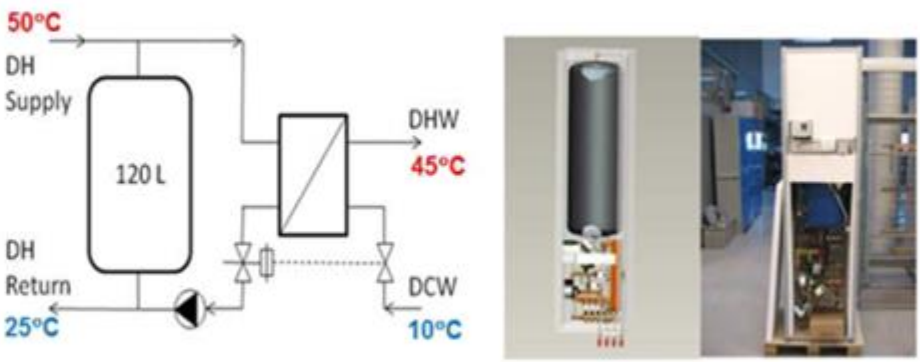

Figure 24. DHW preparation unit with heat storage on the primary side [59].

4.2 Distribution side

The distribution side of the DHS has been the most researched in the DH field over the last decade. In general, these articles could be split into three groups: insulation, temperature levels and hydraulic optimization. The most interesting questions that are researched by author are discussed below. More information can be found in publications 1, 2 and 4.

As a main rule for the efficient operation of the DHN, the route from the heat source to consumers must be as short as possible, and the heat demands must be concentrated in order to minimize distribution costs and heat loss. Consumption concentration is measured by energy consumption density – delivered energy (watthour) per pipe length: the higher the number, the better efficiency can be achieved. Low heat densities in sparse areas lead to increased distribution costs and energy loss [113], [114].

Another important aspect is security of supply: network main pipelines used to be built in loops in order to be able to continue supplying heat even if one of the pipes was out of order. This causes consumption density decrease, which results in increased network heat loss. Newer networks rarely use pipe looping: the quality of the pipes is high enough and additional or reserve connections are built only for very important objects, such as hospitals. Alternatively, a backup heat-only boiler station could be installed, however investing in one would be much more expensive than building additional pipelines and paying corresponding service fees, of cause each case must be analysed separately in detail. Very important consumers often have a special connection spot for a small portable heat plant and the DH company must own such heat sources and get them running within a couple of hours in case of emergency.

During the course of this research, it was determined that there are no major obstacles hindering the transition towards the 4th generation: the same pipes can be used after the transition, as for the pre-insulated pipes, there is no need to change the class of insulation, as it is economically unfeasible. [115]. Some pipes might have to undergo a diameter change due to a significant change in consumption. Proper planning and accurate calculations are the main requirements for the 4GDHN.

4.2.1 Connecting new consumers

Almost all DH networks are expanding, with potential consumers appearing all around the network or on some longer distance, and so forecasting future network growth is no easy task. DH companies should make a decision whether it is worth investing in the network to connect a new consumer or not. Some companies say that every new consumer connection will pay off in the long term, while others ask the new consumers to pay connection fees in order to cover at least some network expenses.

Based on *chapter 3.3,* heat loss, consumption density and pipe diameter should be considered together in order to make a decision regarding the new consumer connection. It is suggested that relative heat loss should be used as a basic criterion, because it is already widely used for economical calculations, network evaluation and investment decision making. The minimum required consumption density for maintaining a certain level of relative heat loss can be determined using the following *equation (3)*.

$$Q_{dens} = \frac{U(T_1+T_2-2T_{env})\cdot 8760}{Q_{hl,\%}} \text{ [kWh/m]} \tag{3}$$

Examples of typical consumption density required for the 2nd and 4th generation networks are shown in *Table 6*. For the 4GDH networks, the required consumption density is about 40% less for the same relative heat loss amount, due to much lower temperatures.

Table 6. Network consumption density and relative heat loss.

			2nd generation			4th generation		
DN	Pipe type (series 2)	Therm al conduc tivity, W/mK	Annual heat loss*, kWh/m	Minimum required consumption density, kWh/m 10% rel.HL	15% rel.HL	Annual heat loss**, kWh/m	Minimum required consumption density, kWh/m 10% rel.HL	15% rel.HL
25	33.7/110	0,152	145	1451	968	85	852	568
32	42.4/125	0,166	159	1585	1057	93	931	620
40	48.3/125	0,187	179	1786	1190	105	1048	699
50	60.3/140	0,211	201	2015	1343	118	1183	789
65	76.1/160	0,237	226	2263	1509	133	1329	886
80	88.9/180	0,249	238	2378	1585	140	1396	931
10	114.3/22	0,26	248	2483	1655	146	1458	972
12	139.7/25	0,3	286	2865	1910	168	1682	1121
15	168.3/28	0,341	326	3256	2171	191	1912	1275
20	219.1/35	0,363	347	3466	2311	204	2035	1357
25	273/450	0,354	338	3380	2253	198	1985	1323
30	323.9/50	0,406	388	3877	2584	228	2276	1517
35	355.6/56	0,392	374	3743	2495	220	2198	1465
40	406.4/63	0,407	389	3886	2591	228	2282	1521

*heat loss calculated for annual average temperatures T_1=75°C, T_2=50°C, T_{soil}=8°C.
**heat loss calculated for annual average temperatures T_1=50°C, T_2=30°C, T_{soil}=8°C.

This calculation does not consider network hydraulics as a future possible expansion area, which could change the required pipe diameter, however the initial pipe diameter estimation can be done.

It should be emphasised that the required consumption density is about 40% less for the 4th generation network due to reduced temperature levels. It also shows that for existing networks even the consumption is reducing, the existing pipes can be used further and the relative heat losses will stay on same level.

4.2.2 Insulation replacement (publication)

Pipe insulation is the most important thing when it comes to maintaining network efficiency and reducing heat loss. In networks constructed before the 1990s mineral wool was used for pipe insulation, and the pipes sat inside concrete channels. Recently, pre-insulated pipes with polyurethane insulation were introduced; these pipes are installed directly in ground. The thermal conductivity of mineral wool is comparable with polyurethane, however, after some time mineral wool is usually start to pack on the top of the pipe and sag on the bottom (*Figure 25*). Another problem common with the old types of insulation is moisture: channel condensation causes the ceiling to drip, precipitation water and groundwater sometimes enter the channel due to inadequate waterproofing or damaged channel hydro insulation. As a result, insulation-related heat loss is much higher than it was at the beginning due to increased thermal conductivity.

Figure 25 Old pipes with mineral wool and tar paper insulation. The packed insulation on the top and sagging on the bottom.

Pre-insulated pipes are completely waterproof, and pipe insulation has a low thermal conductivity [116]. The pipeline type change from channel layout to pre-insulated pipes is largely used in networks; although the condition of older steel pipes is often good, its wool insulation has worn out. In these cases, it might be far more reasonable to replace the wool insulation with new prefabricated polyurethane foam shells, especially for main pipelines with DN>500mm, rather than rebuilding the network with pre-insulated pipes [117].

In order to perform a heat loss analysis based on real-life data, an experiment was conducted on the Tallinn DHN: the insulation of a 532 m long 1200 mm pipe section was replaced with prefabricated polyurethane (PUR) foam shells. As a result, the heat loss decreased by 3.35 times compared to the old insulation. After the experiment proved to be a success, insulation of the entire main DH pipe (total pipe length is 10730m) was performed. The renovation of the main pipeline was finished in the summer of 2015. Initial results show that relative heat losses in the Eastern part of Tallinn (total length about 120km) supplied by the renovated DH main pipe have decreased from 20.2% to 16.0%.

Insulation replacement in major pipelines proved to be an effective solution for the DH transition to the 4th generation, as it can provide a significant reduction of the heat loss at a reasonable cost. More in-depth information can be found in Publication 4.

4.2.3 Network parameter optimization (publication)

Heat loss in the DHN is caused by the temperature difference between heat transfer media and pipe's surrounding environment. Thermal flux through a cylindrical body has a linear relation to the temperature difference (*equation 4*).

$$Q = \pi \cdot L \cdot d \cdot (T_1 - T_2) \cdot K \text{ [W]} \quad (4)$$

Reducing the heat transfer media temperature schedule is an efficient way to reduce heat losses. Usually, the supply temperature can be reduced in average by 10-20K without exceeding hydraulic limitations of the old networks, because they were usually constructed with future growth and development in mind, and are currently oversized.

The change of the temperature difference between heat transfer media means that less heat can be transferred using the same pipe diameter (*Table* 7). With the temperature reduced by 5K, there will be 10% less heat delivered at the same media velocity. For most networks, reserve capacity was planned for during the network design stage, and limited temperature reduction won't cause any problems, however, a reduction by 15K or more could mean that pipe diameter must be increased.

Table 7. Maximum energy delivered (kW) with a velocity limit of 2m/s.

	Temperature difference, K				
DN	50	45	40	35	30
25	267	240	213	187	160
32	454	409	363	318	272
40	610	549	488	427	366
50	975	877	780	682	585
65	1622	1459	1297	1135	973
80	2233	2010	1787	1563	1340
100	3764	3387	3011	2635	2258
125	5761	5185	4609	4033	3456
150	8432	7588	6745	5902	5059
200	14484	13036	11587	10139	8691
250	22696	20427	18157	15887	13618
300	32085	28876	25668	22459	19251
350	38920	35028	31136	27244	23352
400	50886	45797	40709	35620	30532

Fortunately for the distribution, consumer buildings renovation reduces heat consumption by 20% to 50%, which means that with the temperature reduction the pipeline diameter may stay the same or can even be reduced by a size or two.

Additional consumer connections must be taken into account and each case must be analysed separately.

A more detailed analysis of network parameter optimization can be found in Publication 1.

To conclude the analysis of the distribution aspect, we can say that the network is not a barrier to the DHS's transition to the 4th generation: the insulation can be replaced during routine pipe replacement, in large pipes insulation can be replaced without changing the steel pipe. In most cases, pipe sizes are identical for both the 2nd and the 4th generation systems, due to the fact that with temperature reduction, the consumption also decreases.

4.3 Production side

Heat production site is the hearth of the DHS – here the heat is passed from the energy source onto heat transfer media and the media receives initial pressure difference in order to move through the piping system. A variety of fuels can be used as the energy source, including gas, oil, wood chips, waste and nuclear fuel; alternative energy sources, such as solar, geothermal and even wind power are becoming more and more popular. The use excess energy from low temperature sources is problematic, mainly because the consumers are not ready for it; high-temperature sources, such as glass, paper or cement mills are widely used in Europe, however, such sources often are located far from the DH networks.

Today, it is out of question that fossil fuels must be avoided as much as possible. It is acceptable to use them only in case all other heat sources are not available, or to cover peak loads. Fossil fuel power plants are less expensive to build (€/MW) and maintain, they have much less service costs and they can be fully automated without any additional major expenses, which is important for peak plants.

As a fundamental idea, the order of heat source priority should as follows:

1. Waste heat from industrial processes – the heat that is generated in any case and needs to be used, otherwise it will be wasted. The best examples of such heat sources are glass, porcelain, pulp and paper industry and others. Also, the heat that is already produced by the consumer should be utilised, e.g., refrigeration systems in supermarkets.
2. Energy from solar, wind and geothermal sources – “free” energy obtained from the environment that emits no or very little CO_2. All kinds of thermal energy storage can be used with these energy sources, even surplus electricity generated by wind turbines can be converted into thermal energy and subsequently used by the DHS.
3. CHP waste incineration plants – the 4R’s rule must be applied to any kind of waste: rethink, reduce, reuse, recycle. Rethink – find a way to manufacture the product without producing waste by using other technologies, different raw materials or by refraining from manufacturing the product. Reduce – use the best technology available to reduce the amount of waste. Reuse – find a way to use the waste to manufacture the same (or different) type of product using very little or no additional energy. Recycle – convert the waste into new materials and objects using enough additional energy to power the conversion process. The last step should be making useful energy from waste. It is less harmful to incinerate it using the most advanced technology with a flue gas filtration system, and get electricity along with heat, rather than send it to a landfill and capture methane, at best. Waste can also be stored for a short time and transported over long distances in order to produce energy elsewhere.
4. CHP production facilities with a prioritised use of renewables – in this case it is biomass which is very popular, as it has near-zero CO_2 emissions, and the combustion technologies are well-known. However, biomass is more useful before it actually become biomass, when it is still growing in forests and fields. CHP technology must be prioritized over heat-only technology due to world increasing electricity consumption.
5. Heat-only production facilities with a prioritised use of renewables –this option should mainly be used for very small networks, individual solutions, or as peak/reserve solutions.

Today, tri-generation plants are already operating, simultaneously producing electricity, heat and chilled water. Any fuel can be used, even solar energy via thermal collectors [27].

The future is quad-generation: the features of the tri-generation system, with combined electricity, heat and cooling but also including the recovery of carbon dioxide from the exhaust gas. The carbon dioxide is scrubbed and can be used in industrial processes or it can contribute to carbon sequestration [77]. Another feature of the quad-generation system is the production of synthetic natural gas from biomass [118]. The syngas can be used as a fuel for the plant, gas engines or supplied to other users via a pipeline (*Figure 26*). An additional source of hydrogen is required for gas upgrading, e.g., wind energy can be used for hydrogen production [119].

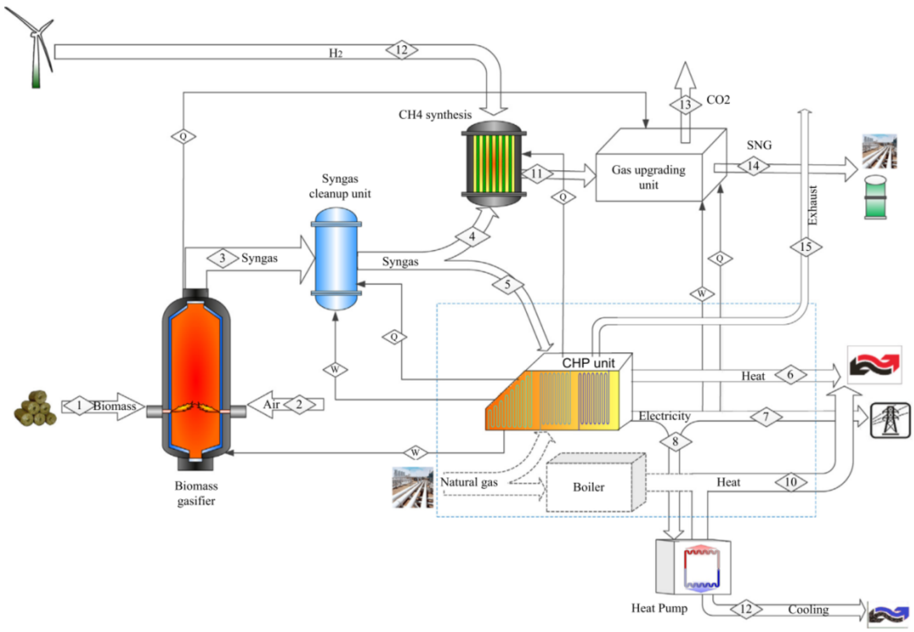

Figure 26. A simplified scheme of quad-generation with synthetic gas production [120].

4.3.1 Heat production equipment

In the following paragraphs, the components of production equipment, as well as the production process are overviewed in order to determine energy loss and ways to avoid or minimize it, increasing production efficiency as a result.

Insulation. The relative amount of heat loss through boiler insulation is usually very low and is in the range of 1-2%. Typically, the operating temperature of the boiler is the same throughout the year due to design principles and corrosion prevention, so the heat loss though the surface is a constant number. However, being expressed as a percentage of the boiler's output (relative losses), the loss increases as boiler output is reduced. Since the boiler surface area relates to its volume, the relative loss is also higher for smaller boilers. That is one of the reasons why large-scale production is more efficient than small-scale production. In general, it can be stated that the current state of insulation quality and quantity is economically reasonable and no major changes are expected in the future. To reduce the loss levels and increase combustion efficiency, some combustion air can be taken from between the insulation and the metal structure of the boiler: combustion air is preheated, surface temperature is reduced, resulting in decreased heat loss.

Combustion. Today's combustion technology is also well-developed and it is possible to say that heat generation efficiency is nearly perfect for conventional boilers. The efficiency could be much better but due to environmental restrictions, n such as NOx pollution, fuel combustion conditions are not the best, and overall efficiency is less than maximum theoretical efficiency. Usually, it is an issue for renovated boilers that were not designed for low temperatures and longer flames; new boilers are designed in accordance with the minimum efficiency loss standards.

Flue gas heat loss. Energy losses from high-temperature flue gas can be easily reduced through the use of economisers, especially of the condensing type or scrubbers [121]. The actual heat recovery for power stations using wood chips is 15% to 25% of the boiler load, depending on fuel moisture, flue gas temperature and inlet water temperature; for gas-fired power stations the heat recovery is usually about 7% to 12% because of much lower water content in flue gasses, and it is mostly dependent on water temperature.

Additional heat recovery can be achieved by using absorption heat pumps (*Figure 27*). In this case, flue gas can be cooled down to 20-25K and additional heat recovery is about 15% to 25% of the boiler load, or even 40% under ideal conditions (Table 8) [11], [120].

Table 8. Economiser and absorption heat pump performance (Helsingør DH, 2015).

Month	Boiler production, MWh	Heat from economizer, MWh	Heat from AHP, MWh	Heat from AHP, %	Total additional heat, MWh	Total additional heat, %
1	3283,3	495,3	0	0,0%	495,3	15,1%
2	3414,3	544,2	0	0,0%	544,2	15,9%
3	2951,9	456,2	0	0,0%	456,2	15,5%
4	3589,8	541,4	0	0,0%	541,4	15,1%
5*	3452,9	531,4	854,4	24,7%	1385,8	40,1%
6	2346,3	361,1	829,4	35,3%	1190,5	50,7%
7	1605,6	247,1	625,3	38,9%	872,4	54,3%
8	2391,3	368,0	757,4	31,7%	1125,4	47,1%
9	2997,8	461,4	1127,7	37,6%	1589,1	53,0%
10	2447,6	376,7	773,1	31,6%	1149,8	47,0%
11	2066,9	318,1	687,3	33,3%	1005,4	48,6%
12	3329,7	512,4	1432,4	43,0%	1944,8	58,4%
TOTAL	**33877,4**	**5213,3**	**7087**		**12300,3**	**36,3%**

*Absorption heat pump was installed in May 2015.

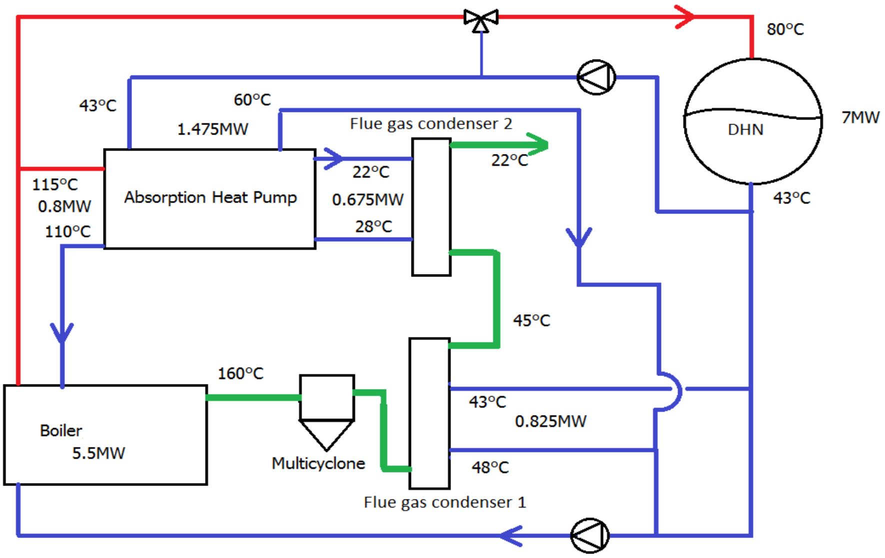

Figure 27. Scheme of a boiler house with a flue gas condensing economiser and an absorption heat pump.

Additionally, scrubber-type economizers reduce the amount of solid particles in the flue gas, which is very relative topic with the view to future stricter rules [122]. Normally, scrubbers require flue gas filtration, so the amount of solid particles is less than 200-250mg/nm^3 before scrubber, which can usually be achieved by multicyclone, however an electrostatic precipitator is still recommended in order to avoid clogging. The amount of particles by using scrubbers is reduced by 3 times , which, in some cases, could be enough to reach the 50mg/Nm^3 limit fulfill [122].

Rotating devices. Pumps, fans, ventilators and other devices with an electric motor must be equipped with frequency regulators. An exception can be made for devices with low annual operating time, or devices operating at nominal load most of the time. The payback period is usually around 1 to 3 years as frequency regulator costs are very acceptable, however, there could be a longer payback period for high voltage motors.

Heat storage. Long- and short-term TES is used both in production and the network, but consumers can also install heat storage (chapter 4.1.7.1). TES is an crucial part of the 4GDHS, as it helps to increase the share of wind and solar energy (power-to-heat technology must be used); reducing load fluctuations, thus avoiding the use of peak boilers.

Heat pumps. Heat pumps are growing more and more popular with each year; they are an important part of the 4GDH, as they make reusing low-temperature energy sources, such as sea, sewage, production facilities energy, etc. possible.

All in all, there are no major issues production-wise that could interfere with the DHS transition to the 4th generation: a lot of advanced technologies are available, and no major improvements are expected in the future. Energy loss during production can be almost eliminated by using various technologies.

There are some issue that cannot be solved with the help of technical solutions, e.g., sources of surplus energy might not be available near the DHS; some renewable energy sources are highly dependent on the location; solar panels used for large networks, require very large land areas and a large-scale TES.

5. Solutions for the DH transition to the 4th generation

In Chapter 2.2 of this paper, the main barriers to the transition towards the 4GDHS were described, in Chapter 4, each aspect of the DHS was discussed in great detail, and as well as the roots of the barriers were identified. In this chapter, solutions are provided for each aspect of the DHS, in order to overcome the identified barriers. As each network has its own unique technical characteristics and legal environment, every network must be analysed individually. Some of the provided solutions will work better for some networks, and others won't. In short, it is technically possible for the existing networks to transition, however, the willingness to make changes and the development of motivational tools are much more important.

Government and legislation.

Legislative support often serves as the basis for technical developments in the DH field; local laws and regulations must ensure the trust of both energy/network companies and consumers, and their willingness to cooperate with one another, as well as, motivate all parties to use the best technologies available, in order to increase the overall system efficiency and reduce environmental pollution. Such regulations include allowing multicomponent and seasonal tariffs, prosumer regulations, substation standardisation, monopoly and ownership regulations, emission standards, etc. For example by multi/component tariff system it is possible to motivate better device installation through discount system for consumers, which return temperature is low or temperature difference is high. Publicly available DHS performance statistics, benchmarking and the introduction of primary energy factors for various systems should stimulate investment in energy efficiency due to understanding a particular company's current situation and its position compared to other companies.

Production.

The most important thing is to use the best technologies available in order to reduce losses and environmental pollution. All in all, there are no barriers to the 4GDH in terms of production. In the 4GDHS, surplus energy must cover most energy needs; however, it is difficult to avoid fuel incineration in large networks. Depending on the implemented solutions, the following technologies support the transition to the next generation: flue gas condensing economizers, heat pumps, seasonal and short-term TES, motor frequency regulators. Various software solutions are available that help predict consumption changes and find the best production order in terms of efficiency, emissions, costs and other parameters.

Distribution.

Network optimisation has been one of the most popular topics in the district heating field over the last decade. In general, it is possible to use existing networks with the 4GDHS parameters applied to them; pipeline parameter optimisation may be required, however, consumption reduction is often compensated by the reduction of temperature. For the renovation of existing pipes and new pipe installation, it is crucial to use network simulation software in order to obtain accurate pipe calculation results. The construction process must be subject to strict supervision to ensure the best quality and long service life of the pipe, and especially the sealing of pre-insulated pipes against moisture.

Consumers.

Consumers are the most problematic aspect of the existing large DHSs transition. In short, consumers are not ready to consume low-temperature heat and they have a very little understanding of the system's operation, and as a result they do not have enough knowledge and motivation to support technological improvements. First, we need to educate the consumers on the way the system operates and build a trusting relationship between all parties - this will help the consumers understand why technological improvements are necessary for their systems, and how to get them done. In terms of technology, the following actions must be performed: reduce the temperature of heating devices; substation automation configuration and parameter optimisation, e.g., temperature schedule, night temperature setback, hot water circulation timings, etc.; new technologies must be implemented in substations to achieve ultra-low supply temperature, e.g., heat pumps, high-efficiency heat exchangers. It is important that consumers and DH companies cooperate, support and share knowledge all the way from the design stage of the heating system and until the demolition of the house.

Conclusions and future work

Primary energy, efficiency, sustainability, CO_2 – are the key word in today's world. District heating plays an important role in solving energy and environmental problems. The subject of DH is incredibly compelling to research, the more you delve into it the more questions arise. The most significant topics have been described in this paper in detail, others have a short description, but all of them have been researched by the author, and will continue to be studied further and used in DHS development.

District heating has been around for a long while, however, it still has great development potential, and there are a lot of cities and countries where the share of DH share could be increased by 5 to 20 times. Existing large networks can be described as a mixture of the 2nd and the 3rd generation systems, with some of them closer to the 4th generation concept, but none of the large networks is found as a true 4th generation system. The main problem lies with high temperatures caused by consumers' inability to use low-temperature energy and low temperature utilization, which also causes high return media temperature. Some of the smaller systems have already transitioned to the 4th generation, led by Denmark. New DH systems can be designed according to the 4th generation parameters right from the start.

In short, it is possible to upgrade existing networks to the 4th generation, as there are only a few technical issues that already have solutions, but the main barriers are unwillingness to change, and technical limitation preventing consumers from using low temperature. Despite the fact that low-temperature solutions for consumers are well-designed and available on the market, high-temperature devices are still used in both renovated and new buildings. Most consumers/designers focus on analysing their house energy levels, disregarding any possibilities to improve efficiency of the entire system, which could lead to more significant energy savings, and much better environmental situation.

Future DHS developments are not just technological changes, but a social process, and without it the technical aspect will flounder or be side tracked. The transition to the 4th generation must begin with a social program that will educate consumers about system operation and improvement benefits are spread out in order to motivate them to accept technological changes. The next step is to ensure legislative support, and after that technological changes can be performed.

Most information found in this paper, along with analytical findings is based on author's observations and experiments conducted with the DH networks located in Estonia and nearby countries. The same barriers have been identified for the neighbouring countries, mostly in large networks, but also in small and medium-sized networks. The same solutions can be applied to other network one way or another. The author's plan is to develop an application allowing to conduct an in-depth DHS analysis, including a detailed questionnaire, resulting in a step-by-step instruction for the increase in DHS efficiency and transition to the next generation of district heating. Performed researches can be done more deeply in other directions and the results be used in future works, e.g. deep consumer data analuse can be used in economics for detailed profitability research or understanding how tariffs are changing consumption.

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Abstract

Obstacles for Implementation of 4th Generation District Heating for Large Scale Networks

District heating (DH) is a well known technology for delivering heat from sources to consumers. Despite the fact that the first commercial system is in use since 1877, the academic interest is growing every year and the scientific division into four generations appeared only in 2014. According to proposed categorisation most of today's DH systems belong to the second or the third generation, only a few can be characterized as the fourth generation and none of them is a large network.

The aim of the paper is to analyse DH sides, which are production, distribution and consumer, in order to identify the barriers in transition process and find the solutions to overcome these obstacles. As a support, additional targets were raised: find connections between DH sides and develop methodologies for DHS and DHN evaluation.

In the framework of this thesis several experiments were performed, such as night temperature setback influence on DHS and mineral wool insulation infield comparison with prefabricated polyurethane foam shells for the pipes DN1200 by measuring cooling rate. Provided methodologies are tested on Estonian DH systems as study cases, results are in strong correlation with expected numbers and can be used for other systems. Described methodologies can be supplemented with additional criteria or joined together in full scale DHS analytical tool.

The conclusion of the paper is that the 4th generation is possible to reach in large scale networks only by simultaneous improvement of all DH sides, however the main focus must be on the consumer side as the main obstacles are found there. As a main barrier the lack of motivation to improve from the consumer side can be highlighted, also insufficient knowledge of DHS overall working principles; modern technologies are advanced enough and allowing transition of existing networks to the fourth generation.

Laiendatud kokkuvõte

Takistused neljanda põlvkonna kaugkütte rakendamisel suurtes kaugkütte võrkudes

Primaarenergia, efektiivsus, tõhusus, säästlikkus ja CO_2 on käesoleva aja võtmesõnad. Maailma energiatarbimine kasvab igal aastal, ning sellega kaasnevad muutused looduses. Soojusenergia on oluline osa maailma energiakasutusest, ning suuresti toimub see kaugkütte süsteemide abil. Kaugküte (edaspidi KK) on väga levinud Põhjamaades ja Balti riikides, kuid Kesk- ja Lääne Euroopas on suur potentsiaal KK kasutusele võtmiseks, ning arendustöid tehakse üle kogu maailma.

Tänapäeval jagatakse KK süsteemid neljaks põlvkonnaks. Peamised karakteristikud, mille alusel süsteeme jaotatakse, on temperatuuride tase võrgus ja kasutatava energia päritolu. Olemasolevaid süsteeme, eriti suuri, võib pidada teise ja kolmanda põlvkonna süsteemide seguks: energiaallikaks on enamasti taastuvad kütused või jääksoojus tööstusest, ning maksimaalne temperatuuride tase võrgus on 90-110 kraadi ringis. Et nimetada KK süsteemi neljanda põlvkonna süsteemiks, peab kasutatav energia olema CO_{2-} ja kütusevaba, ning temperatuur ei tohi ületada 50-60 kraadi Celsiust. Samuti peab kogu süsteem olema ühendatud teiste võrkudega (elekter, gaas, kaugjahutus jne).

Käesoleva töö eesmärk on analüüsida, miks olemasolevate võrkude üleminek neljanda põlvkonna süsteemide suunas toimub suhteliselt aeglaselt, kuigi vajalikud tehnilised lahendused selleks on turul olemas. Töös on KK süsteemid jagatud kolmeks komponendiks: tootmine, võrk ja tarbija. Iga komponenti analüüsiti takistuste leidmiseks eraldi. Töö käigus töötati välja metoodika KK süsteemi ja võrgu hindamiseks, KK arenguprotsessi jälgimiseks ning erinevate süsteemide võrdlemiseks. Kuigi KK tehnoloogia on üsna vana (esimene kommertsvõrk loodi New Yorgis aastal 1877), hakkas teaduslike artiklite arv selles valdkonnas suurenema alates 2010 aastast, kusjuures enamik artiklitest on pühendatud võrgu optimeerimisele.

Töös püstitatud hüpotees on, et suurtes kaugküttesüsteemides on neljanda põlvkonna süsteemi staatuse saavutamine võimalik ainult kõigi osade samaaegsel arendamisel, kuid suurem rõhk peab olema suunatud tarbijale, kuna just tarbijaga on seotud suurimad väljakutsed süsteemi arendamisel.

Töö käigus on leitud järgmised takistused: madala temperatuuri rakendamise suurim takistus on tarbija paigaldised, mis pole võimelised tagama ruumide kliimatingimusi, kui kasutatakse soojuskandjat temperatuuriga kuni 50-60 kraadi. Vanade seadmete asendamiseks ja ka uute süsteemide ehitamiseks kasutatakse vanad standardid, kus arvutusliku soojuskandja temperatuurina kasutatakse 75-85 kraadi, et tagada seadme kompaktsus ja madalam investeeringu hind. Tänapäeval väheneb renoveeritud hoonetes hoone soojuslik tarbimine sageli 30-50% võrra, mis võimaldab kasutada olemasolevaid seadmeid väiksema temperatuuriga. Teine probleem on soojuskandja madal temperatuuride vahe ja kõrge tagasivoolu temperatuur. Ka seda põhjustavad vanade standardite järgi valitud seadmed, paigaldus- ja juhtimisvead ning puudulik hooldus. Lisaks tekitab probleeme soojusetarbimise ebaühtlus alternatiivsete soojusallikate tõttu. Näiteks soojuspumpade kasutamise puhul jäävad tippkoormuse võimsused samaks, kuid enamasti on tarbimine oluliselt väiksem, mistõttu kasvavad võrgu kaod, langeb tarbimistihedus jne.

Kütusevabade energiaallikate kasutamist pidurdavad mitmed erinevad tegurid: fossiilkütuste hinnad on suhtelised madalad, ja taastuvate ning kütusevaba energiaallikate kasutamine nõuab suuremad alginvesteeringud; kütusevabade allikate energia temperatuur on väiksem kui tarbija on valmis võtma vastu; samuti kütusevabad energiaallikad võivad paikneda kaugküttesüsteemist kaugel.

Neljanda põlvkonna süsteemi tähtsamaim karakteristik on suur efektiivsus, ehk kadude madal tase. Tootmiskadusid on suhteliselt lihtne leida ja kõrvaldada, näiteks kui paigaldada kondenseerivad ökonomaiserid, kuid võrgu renoveerimine ainult kadude vähendamise eesmärgil pole enamasti majanduslikult põhjendatud. Üldiselt ei leitud tootmises takistusi, pigem takistasid jääk- ja madalatemperatuurilise soojuse kasutamist süsteemi teised osad. Tihti tehakse võrku puudutavates küsimustes valesid otsuseid, kui tuginetakse suhteliste soojuskadude arvutusele, mis võib viia valede järeldustele. Kaod peavad olema arvutatud füüsiliste parameetrite järgi, arvestades näiteks, soojusläbikande tegurit (W/m^2K). Võrgu dimensioneerimisel täna ja tulevikus on vaja lähtuda täpsetest arvutustest, mis põhinevad tarbija tarbimisprofiili analüüsil. Selleks tuleks kindlasti kasutada vähemalt tunnipõhist kauglugemist.

Tehnilistele takistusele lisanduvad ka seaduslikud- ja muud takistused. Näiteks võivad turu ülereguleerimine ja tarbija huvide liigne kaitsmine viia süsteemi efektiivsuse vähendamisele ning takistada arengut ja optimaalsete parameetrite valimist. Tihti üritavad süsteemi osalised leida säästlikumaid lahendusi, mille väljatöötamisel ei arvestata teiste pooltega ja mõjudega kogu süsteemile (nii üksik võrk kui ka terve riigi või maalima energiasüsteem). Madal usalduse tase nii erinevate ettevõtete kui ka ettevõtte ja tarbija vahel pärsib koostöö tegemist ja süsteemide parendamist. Suurte süsteemide muutmist pidurdab ka süsteemi suurus – muutusi pole võimalik teha lühikese aja jooksul korraga, investeeringute mahud on väga suured.

Põhilised lahendused takistustest üle saamiseks ja olemasolevate süsteemide neljanda põlvkonna süsteemideks arendamiseks on:

- Seadusandluse korrigeerimine eesmärgiga toetada ja stimuleerida efektiivsuse tõstmist kõikides süsteemi osades.
- Kõikide osapoolte õpetamine ja teadmiste levitamine süsteemi tööst.
- Parima tehnoloogia kasutamine kõikides etappides, s.o. arendamisel, projekteerimisel, ehitamisel, käitamisel. Selleks peab kasutama tänapäevast modelleerimistarkvara ja tehnilisi lahendusi nagu kauglugemine, ning pidevalt otsima uusi võimalusi.
- Parimate tehniliste lahenduste kasutamine: kondenseeruvad ökonomaiserid, sagedusmuundurid, soojusvahetid, soojussalvestid jne.
- Tarbijate paigaldiste range kontroll eesmärgiga mitte lubada paigaldada lahendusi, mis ei ole kasulikud kogu süsteemile.

Tööd on võimalik arendada edasi mitmes suunas ning kasutada selle tulemusi ka teistes sektorites, näiteks analüüsida tarbija käitumist põhjalikumalt ning modelleerida tariifide mõju tarbimisele. Tulevikus planeeritud luua rakendus, mis aitab teha detailse KK süsteemi analüüsi ning luua juhend konkreetse süsteemi edasiseks arendamiseks.

Appendix

Publication 1

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Methodology for the Improvement of Large District Heating Networks

Anna Volkova[1], Vladislav Mashatin[2], Aleksander Hlebnikov[3], Andres Siirde[4], [1-4]*Department of Thermal Engineering, Tallinn University of Technology*

Abstract **– The purpose of this paper is to offer a methodology for the evaluation of large district heating networks. The methodology includes an analysis of heat generation and distribution based on the models created in the TERMIS and EnergyPro software Data from the large-scale Tallinn district heating system was used for the approbation of the proposed methodology as a basis of the case study. The effective operation of the district heating system, both at the stage of heat generation and heat distribution, can reduce the cost of heat supplied to the consumers. It can become an important factor for increasing the number of district heating consumers and demand for the heat load, which in turn will allow installing new cogeneration plants, using renewable energy sources and heat pump technologies.**

Keywords **– cogeneration, district heating, energy efficiency, energy systems, pipes, simulation**

I. INTRODUCTION

Properly operating district heating systems can provide improvement in energy efficiency, reduce emissions, improve energy security and competitiveness and creating of new jobs. A district heating network includes the infrastructure for centralized heat production and distribution to the consumers for providing space heating and hot tap water in a wider area. The district heating system can be considered energy efficient and cost-effective only at optimal operation conditions and minimum heat loss.

One of the actions mentioned in the European Union (EU) strategy Energy 2020 is to increase the uptake of high efficiency district heating systems. A high efficiency district heating system can only be provided when efforts are concentrated on the whole energy chain, from energy production, via distribution, to final consumption [1].

There are more than 5000 district heating systems in Europe, currently supplying more than 9% of total European heat demand. District heating systems are mainly used in the northern European countries, such as Sweden and Finland [2]. As regards to Latvia, Lithuania and Estonia, the percentage of district-heated households is around 60-75%.

The main advantages of district heating are efficiency and reliability compared to the individual heating systems. Efficiency can be reached when heat is produced simultaneously with electricity in the cogeneration process. More options of flue gas cleaning are available for larger heat generation units than for small scale boilers. District heating is a good solution for the areas with high population density and multiple dwelling houses, because the investments per household can be reduced. Due to the fact that the connection to a single-family house is rather expensive, district heating is a less attractive solution for the countryside.

Large district heating networks supply heat usually in big cities, since the level of heat consumption in large areas is high. Large district heating systems are typical for Estonia. District heating is used in all bigger cities in Estonia, including the capital Tallinn [3].

The purpose of this paper is to offer a methodology for the improvement of large district heating networks. For the approbation of the offered methodology, the data on the Tallinn district heating system was used as a basis of the case study.

District heating systems offer a potential for renewable heat generation technologies. The most popular renewable energy source for heat generation is biomass, which includes agricultural, forest, and manure residues and to an extent, urban and industrial wastes, which under controlled burning conditions, can generate energy, with limited environmental impacts [4-6]. Geothermal sources as renewable energy can be used for district heating system and geothermal district heating has been given increasing attention in many countries during the last decade [7]. The expansion of district heating will help utilize heat production from the above mentioned renewable energy sources [8].

The developed district heating systems promote cogeneration development. When a cogeneration plant supplies heat to the district heating system, its capacity is defined by maximum heat load of this system [9, 10]. In some cases, a thermal storage unit is attached to the cogeneration plant for efficient operation of the district heating system [11]. The cogeneration plant with district heating provides an alternative energy production and delivery mechanism that is less resource intensive, more efficient and provides greater energy security than many popular alternatives [12].

II. METHODOLOGY

As it was mentioned before, only an optimally operated district heating system can be considered energy efficient. The efficiency of operation should be evaluated both relative to heat generation (boiler houses and cogeneration plants) and heat distribution networks (pre-insulated pipes).

A. Evaluation and improvement of heat distribution

The improvement of a district heating network is a complex task where many parameters should be taken into account. There are three ways to improve a district heating system by reducing the heat loss - the low, medium and high investment scenarios as described in the following paragraphs.

The low investment scenario assumes reduction of supply temperature and increased water flow. This can be possible only in case the network pipe dimensions are larger than required. In this case the pressure will grow, which means that the number of damaged pipes may increase. The increased pressure can also be a problem for the customer systems. Additional pumping capacity is required in power plants.

The medium investment scenario assumes replacement of pipe insulation. The insulation can be replaced when the steel casing of pipe is in good condition, otherwise the pipe should be fully replaced. Selection of insulation thickness is a complex task where many parameters should be taken into account: material and work cost, thermal conductivity of new and old insulation, pipe diameter, environmental temperature, water temperature and so on.

The high investment scenario assumes reconstruction of pipelines with the installation of pre-insulated pipes and increasing or decreasing their diameter, if needed. The new diameter should be selected very carefully, at the same time considering the future network development possibility. As a matter of fact, it is possible to replace all the pipes only in small networks; otherwise the project cost will be too high.

It is not possible to carry out such improvement without creating a virtual model and trying all possible scenarios, especially in large networks where many heat suppliers can work together in different combinations. For the evaluation of heat distribution, a special model was created using the commercial TERMIS software [13]. Simulation can be done using other software like Bently sis HYD or Zulu Thermo, but TERMIS is considered to be the most advanced, powerful and extensive district energy network simulation platform for improving system design and operation. Different types of improvement of European district heating systems were made using commercial TERMIS [13-15]. TERMIS is a hydraulic modeling software tool, which gives an overview and control of district energy network by simulating the flow, pressure and thermal behavior. With TERMIS, it is possible to reduce energy loss and reduce CO2 emissions [13].

Before creating the model, it is necessary to create a database, which should include the data on all the pipes with their dimension, insulation, coordinates, roughness and single pressure loss description; the consumer data like seasonal consumption of heat and tap water; environmental data like the air temperature for overhead pipelines and soil temperature for subsurface pipelining to calculate the heat loss.

B. Evaluation and improvement of heat production

Usually in large-scale district heating systems various energy sources are used: large and small boiler houses and cogeneration plants. Both fossil fuel and wood fuel can be used for heat production. The operation efficiency of boiler houses depends on the manufacturing year of the installed equipment. The renovated or new boiler houses have higher efficiency and are easily operated.

As regards cogeneration plants, especially those based on wood fuel, the efficiency begins to fall when the load is less than 70 %. Besides, the investments in cogeneration plants operation are much higher than in boiler houses. That is why, it is more important to operate the cogeneration plants at the maximum load. The boiler houses are often used as peak demand covering units.

The following indicators should be used for the evaluation of heat production: type of production unit (boiler house or cogeneration plant), heat capacity (for cogeneration plant the electrical capacity, additionally), age of a heat production unit, fuel type (fossil fuel of renewable fuel), energy efficiency, and shut-downs.

It is important to find the right solution in the operation strategy for all heat production units. Priority should be given to CHP production. Boiler houses are used only in case the heat supplied from a cogeneration plant is insufficient.

Different types of modeling tools for the economic analysis and optimal operation of cogeneration plants have been developed in recent years. As examples SEA/RENUE, CHP sizer, Ready Reckoner, EnergyPro can be mentioned [16]. EnergyPRO was chosen for evaluation of heat production in the district heating system, because it is modeling software which allows carrying out detailed technical and financial analyses of energy projects. For the optimization of cogeneration plants, the priority in EnergyPRO software tool is that the cogeneration plant meets the heat demand for the period being analyzed [17].

A simple model, which was created using the EnergyPro software, can be applied to determine the optimal operating strategy. The current situation and development scenarios can be compared, using the following parameters: heat production, fuel consumption, electricity production, operation time.

III. Case Study

A. Tallinn Municipality District Heating System

Tallinn is the capital of Estonia located on the northern coast of the country. Tallinn is the largest city in the country with about 415,000 inhabitants.

District heating networks in Estonia are mostly old and in poor condition. The state of the district heating networks of Tallinn is typical for the rest of Estonian district heating systems. In Tallinn the heat is supplied to the consumers through a 429-kilometre long heating network including 119 km of pre-insulated pipes (27.7%), 22.2 km is a pipeline with the renovated PUR insulation; 46% of the whole pipeline network is canal pipes and 8.2% overhead pipeline. Other pipelines are in tunnels and underground. The diameter of the main pipeline is up to 1200 mm. The peak heat load of the Tallinn district heating system was 640 MW (-22.6ºC) in the 2010/2011 heating season while in the 2009/2010 heating season it was higher reaching 695 MW (-23.4ºC). The minimum heat load during the summer period is 55-65 MW [3]. The district heating systems of Tallinn were mostly constructed in 1960-1980 and their average age is 23 years as of 2012. The district heating systems of Tallinn consist of

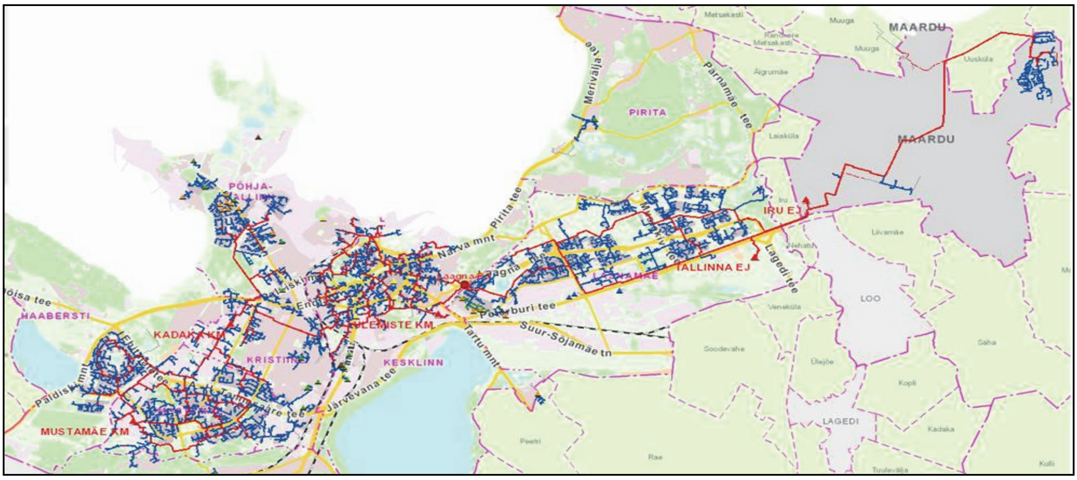

Fig.1. Tallinn district heating network

three connected districts of central heat supply where one of them is divided into two smaller districts, and 26 local boiler houses. Currently two cogeneration plants and three large-scale boiler houses supply heat to the districts of Tallinn. Almost the whole district heating network belongs to the Tallinna Küte company [18]. The Tallinn district heating network is shown in Figure 1.

Most of the pipelines were built during the rapid industrial growth of the city and thus the pipelines were oversized with a view of future development. After the collapse of the Soviet Union, however, many industries were closed. At the moment there are two main problems in the network: bad insulation and oversized pipelines; as a result, heat losses are high. According to the Tallinna Küte AS development plans, the relative heat loss should be reduced by 20%.

B. *Heat distribution*

Model description

A model was created for the Tallinn district heating network. The model was designed for 9868 pipes, over 3658 consumers and 9800 nodes with the geographic information included.

Different scenarios were simulated for the hydraulic and heat loss analyses:

- current consumption and temperature schedule;
- current consumption and maximum temperature decrease by 15°C;
- consumption reduced by 20% and current temperature schedule;
- consumption reduced by 20% and maximum temperature decrease by 20°C.

In the fourth scenario the temperature is decreased by 20°C and due to the reduced consumption, the water flow can be increased further. For the heat loss analysis, the average seasonal temperatures were decreased by 10°C. All scenarios were calculated twice: for the maximum consumption at -22°C to analyze the hydraulics and for the average seasonal parameters to analyze the heat loss.

Input data and assumptions

All the data has been taken from the Tallinna Küte GIS and converted to fit the TERMIS model. Tallinna Küte also has a large statistical database on different parameters in the critical points and consumption of each household during the last ten years. The parameters in critical points are required for model tuning; the number of points depends on the network. The GIS data and other databases can easily be interconnected by using Model Manager. Depending on the model, the estimated or average seasonal consumption can be used while the average seasonal consumption is more justified in most cases. First simulation can be made when the plant parameters like water flow, pressure and temperature are given. After first simulation with the adjustment factors applied, the simulation results should be identical to the known parameters in critical points. Only in this case the input parameters can be changed and it can be assumed that the simulation result is correct.

Results

The results of model simulation are shown in Table I and Table II. Table I shows the results at the maximum consumption and should be used for hydraulic parameters analysis, the Table II shows the seasonal average results and should be used for heat loss analysis.

TABLE I

SIMULATION RESULTS FOR THE MAXIMUM CONSUMPTION AT -22°C

Outdoor temp. -22°C	**today**	**-15°C**	**-20%**	**-20°C /-20%**
Production, MW	678	670	558	546
Consumption, MW	600	600	480	480
Heat loss, MW	78	70	78	66
Heat loss, %	11.5%	10.4%	14.0%	12.1%
Water flow, t/h	11180	14070	8920	11890

As it can be seen in Table II, with changing the yearly average temperature by 10°C, it is possible to reduce the average relative heat loss for a heating season by 1.1% points that makes about 23.2 GWh (for the 5800h heating season) or over 4200 t/CO_2 in case the consumption stays at the same level as today. In case the consumption will be reduced for 20% in the future, the relative heat loss can be reduced by 1.3% compared to the current temperature schedule. However, the relative loss would be higher compared with the present consumption. A possible solution in this case the temperature lowering could be higher, especially, as it can be seen, water flow is only 6.5%.

TABLE II

SIMULATION RESULTS FOR AVERAGE SEASONAL PARAMETERS

Season average	**today**	**-10°C**	**-20%**	**-10°C /-20%**
Production, MW	324	320	267	263
Consumption, MW	279	279	223	223
Heat loss, MW	45	41	44	40
Heat loss, %	13.9%	12.8%	16.5%	15.2%
Water flow, t/h	7280	9260	5800	7340

It should be mentioned that the total water flow and pressure difference in the network will grow. It means that more powerful pumps should be used. Electricity consumption will grow, but the heat savings will be bigger than the increase of pumping cost. Besides, in case of Tallinn, most of the pipes are oversized and the growth of pressure difference is not so rapid.

C. Heat production

<u>*Model description*</u>

The model of the current situation was built using the EnergyPro software. The components included in this model are shown in Table III. The model consists of three sites. Site 1 includes 2 boiler houses operated during the heating season and a heat consumer. Site 2 includes a heat consumer, which is supplied by the heat produced in Site 1 and Site 3. Site 3 includes 2 energy units: the Tallinn CHPP where heat and electricity are cogenerated and Iru Plant where only two boilers are operated with no electricity generation. Besides, a heat consumer is included in Site 3. During the summer period only the Tallinn CHPP is operated supplying heat for hot water production to the whole district heating system. During the winter period all energy units are operated while the heat produced in Sites 1 and 3 is used to cover the heat demand of these sites and supplied to Site 2 also. The description of the model components is presented in Table III.

The sites of the model are shown in Figures 2-4.

On the territory of Iru Plant a waste incineration plant is planned to be built where electricity and heat will be generated from the municipal waste (Site 3). To forecast the possible operating process, two scenarios were simulated, with and without a new incineration unit.

The future changes in Site 3 are shown in Figure 5.

Data about the new unit are presented further.

TABLE III

COMPONENTS OF THE TALLINN DH MODEL

Site 1		
Heat sources	Mustamäe boiler house	Natural gas, heat capacity 100 MW, fuel input 106, working time, 15/09-15/05
	Kadaka boiler house	Natural gas, heat capacity 129 MW, fuel input 138, working time, 15/09-15/05
	Site 2	When the boiler houses in Site 1 are shut down, heat is supplied via Site 2
Heat load	Demand in Mustamäe District	Annual heat demand is 693 GWh, 11% of the demand is hot water heating load, 89% of the demand depends linearly on ambient temperature during the heating period. The data on the ambient temperature in Tallinn for 2010 were used for simulation
	Site 2	During the heating period the heat produced in Mustamäe and Kadaka boiler houses is supplied to Site 2
Site 2		
Heat sources	Site 1	Heat produced in Site 1 (by Mustamäe and Kadaka boiler houses) during the heating season is supplied to Site 2
	Site 3	Heat produced in Site 3 (by the Tallinn CHPP and Iru Plant) during the heating season and in summer supplied to Site 2
Heat load	Demand in Kesklinna District	Annual heat demand is 380 GWh, 11% of the demand is hot water heating load and 89% of the demand has a linear dependence on the ambient temperature during the heating period. The data on the ambient temperature in Tallinn for 2010 were used for the simulation.
	Site 1	During the summer period, the heat supplied from Site 3 is distributed in Site 1
Site 3		
Heat sources	Tallinn CHPP	Wood, heat capacity 65 MW, electrical capacity 25 MW, fuel input 125, working time year-round supply
	Iru Plant	Natural gas, 353 MW
Heat load	Demand in Lasnamäe District	Annual heat demand is 561 GWh, 11% of the demand is hot water heating load and 89% of the demand has a linear dependence on the ambient temperature during the heating period. The data on the ambient temperature in Tallinn for 2010 were used for simulation.
	Site 2	During the heating period and in summer the heat produced in Tallinn CHPP and Iru Plant is supplied to Site 2, during the summer time when other heat generation units are shut down, the heat is supplied via Site 2 to Site 3
Transmissions		
Transmis sion 1	Heat from Site 1 can be supplied to Site 2 and from Site 2 to Site 1, the maximum capacity 200 MW, loss 10%	
Transmis sion 2	Heat from Site 3 can be supplied to Site 2 and from Site 2 to Site 3, the maximum capacity 173 MW, loss 10%	

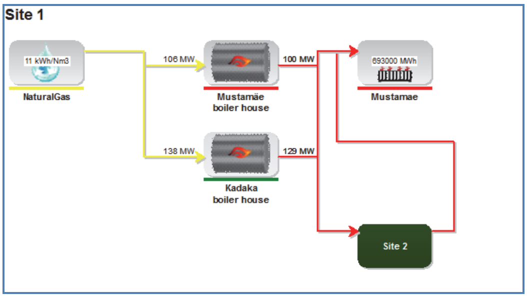

Fig. 2. Model of Tallinn district heating system, Site 1

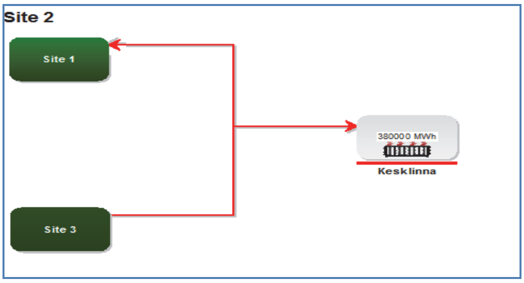

Fig. 3. Model of Tallinn district heating system, Site 2

Input data and assumptions

Actual data on operating heating plants were used (Table III). For the heat demand simulation, it was assumed that 89% of heat demand is linearly dependent on ambient temperatures and 11% of the demand goes to cover hot water consumption. The average annual heat demand for the last three years (2008-2010), which is 1691 GWh, was taken as a basis for the calculation

As it was mentioned above, the simulation was made for two scenarios: with and without a new waste incineration plant. The data on the waste incineration plant used in the simulation are shown in Table IV.

TABLE IV

PARAMETERS OF WASTE INCINERATION PLANT [19, 20]

Waste incineration plant	
Fuel	Waste
Heat value of fuel	10.5 MJ/kg
Fuel input	80.5 MW
Heat capacity	50 MW
Electricity capacity	17 MW

For simulating the operation, one more indicator should be included. This indicator is the priority of unit operation. The assumed priorities according to the operation strategy are shown in Table V.

In both cases the highest priority is the Tallinn CHPP. Tallinn CHPP is a plant, which was launched in cogeneration mode in 2009. Wood chips are used as a fuel for electricity and heat production.

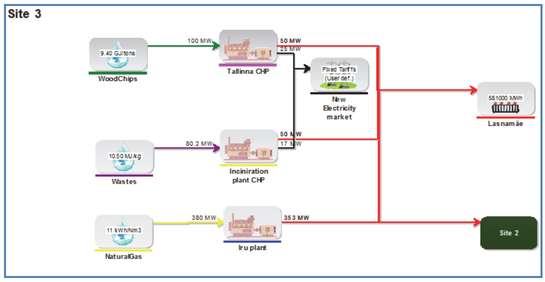

Fig. 5. Model of Tallinn district heating system, Site 3 (with an incineration plant)

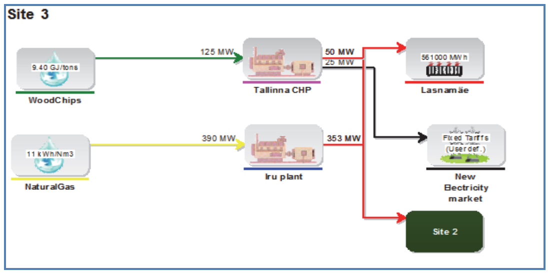

Fig. 4. Model of Tallinn district heating system, Site 3

The Mustamäe and Kadaka boilers have almost the same parameters and that is why they have the same priority. The Iru Plant is owned by another company and will be bought from the owner.

When the incineration plant will start to operate, its priority will be very high, because it is an environmentally friendly and energy efficient technology.

TABLE V

OPERATION STRATEGY PRIORITIES

Unit	Priority (current situation)	Priority (with the incineration plant)	Partial load allowed
Tallinn CHPP	1	1	yes
Iru Plant (boiler)	4	4	yes
Mustamäe boiler	2	3	yes
Kadaka boiler	2	3	yes
Incineration plant (CHP)	-	2	yes

Results

The results of simulation are shown in Table VI. The simulation showed that in case the incineration plant is used additionally, electricity generation will increase by 43 %. The consumption of fossil fuel - natural gas will decrease by 20%.

The year-round operation of the system is shown graphically in Figure 6. Figure 6 shows that Tallinn CHPP operates all year round. The Mustamäe boiler house operates throughout the heating period, but the Kadaka boiler house and Iru Plant are used for peak loads.

Figure 7 shows the operation forecast for the second scenario when the incineration plant is added. The Tallinn

CHPP operates all year round. The incineration plant works at full load throughout the heating period. The Mustamäe boiler house operates during the whole heating period, but at partial load. The Kadaka boiler house and Iru Plant work less than in the first scenario.

TABLE VI
SIMULATION RESULTS FOR HEAT PRODUCTION

Indicators	Without the incineration plant	With incineration plant
Heat production (GWh)	**1,854.60**	**1,857.30**
Tallinn CHPP	438.00	438.00
Incineration plant CHP		278.40
Mustamäe boiler house	711.00	667.10
Kadaka boiler house	394.40	354.70
Iru Plant	311.20	119.10
Electricity production (GWh)	**219.00**	**313.60**
Tallinn CHPP	219.00	219.00
Incineration plant CHP		94.66
Fuel consumption (GWh)	**2,314.00**	**2,467.40**
Natural gas	1,438.00	1,144.80
Wood	876.00	876.00
Waste		446.60
Working hours		
Tallinn CHPP	8760	8760
Incineration plant CHP		5568
Mustamäe boiler house	5616	5616
Kadaka boiler house	5064	4008
Iru Plant	5136	2544

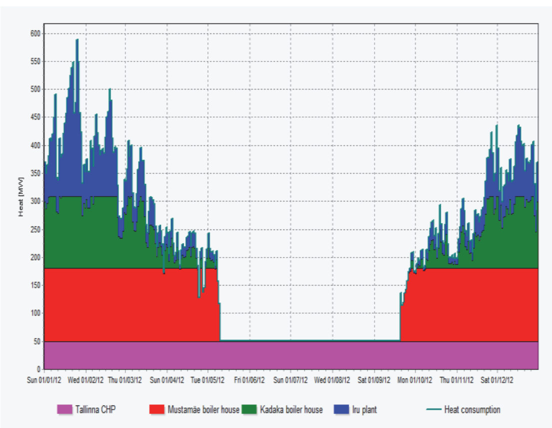

Fig. 6. Heat load of Tallinn District Heating Network. Simulation of the current situation

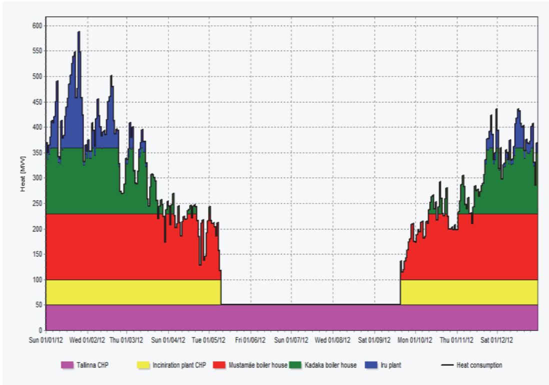

Fig.7. Heat load of Tallinn District Heating Network. Simulation of the scenario with an additional waste incineration plant

IV. CONCLUSIONS

The reliability and cost-efficiency of district heating depends on the efficiency of its operation. In this paper a methodology for the assessment and efficiency increasing of heat production and distribution was offered.

As a case study, the Tallinn district heating system was analyzed. The Tallinn district heating system includes 4 heat plants, which cover the heat demand in 3 districts. For the evaluation of district heating network, a model was created using the TERMIS software. For the heat loss analysis and hydraulic analysis, four different scenarios were simulated: the current situation, decreased maximum flow temperature by 15°C, decreased consumption by 20% and decreased temperature by 20°C with the decreased consumption by 20%. As a result, the decrease of relative heat loss by 23.2GWh during the heating season compared to the current situation was gained.

For the evaluation of energy production, a model was created using the EnergyPro software. The system was split into three sites. This model was used for the simulation of two scenarios: the current situation and the case where a new incineration cogeneration plant will be installed. The actual data for the last years were used for the simulation. The results of simulation showed that, according to the current situation, the cogeneration plant should work all year round, the boiler houses should operate during the heating period and the Iru Plant boiler should be used only for the peak heat load. In case when the incineration plant is added, it can operate at full load during more than 5500 hours per year. Heat generation in this plant will decrease the consumption of natural gas by 20%. The amount of electricity production in the cogeneration mode will increase by 43%. The evaluation of district heating demand was made mainly from the technical point of view.

The effective operation of the district heating system, both at the stage of heat generation and heat distribution, can reduce the cost and price of heat supplied to the consumers. It can become an important factor for increasing the number of district heating consumers and demand for the heat load, which in turn will allow installing new cogeneration plants, using renewable energy sources and heat pump technologies.

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Anna Volkova, Dr.sc. ing., has been post-doc researcher in the Department of Thermal Engineering, Tallinn University of Technology since 2009. Since 2003 she has been working in Riga Technical University. Her doctor PhD thesis was defended in the Riga Technical University in 2008. The main research topics are cogeneration, energy efficiency, district heating. A. Volkova is co-author of about 30 scientific publications.
Address: Kopli 116, Tallinn, 11712, Estonia
E-mail: anna.volkova@ttu.ee

Vladislav Mashatin, Mg.sc., Tallinn University of Technology, Department of Thermal Engineering He has a bachelor (2009) and master degree (2011) in thermal power engineering and he is a PhD student of the Department of Thermal Engineering of the Tallinn University of Technology. The main research interests are energy efficiency, district heating, thermal storage, cogeneration. V.Mashatin regularly participates in local and international conferences.
E-mail: shatrey@gmail.com

Aleksandr Hlebnikov, PhD, has a diploma of thermal engineering (1994), master of science degree in thermal engineering (2000), PhD in engineering (2011). He is a part of academic staff in the Department of Thermal Engineering, Tallinn University of Technology, starting from 1994 and currently works as a docent. The main research area is district heating systems and energy efficiency. A.Hlebnikov is co-author of about 25 scientific publications.
E-mail: aleksandr.hlebnikov@ttu.ee

Andres Siirde, PhD, professor, Head of Chair of Thermal Power Equipment, the Department of Thermal Engineering of theTallinn University of Technology. A.Siirde has been a part of academic staff of TUT since 1984. He has a Industrial Thermal Power Engineer Diploma (1980) and doctoral degree (1984). The main research areas are oil shale, cogeneration, SEG emissions, energy efficiency. A.Siirde is author of about 60 publications.
E-mail: andres.siirde@ttu.ee

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The Impact of Alternative Heat Supply Options on CO_2 Emission and District Heating System

Vladislav Mashatin*, Siim Link, Andres Siirde
Department of Thermal Engineering, Tallinn University of Technology
Ehitajate tee 5, 19086, Tallinn, Estonia
vladislav.mashatin@soojus.ee

The energy demand for space heating and ventilation has huge potential. The impact of three alternative energy supply solutions such as exhaust air heat pump coupled with district heating, district heating coupled with room based heat recovery ventilation unit, and air-to-water heat pump coupled with mechanical exhaust ventilation and district heating have been studied in the case of a refurbished Soviet time residential building. District heating coupled with room based heat recovery ventilation unit exhibits the lowest primary energy demand and CO_2 emission. Air-to-water heat pump coupled with mechanical exhaust ventilation and district heating and using the district heating coupled with mechanical exhaust ventilation (so called base scenario) are quite equal from the point of view of primary energy demand. The CO_2 emission is clearly higher for air-to-water heat pump option than for the base scenario and other studied alternatives. However for all alternatives the relative heat losses in district heating network are growing.

Introduction

The energy demand for space heating and ventilation has huge potential for energy saving not only in Estonia, but also in other countries (Fouih et al., 2012) and there is a growing call for energy efficient and environmentally friendly heating systems (Sakellari and Lundqvist, 2005). Since buildings have a long life span, lasting for 50 y or more (Wan et al., 2011), energy conservation and strategies to reduce energy consumption in buildings are strictly important (Mardiana-Idayua and Riffat, 2012).
Since the beginning of 2010s intensive refurbishment of residential buildings has taken place in Estonia. On the one hand the major stimulus forcing the refurbishment of residential buildings is the supporting system available through Fund KredEx, the maximum financial support was 35 % from the total investment cost. On the other hand, since 2006 the district heating price has increased over two times in the city of Tallinn, from 30 €/MWh to 79 €/MWh in 2012, incl. taxes (AS Tallinna Küte). The rapid increase of district heating price and available support mechanism makes renovation attractive for the flat owners of residential buildings.
It is well known that in case of regular mechanical exhaust ventilation, the air heating cost are relatively high (Kõiv et al., 2013) and alternative solution is preferred. The topic of heat recovery from exhaust air has been widely dealt with in literature and it will become increasingly more important, considering the need for improved insulation of envelopes with the consequent increase of the relevance of ventilation loads in the energy balance of a building in terms of modeling (Sakellari and Lundqvist, 2005) and further energy analysis (Fracastoro and Serraino, 2010).
The impact of three alternative energy supply solutions coupled with different solutions for ventilation on the district heating network and total CO_2 emission are studied in this paper. The alternatives are compared with respect to the usage of district heating for heat supply and regular mechanical exhaust ventilation in the refurbished residential building. The total heat consumption of different systems such as domestic hot water (DHW), space heating and ventilation are treated jointly, while some systems enable to transfer heat from one system to another and therefore the building must be considered as a whole.

1. A building

During Soviet times, the residential buildings were in most cases built according to standard projects. There were several standard projects available, but in this study all calculations are made for a refurbished Soviet time residential house - the standard project No 111-121-E2 as shown in Figure 1. These types of buildings were mainly built in 70s and 80s of the last century. The data characterizing the building according to the standard project No 111-121-E2 is presented in Table 1

Table 1: Main data of residential building of standard project No 111-121-E2

Item	Value
Number of apartments:	60
Number of floor:	5
Number of sections:	4
Apartments per section:	15
Heated floor area:	~3 315 m^2
Building volume:	~12 551 m^3
Inside volume of heated space:	~8 556 m^3

Figure 1: Illustration of refurbished soviet time residential building of standard project No 111-121-E2

The heat supply and ventilation systems alternatives studied in this work apply to a refurbished building, i.e. the following key refurbishment measurements have been taken into account:

- Insulation of external walls – 100 mm, λ=0.04 W/(m^2K)
- Insulation of roof – 250mm, λ=0.04 W/(m^2K)
- 2-pipe heating systems with thermostatic valves
- New double-glazed windows, U=1.7 W/(m^2K) and g=0.65

The average indoor temperature of the building is usually 21-22 °C. The heat loss through the cellar is calculated according to the method described elsewhere (Staroverova and Shillera, 1990).

2. Base scenario and alternative solutions

Three alternatives solution are compared with the so called base scenario from the economic point of view. In each case, the total primary energy demand for space heating, ventilation and DHW is calculated and compared, in addition total CO_2 emission were calculated. The building chosen for this study is connected to the district heating network. The alternatives depict the commercial solutions available in the market.

2.1. Base scenario

In the case of base scenario, the total heat for ventilation, DHW and space heating is supplied from the district heating network. The fresh air enters the building through the fresh air valves and is exhausted by the exhaust air ventilator as illustrated in Figure 2.

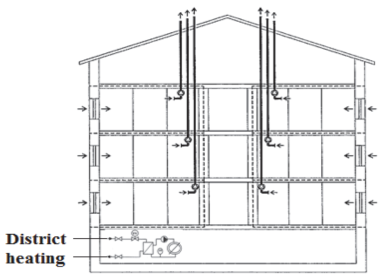

Figure 2: Basic schema of base scenario

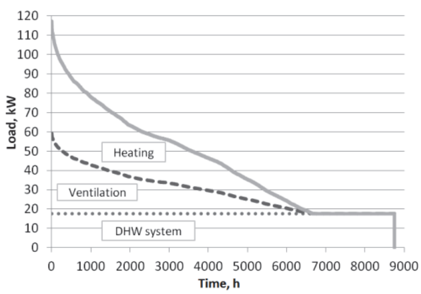

Figure 3: Annual heat load curve

The data on energy consumption in 2011 were gathered by actual measurements of the building equipped with an exhaust air heat pump (EAHP) supplying heat for space heating, ventilation and DHW together with district heating as described in Chapter 2.2. For the base scenario an assumption was made that all

the heat produced by heat pump and consumed from district heating network is 100 % equal to the heat consumed from the district heating network.
Based on the measured data the energy balance was composed using the standard steady-state calculation method based on the reference year. The method is described elsewhere (EN ISO 13790:2008). The total heat demand was 393 MWh/y: heating – 139MWh/y, ventilation – 99MWh/y, hot water – 155MWh/y.
The heat demand for DHW with losses was estimated based on the summer months when there was no heating in the building. The estimated total heat gain for the residential building was 58 kWh/(m^2a) (EN ISO 13790:2008), and the utilisation factor 0.65 (Kõiv and Rant, 2013). The heat loss through the envelope was estimated according to the areas and thermal transmittance of different parts of the building. Based on the measured values of energy consumption, the estimated energy demand for the DHW system and heating, and that for ventilation were calculated. According to the above described calculation route, the average air change rate of the building is 0.5 h^{-1}(with the floor height of 2.5 m), which matches the air change rate of the indoor climate class III (EN 15251:2007) or 0.35 L/(s m^2). The calculated balance temperature was 13 °C.
Based on the reference year of energy calculation, the register data of heat consumption and distribution of heat, the heat load curve was found as seen in *Figure 3.* We can see that the maximum heat load is 117 kW.

2.2. Alternative 1

Alternative 1 consists of an exhaust air heat pump (EAHP) for heat supply to heating, ventilation and DHW system along with district heating (as seen in Figure 4). The fresh air enters the building through fresh air valves and is exhausted by an exhaust air ventilator. The EAHP system covers the base load and additional heat demand is covered by the district heating network, i.e. if EAHP is unable to raise the supply water temperature in the heating or DHW system to the desired level, additional heat is supplied form the district heating network. The system is described in more detail elsewhere (Kõiv et al., 2012). The technique of heat recovery from ventilation air started already in late 1970s due to an energy crisis (Fehrm et al., 2002).

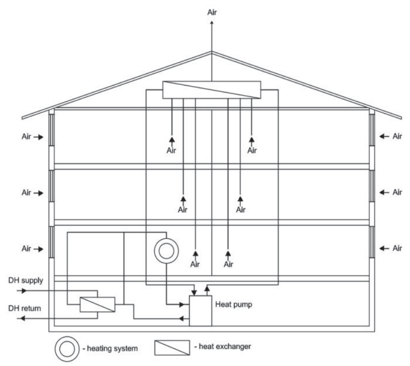

Figure 4: Basic schema of alternative 1

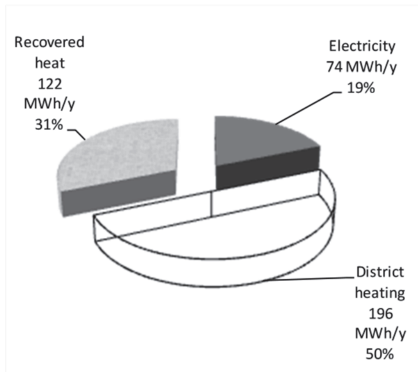

Figure 5: Distribution of heat by sources (alternative 1)

The above described actual measurements of the building were carried out in 2011. The gathered data was recalculated for the reference year. The average air change rate of the building is 0.5 h^{-1} as described in the previous chapter. Based on the measurements, the heat balance was composed for the reference year as seen in Figure 5**Error! Reference source not found.**: recovered heat – 122 MWh, district heating – 196 MWh, electricity – 74 MWh.

2.3. Alternative 2

In the case of Alternative 2, heat is totally supplied from the district heating network. The room based small ventilation units equipped with a plate heat exchanger for heat recovery are used. Figure 6 illustrates the concept of heat supply Alternative 2. The heat recovery temperature ratio for this type of heat exchangers is 60 % (Abel and Elmroth, 2007). Taking into account the heat recovery temperature ratio, supply air temperature of 16 °C and climate conditions in Tallinn, the energy efficiency of annual heat recovery for the ventilation unit is estimated to be 78 % (Abel and Voll, 2010), also offered commercially (Meltem, 2013). The average air change rate of the building is 0.5 h^{-1} as described above.

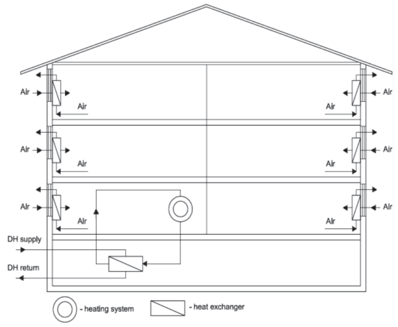

Figure 6: Basic scheme of alternative 2

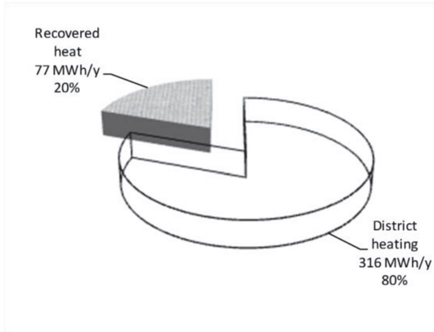

Figure 7: Distribution of heat by sources (alternative 2)

Based on the energy efficiency of annual heat recovery, the annual heat demand from the district heating network could be calculated. Heating and DHW are 100 % covered by district heating, but the heat for ventilation only partially. The recovered heat by room based ventilation units contributes 20 % to the total heat demand as seen in Figure 7.

2.4. Alternative 3

In the case of Alternative 3, the base heat load is covered by an air-to-water heat pump. In our study the peak load was covered by district heating during colder days. Regarding to ventilation, fresh air enters the building through the fresh air valves and is exhausted by an exhaust air ventilator as illustrated in Figure 8 . The average air change rate of the building is 0.5 h^{-1} as described above.

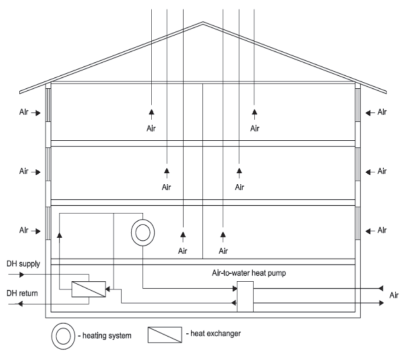

Figure 8: Basic schema of alternative 3

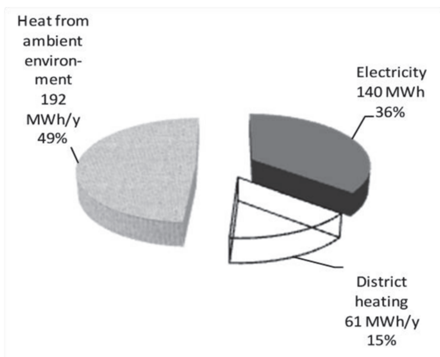

Figure 9: Distribution of heat by sources (alternative 3)

In the case of Alternative 3, the output and power consumption of heat pump were determined based on the Alpha-InnoTec LW310A heat pump unit, in particular case two units were foreseen. The calculations were made based on the Estonian reference year for energy calculation on an hourly basis. The air to water heat pump (AWHP) data in the case of different supply water temperatures, such as output vs ambient temperature and AWHP coefficient of performance vs ambient temperature were used, taking into account the electricity consumption for de-frosting cycles as well. The first priority for an AWHP unit was set to be heating and ventilation and if there was an excess of load, the AWHP was used for heating DHW as well.

The bivalent point could be seen at 0.1 °C which in general, is considered to be the optimum range 0±2 °C for residential buildings in the Estonian climate.
The seasonal coefficient of performance (SCOP) describing the performance of heat pump's average annual efficiency for heating and ventilation was found to be 2.66. For DHW the SCOP was found to be 2. The SCOP values were in good accordance with the national decree on the calculation methods for energy performance of buildings (MEC, 2012).
In the case of refurbished residential building as described above, the share of heat taken from the ambient environment could reach as high as 49 % from the total heat demand for heating, ventilation and DHW as seen in Figure 9.

3. Results and Discussion

The emissions of CO_2 and need for primary energy were calculated for the base scenario and alternatives as seen in Table 2. Natural gas is the main fuel used for district heating in Tallinn. The data on relative network loss in the Tallinn district heating network (17 %) and annual efficiency of boiler houses (92 %) (AS Tallinna Küte) is used in the calculation of primary energy demand for district heating. The CO_2 emission for district heating is calculated according to the method described in the national decree (Environment).

Table 2: Primary energy need and CO_2 emission

Item	Unit	Base scenario	Alternative 1	Alternative 2	Alternative 3
Consumption of district heating	MWh/y	393	196	316	62
DH Primary energy	MWh/y	509	254	408	80
Consumption of electricity	MWh/y	0	74	0	140
Electricity primary energy	MWh/y	0	228	0	430
DH CO_2 emission	t/y	109	55	88	17
Electricity CO_2 emission	t/y	0	81	0	152
Total primary energy	MWh/y	509	482	408	510
Total CO_2 emission	t/y	109	135	88	169

The data on the relative power network loss in the Estonian power grid (7.1 %) (Statistics Estonia, 2013) and annual average net efficiency of the circulating fluidized bed (CFB) power unit (35 %) are used in the calculation of primary energy demand for electricity production. Approximately 90 % of supplied electricity is produced from oil shale in Estonia. The estimated specific CO_2 emission factor per produced MWh of electricity by the CFB unit is 1.01 t/MWh_e (Plamus and Soosaar, 2011).
Alternative 2 exhibits the lowest primary energy demand and CO_2 emission. Alternative 3 and base scenario are quite equal from the point of view of primary energy demand. The CO_2 emission is clearly higher for Alternative 3 than for the base scenario and other studied alternatives.
In order to analyse possible relative heat loss in network the assumption were made that all buildings in city were implement Alternative 1 to 3 solutions and the proportion of used energy will remain. The total heat consumption in the district heating network of Tallinn city is 1,638 GWh, 74 % of these is consumption of residential building sector. The yearly absolute heat loss of the Tallinn district heating network is 343 GWh. According to previous experiences the total district heating consumption after renovation of building envelope and improving ventilation is expected to decrease by 35 %, which is taken into account converting existent consumption to consumption for base scenario. Applying the base scenario and alternatives on the whole residential building sector in Tallinn the relative heat loss will change as it is seen in Table 3, and as a result for all alternatives relative losses will increase.

Table 3: Alternative effects on relative heat losses

Item	Unit	Today	Base Sc.	Alt. 1	Alt. 2	Alt. 3
Total heat production	GWh	1,981	1,557	1,162	1,403	891
Heat consumption by residential sector	GWh	1,212	788	393	634	122
Heat consumption by others	MWh	426	426	426	426	426
Absolute heat loss	MWh	343	343	343	343	343
Relative heat loss	%	17.3	22.0	29.5	24.4	38.5

4. Conclusions

Alternative heat supply solutions coupled with different ventilations systems such as EAHP coupled with district heating, district heating coupled with room based heat recovery ventilation unit, and air-to-water heat pump coupled with mechanical exhaust ventilation and district heating have been studied. District heating coupled with room based heat recovery ventilation unit exhibits the lowest primary energy demand and CO_2 emission. Air-to-water heat pump coupled with mechanical exhaust ventilation and district heating and using of district heating coupled with mechanical exhaust ventilation (so called base scenario) are quite equal from the point of view of primary energy demand. The CO_2 emission is clearly higher for air-to-water heat pump option than for the base scenario and other studied alternatives. The alternative energy supply units applied by the consumers reducing the consumption of heat from district heating network and clearly increases the relative heat losses and may change economically unperceptive to run DH in area. It must be considered that actual relative heat loss calculation is much more complicated, however it is clear, that such alternative solutions have negative effect on DH network. The more detailed analysis of effects on DH network and production site, especially for cogeneration issues is under study, and will be performed in the future. One solution to avoid such a parallel heat supply units is to lower the district heating price or introduce two-tariff price system, i.e. MW and MWh bases as it is applied e.g. in Helsinki.

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Publication 3

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Evaluation factor for district heating network heat loss with respect to network geometry

Vladislav Masatin*, Eduard Latõšev, Anna Volkova

Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

Abstract

The district heating (DH) networks are widely in use in northern countries. It is often necessary to compare the efficiency of different DH networks from their size and layout and for this purpose mostly the "relative heat loss" is used. Generally, this parameter gives a first impression of the network. However, relative heat loss does not reflect the actual efficiency of pipe insulation or overall efficiency of the network; moreover, at least heat consumption density should be considered. E.g., the average relative heat loss in Denmark is about 20 % and in Sweden only 9 %. Does this mean that the Swedish network insulation is 2 times better? The data from different networks is taken in order to make an analysis and figure out a proper comparison methodology. The following main parameters are taken into account: supply, return and ambient temperatures; the network average diameter and length; annual heat consumption or linear heat density.

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Keywords: district heating; relative heat loss; linear heat density; insulation efficiency

1. Introduction

It is common that for the evaluation of district heating efficiency, the relative heat loss is used. The relative number is the rate of lost heat energy to heat output from a heating plant to the district heating (DH) network. This method can give some impression about the network. However, a more detailed analysis should be performed in order to get the correct understanding of network efficiency. For example, two similar networks may have the same relative heat loss, but the average water temperature in the first network is 85/50 °C and in the second 75/45 °C. In this case, the

* Corresponding author.
E-mail address: vladislav.masatin@soojus.ee

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first network has better insulation and higher efficiency while the second shows a higher potential for renovation. Moreover, the amount of heat consumption per network length or heat consumption density also affects the heat loss. This means that the relative heat loss figure is not always correct and can produce misleading results.

The aim of this paper is to describe and analyze the main factors affecting network heat loss. As a result, a technical evaluation factor will be found for the correct comparison of technically different DH networks. The same factor may be used as an indicator of potential network efficiency increase capacity.

Nomenclature

Q_s	annual consumed energy amount, Wh
Q_p	annual energy amount delivered to DH network, Wh
Q_{hl}	annual heat loss in DH network, Wh
q_{hl}	relative heat loss, %
t_s	annual average network supply temperature, °C
t_r	annual average network return temperature, °C
t_{amb}	annual average network ambient (soil) temperature, °C
K	network effective average heat transmission coefficient, W/m^2K
L	network route length for the pair of pipes (one pipe length), m
D_a	effective average pipe inner diameter, m
G	degree hour number, annual integration of the average distribution temperature difference, °Ch

2. Method

The way to develop a technical evaluation factor is as follows: first, the factors affecting main heat loss are found and described using the heat mass flow theory.

Second, a possibility is examined to connect the factors and describe them as one factor that can describe the technical condition of the network, give a possibility to compare DH networks and evaluate the technical improvement potential.

Finally, the real networks data analysis is performed to check the correlation of technical evaluation factor (TEF) with the real condition of networks.

2.1. *Heat loss components in DH networks*

By definition, the relative heat loss is a ratio between the lost and produced energy (energy output from a plant to the network):

$$q_{hl} = \frac{Q_{hl}}{Q_p} \cdot 100\% = \frac{Q_p - Q_s}{Q_p} \cdot 100\% \qquad (1)$$

By the heat loss definition and heat mass flow theory, the heat flux through a two-piped DH network is [1]:

$$Q_{hl} = K \cdot \pi \cdot D_a \cdot 2L \cdot G, \ where\ G = \left(\frac{1}{2}(t_s + t_r) - t_{amb}\right) \cdot 8760 \qquad (2)$$

Based on the equation we can see that the following parameters affect the network heat loss:

- Overall network heat transmission: presently used insulation materials produce a heat loss level of about 0,100–0,350W/mK from a pair of pipes for the pipes up to DN300 [2];
- Temperature level of network: drop of temperature level in a DH network will bring about the reduction of heat loss due to a smaller temperature gradient between the DH heat media and external environment. The reducing

temperature schedule in the network is one of the easiest possibilities to decrease the loss in case there are no hydraulic problems and consumer substations are able to work with lower parameters and deliver the needed amount of heat to the house heating system [3]. Lower network temperature also has positive effect on production site [4, 5];

- Network geometrical dimensions or network heat transmission area: heat loss in DH networks depends on the heat transmission area of the DH network, which in turn depends on the average network diameter and length. If other parameters in two DH networks are the same, the network with a smaller average diameter and shorter length will have smaller heat loss;
- Others: there are other factors affecting heat loss in DH networks, like the heat transmission factor from water to pipe, pipe wall material, heat transmission from pipe to soil, which mainly depends on the soil moisture content, distance between the pipes, wind speed for above-ground pipes [6].

By combining (1) and (2), it is possible to express the relative heat loss as follows:

$$q_{hl} = 1/(1 + \frac{Q_s}{L} \cdot (K \cdot 2\pi \cdot D_a \cdot G)^{-1}) \quad (3)$$

It shows that the relative heat loss also depends on the heat consumption per network length [6]. Some of the above-mentioned parameters have smaller effect on heat loss and may be neglected; some are almost the same for all networks, but most of them should be taken into account for the network efficiency calculation and network comparison.

2.2. *Factor for the characterization of technical conditions in DH networks*

In order to take all parameters as one factor, the overall heat transfer coefficient (effective average heat transmission coefficient) can be used as a correct parameter for describing the network heat loss. The basic equation for calculating the overall heat transfer coefficient is:

$$K = Q_{hl}/(L \cdot 2\pi \cdot D_a \cdot G) \quad (4)$$

In order to simplify the calculation and not include the pipe insulation material and thickness parameters into the equation, an effective average inner diameter is used here. Generally, all data required for the calculation is available for any DH network. An effective average nominal diameter (DN) can be used instead of the average diameter. However, an error up to 11 % depending on the pipe diameter and wall thickness should be considered.

The comparison of DH networks solely by the heat transfer coefficient will not give an adequate result: the networks with a higher average diameter have a smaller heat transfer coefficient because of the smaller ratio between the network area and delivered energy. For this reason, the average network diameter should be taken into consideration simultaneously with the K-coefficient. The reference conditions of allowed heat transmission will be calculated below.

The high-quality technical reference conditions are defined as preinsulated pipes class 2, buried in soil at 0.5 m depth using the calculation methodology according to EN13941 [8]. The low-quality technical reference conditions are defined as old channel layout pipes with 50 mm mineral wool insulation [9].

A gap between the calculated overall heat transfer coefficient for high-quality and low-quality technical reference conditions is shown in Fig. 1. For this parameter, the difference between old and new insulation is about threefold as also confirmed by other investigations [10, 11]. It can be seen that for the correct comparison of geometrically different networks, the overall heat transmission coefficient should be compared with the average network pipe diameter simultaneously.

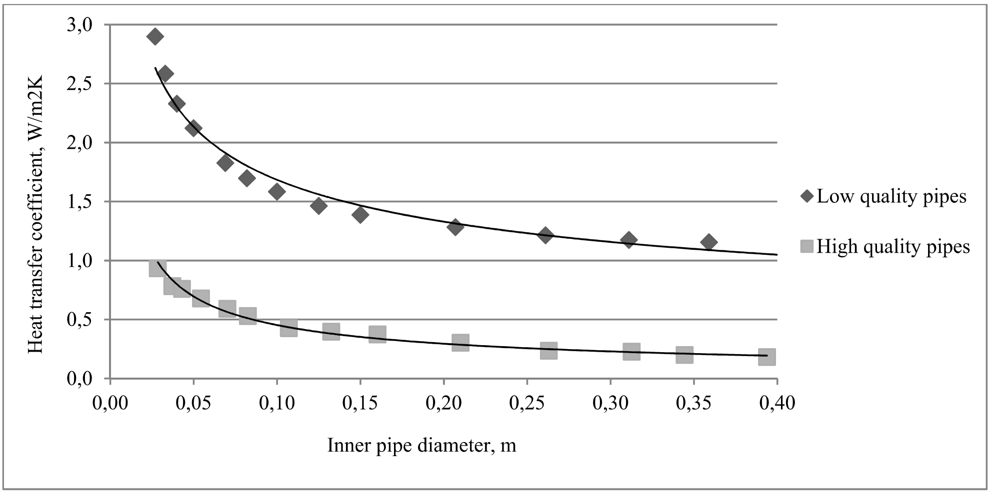

Fig. 1. Overall heat transfer coefficient for high quality (preinsulated) and low quality (old channel layout) pipes.

Both lines in Fig. 1 can be described by power functions with the sufficient accuracy (R-squared values are 0.9696 and 0.9904, respectively) where the low-quality coefficient is described by the following function:

$$K_{low}(D_a) = 0{,}7676 \cdot D_a{}^{-0{,}341} \quad (5)$$

The trend line function of high-quality coefficient is described as follows:

$$K_{high}(D_a) = 0{,}1088 \cdot D_a{}^{-0{,}619} \quad (6)$$

In order to better express the renovation potential or technical evaluation factor (TEF) of the network, the percent scale can be used. When TEF is 0 %, it means that the network has no renovation potential and the network heat transfer coefficient is the same as that for preinsulated pipes with the same inner diameter. When TEF is 100 %, it means that the network is in the same condition as a low quality network; TEF>100 % corresponds to a higher heat transfer coefficient than that in case of the low quality pipe. It may also be a sign that closing of this DH network should be considered because of too low heat consumption density.

Based on the above-mentioned assumptions, the technical evaluation factor of DH networks can be expressed as follows:

$$TEF = \frac{K_{network} - K_{high}(D_a)}{K_{low}(D_a) - K_{high}(D_a)} \cdot 100\% \quad (7)$$

2.3. *Case specific calculations*

In Estonia the data of 16 networks with different geometry (for the network length from 370 to 427000 meters) has been analyzed in order to check their TEF correlation to the real condition in networks (Table 1). The average wear of network pipes for all cases is higher than 15 years and DH networks have mostly the channel layout.

Table 1. Investigated parameters of DH networks and TEF calculation.

No	Average diameter (m)	Network degree hour (K·h)	Heat consumption density (MWh/m)	Heat transfer coefficient (W/m^2K)	Relative heat loss (%)	TEF (%)
1	0,224	498181	3,59	1,05	17,0	77
2	0,294	512416	4,16	1,03	19,0	85
3	0,188	470762	3,50	1,04	14,2	70
4	0,199	498137	3,79	1,17	16,1	84
5	0,306	510577	1,93	1,01	33,8	85
6	0,150	455520	2,62	1,17	16,1	73
7	0,123	451140	2,86	1,37	14,3	83
8	0,088	397536	2,17	2,07	17,4	125
9	0,073	401472	1,78	2,13	18,0	119
10	0,084	432960	1,68	2,49	25,3	155
11	0,166	472320	2,09	1,13	21,0	74
12	0,082	445300	2,36	1,96	16,0	113
13	0,089	615500	1,74	1,38	21,4	70
14	0,065	476256	3,18	0,82	4,8	17
15	0,140	520000	2,90	0,70	10,0	30
16	0,100	471139	3,32	0,96	7,8	41

All networks can be divided into three groups:

- The networks No. 8–10 and 12 have less than 10 % of preinsulated pipes and the insulation condition for the channel layout pipes is poor;
- Networks No. 1–7, 11 and 13 include about 25–35 % of preinsulated pipes, the insulation conditions for the rest is relatively good;
- Network No. 14 and 16 consists for 80–100 % of ten year old preinsulated pipes. Network no 15 is the reference as an average Swedish network [1].

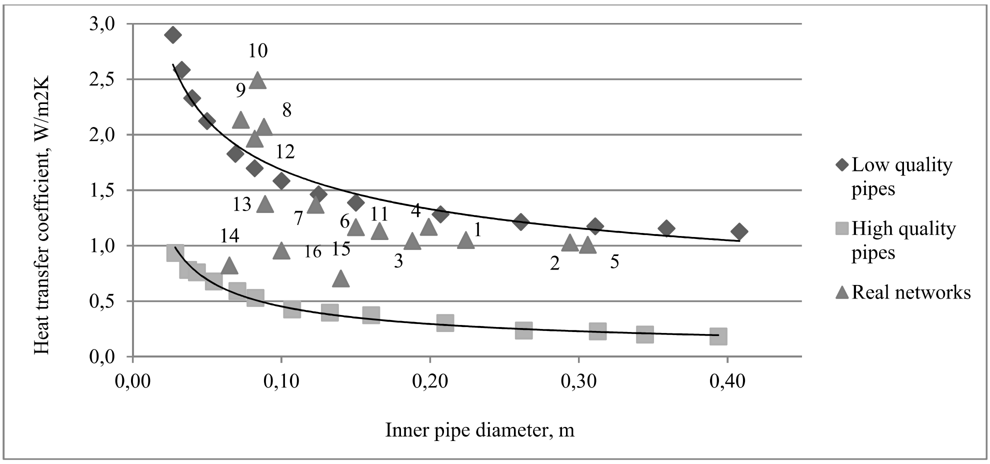

Fig. 2. Overall heat transfer coefficient for high quality (preinsulated) and low quality (old channel layout) pipes, trend lines and case specific calculation results.

3. Results and discussion

The calculation results confirm that most of the analyzed networks have a high heat transmission coefficient, which is close to the low quality reference line. Some small networks have even a higher K-factor than the low quality reference line: this can be explained by worse insulation conditions due to the smaller financial possibilities for renovation (Fig. 2). Those networks require higher attention, and insulation renovation works have to be done as soon as possible. Larger networks usually have about 30 % of preinsulated pipes, but the improvement potential is still high. The networks with higher average diameters have long transmission lines from heat plants to consumers and despite the fact that one network has relative heat loss over 30 %, it could be considered a common network.

We can conclude that the TEF as an expression of effective average heat transmission coefficient for insulation and average diameter is a valid factor to compare the DH networks insulation quality and network heat transmission performance. The described methodology requires additional calculations for the following DH network cases:

- Overground DH networks, due to the wind, precipitations and solar impact on heat transfer have not been taken into account (convection heat transfer) since the reference lines are not suitable for these cases;
- Networks where soil parameters affect heat transfer in the form of moisture: in case of wet soil, reference lines should be higher because of higher heat transfer from the pipe outside surface to soil;
- Complicated networks where more than two parallel pipes are used, or pipe diameters are different for the supply and return pipes, the length of pipes should be taken into account instead of the network length.

When considering preinsulated pipes, the difference between diverse insulation classes and single or twin pipes is too small and this cannot be taken into account in the TEF calculation. For the correct result, it is important to pay attention to the average diameter and network temperature data: a sufficient database of pipe geometry should be available and for temperature calculation, the SCADA data from different network points should be analyzed as well as the temperature of pipe surrounding medium. Especially in case of networks with many pipes located in house basements, e.g. transit lines, the network temperature level should be calculated more accurately.

4. Conclusion

An analysis of factors influencing district heat loss was made and the result described as a mathematical equation. The most important factors are: network temperature level, insulation heat transmission coefficient, network average diameter and length. As a result, an overall network heat transmission coefficient was found as most suitable factor for the network insulation quality analysis and efficiency comparison between networks. The K-factor depends on the pipe geometry and that is why it should be used simultaneously with the average diameter of reference network. Moreover, in order to exclude the pipe and insulation material properties and thickness, the average inner diameter should be used.

For a better comparison of networks, the technical evaluation factor was offered as a degree of renovation potential for the network insulation. The TEF was calculated for 14 networks with different rate of preinsulated pipes, and the correlation was confirmed.

In summary, the relative heat loss number is not a correct factor for the network evaluation, because heat loss depends on many other parameters and network insulation with high relative loss may work well and vice versa. In case of networks where a significant amount of pipes is not in the ground, for the TEF calculation additional correction factors are required for the TEF calculation.

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Publication 4

Mašatin V.; Volkova A.; Hlebnikov A.; Latõšov E. (2017). **Improvement of district heating network energy efficiency by pipe insulation renovation with PUR foam shells.** In: S. Valtere, J. Guščа (Ed.). Energy Procedia (265−269).International Scientific Conference "Environmental and Climate Technologies – CONECT 2016". Elsevier.10.1016/j.egypro.2017.04.064.

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Improvement of district heating network energy efficiency by pipe insulation renovation with PUR foam shells

Vladislav Masatin*, Anna Volkova, Aleksandr Hlebnikov, Eduard Latosov

Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia

Abstract

The paper includes description of an experiment where the insulation of 532 m long 1200 mm pipe section was replaced with prefabricated polyurethane (PUR) foam shells. As a result reduction of heat losses in comparison with old insulation by 3.35 times was calculated. After successful experiment full renovation of DH main pipe (total pipe length is 10730 m) insulation was performed. Renovation of main pipeline was finished in summer 2015. The first results show that relative heat losses in Eastern part of Tallinn supplied by renovated DH main pipe were decreased from 20.2 % to 16.0 %.

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Keywords: district heating; energy efficiency; insulation; pipes

1. Introduction

District heating (DH) has many benefits, such as reliability of heat supply, fuel flexibility, decreasing costs of heat generation due to scale effect and possibility for combined heat and power (CHP) production. But all these benefits can be reached in energy efficient DH networks only [1]. Higher energy efficiency of DH network decreases fuel consumption and amount of greenhouse gas emissions. The increase of energy efficiency in DH network can be achieved through its renovation and heat loss reduction, what can be done in three ways. The first possibility can be

* Corresponding author.
E-mail address: Vladislav.Masatin@utilitas.ee

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implemented with decreasing supply temperature in network [2]. The second approach of DH network renovation can be realised through replacement of pipe insulation [3, 4]. The third way assumes full replacement of pipes, by changing its insulation and dimension parameters if needed [5–8].

The largest DH network in Estonia is the 429-kilometre long DH network of Tallinn municipality. Majority of the pipes were built with a view of future development during the rapid industrial growth. After closing of large industries, the infrastructure of DH network has been changed and at the moment most of main pipe diameters are oversized. One of the most dramatic examples of diameter oversizing in DH is main 11km long DN 1200 pipe, which connects Tallinn city with two CHP plants (Iru plant and Väo CHP). The pipeline was built in years 1980 to 1992, diameter was chosen for heat delivery in about 400 MW. Today's heat delivery is up to 215 MW, however capacity will be increased in 2016 year up to 290 MW when additional CHP plant will be build.

As far as the pipe metal of above mentioned 11 km DH pipeline was in good condition and the insulation poor, it was decided to apply second approach to DH network renovation and change the insulation of main pipelines for reducing heat losses [9].

Large insulation replacement project was started in Tallinn at the end of 2011 and finished in 2015. The main reasons for this project was reduction of heat losses and increase reliability of DH network's main pipeline. The project started with an experiment where the insulation of 532 m long 1200 mm pipe section (part of DH main 11 km pipeline) was replaced with PUR foam shells. The insulation thickness of the supply pipe was 90 mm and of the return pipe 70 mm. The aim of experiment was to evaluate the efficiency increase of a new insulation in comparison with old one. The analysis of the experiment results and pipe operating data before, during and after renovation are presented in the paper.

2. Experiment

DH network heat loss depends mainly on the insulation thermal conductivity, temperature level and thickness of insulation while all other parameters have much less effect; the thicker the insulation, the smaller the heat loss is [10]. At the beginning the heat loss and insulation cost were calculated for different insulation thicknesses, and the optimal thickness were found for the supply pipe about 80–100mm and for the return pipe about 60–80 mm.

The expected average heat loss during heating season for new insulation with the thermal conductivity of 0.032 W/mK is 116 W/m on the supply and return pipes together for the Tallinn DH network case [11].

Expected heat losses during experiment were 131 W/m because during experiment initial water temperature in return and supply pipe was the same. In calculation factors like ductsize, heat transfer between pipes and many others were taken into account [10].

The shells were mainly made of polyurethane foam systems *Suprasec 5005* and *Daltofoam TE 44209*. PUR foam shells were used to insulate pipeline in situ. Before replacing the insulation, the foam shells were tested in the Tallinn University of Technology and the thermal conductivity was confirmed on the level of 0.0315W/mK. Two half-shells were joined around a DH pipeline, then fixed by plastic strapping tape and covered by vapor barrier foil. The experiment included the following steps:

- Disconnection of all consumers from main pipeline and connecting with portable boiler houses;
- Supply and return pipe connection on one side;
- In order to avoid thermal stratification in pipes, the circulation pump was connected to other side;
- Preheating of pipes during 24 h to reach the steady state;
- Cooling of pipeline during long period;
- Monitoring of water media temperature change in pipeline;
- Calculation of heat loss using temperature drop speed.

For the experiment an underground pipeline placed in a concrete duct with the total length of 532 m, outside diameter of 1220 mm, internal diameter 1196 mm was chosen (volume of two pipes 1195.3 m^3). The old insulation was sagged and packed. The thickness of insulation on the top of the pipe was about 2 cm and below the pipe free space between the pipe and insulation was over 10 cm. The pipeline was preheated to 73 °C degrees during 24 h to reach the steady state and avoid the heat loss for heating pipe, insulation and other elements. The initial temperature during tests was conditioned to the yearly average supply temperature about 75 °C. To avoid thermal stratification of water during the experiment, one pump was used in Point A (Fig. 1) to provide the water flow 1000 m^3/h (around 0.25 m/s) during all the time of experiment. The same weather conditions were chosen for both experiments, that's why the experiment was realized in late spring and in the beginning of autumn. The daily outdoor temperature during both experiments was 12–17 °C, the soil temperature about 12 °C.

The results taken from temperature sensors are displayed in Fig. 2. As it can be seen, the average temperature drop in the second experiment was about 3.4 times lower compared to the experiment with pipes having old insulation. It was also noticed that the air temperature in the channel decreased; unfortunately, the actual temperatures were not measured. The temperature variation during first experiment can be explained by the insufficiently preheated section of pipe, around 10 m^3 and 45–50 °C, which is less than 1 % of the whole pipe volume. The temperature variation during the second experiment was not significant. Experiment measurement data is presented in Table 1.

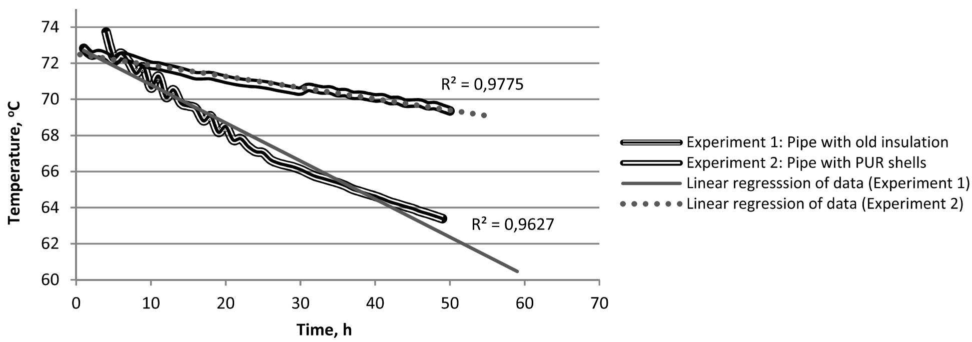

Fig. 1. Temperature measurements during experiments.

Table 1. The experiment measurements.

	Experiment 1	Experiment 2
t′, °C	73.73	72.82
t″, °C	62.89	69.36
Experiment time, h	47	50
Cooling equation	– 0.062 x + 72.63	– 0.2111 x + 73.97

The water cooling is taken liner for the further calculation because of short time and small temperature difference, the error is not over 3.5 % with confidence level of 95 %. Also using this assumption the heat loss calculation can be done using specific heat capacity calculation equation:

$$Q = m \cdot c \cdot (t' - t'') \quad (1)$$

where

Q lost heat amount during experiment, kWh;
m mass of water used in experiment, kg;
c water heat capacity, kWh/kgK;
t', t'' initial and final temperature of water, °C.

The slope of cooling equation can be used for heat loss calculation instead of taking initial and final temperature. Calculated heat losses are 494.6 W/m for old insulation and 145.9 W/m for new insulation, the heat loss reduction is 3.39 times.

3. Results of insulation renovation project

After successful experiment full renovation of DH main pipe (total pipe length is 10730 m) insulation was started. The insulation was replaced during 6 years. Insulation replacement tempo during this period is shown in Fig. 3. Due to the fact, that insulation replacement works were carried out during summer, time period used for calculation was taken from 1 May to 30 April. Heat consumption and heat losses of DH network part, supplied by main pipe are shown in Fig. 3.

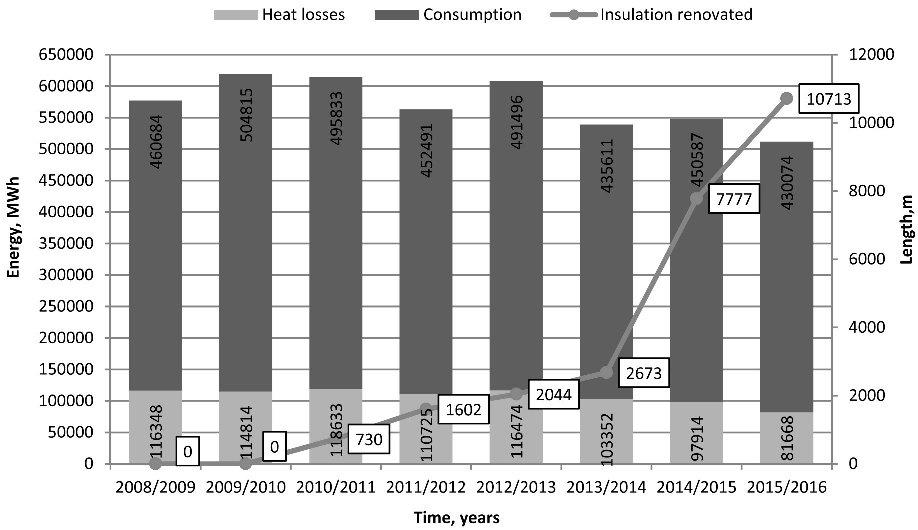

Fig. 2. Operating data of DH network area supplied by main pipe (renovation related) during and after insulation renovation project.

It should be mentioned, that after the main pipe renovation project implementation DH network reliability increased through indicating and renovating such depreciated DH elements as anchors, pipe thermal expansion compensators, concrete ducts hydro insulation and replacement of some concrete ducts. Increased reliability has allowed avoiding preheating of 4000 m reserve pipeline DN1200. The preheating was required during long periods when outside temperature dropped below – 10 °C and the estimated annual heat losses were 750 MWh.

4. Conclusions

The onsite experiment was done in order to estimate pipeline heat loss reduction by changing old mineral wool insulation to prefabricated PUR foam shells. Experiment was done on 532 m long pipeline DN1200, as a result reduction of heat losses by 3.35 times was calculated. After successful experiment full renovation of DH main pipe insulation was performed.Full renovation main pipeline were finished in summer 2015.The first results show that relative heat losses in Eastern part of Tallinn supplied by renovated DH main pipe were decreased from 20.2 % to 16.0 %. More detailed analyses can be done in future when more operating data will be collected.

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Methodology for evaluating the transition process dynamics towards 4th generation district heating networks

Anna Volkova*, Vladislav Mašatin, Andres Siirde

Tallinn University of Technology, Department of Energy Technology, Ehitajate tee 5, 19086, Tallinn, Estonia

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ABSTRACT

Currently, the 4th Generation District Heating (4GDH) is an attractive topic in the energy field as it concerns a sustainable and efficient means of delivering heat to houses. The 4GDH concept is characterised by low temperatures, low heat distribution losses, renewable and excess energy utilisation, as well as high efficiency. As a result of implementing the 4GDH concept, existing district heating systems (DHS) are undergoing massive improvement. The barriers faced by existing DHS over the course of the transition process towards the 4th generation are reviewed in the paper; the methodology for the evaluation of the DHS transition process towards the 4th generation is also presented. This methodology allows to assess the transition process dynamics, as well as helps to focus on DHS characteristics, which need to be improved. A large-scale DHS in Tallinn (Estonia) was analysed with the help of the proposed methodology. Supply and return temperatures, the share of renewable energy, and network conditions demonstrated the highest potential for improvement and had the most notable impact on the Tallinn DHS transition process.

1. Introduction

District heating (DH) has been widely used for space heating and in domestic hot water supply for many decades [1]. Nowadays, there appear to be promising possibilities for DH in future energy sector developments; however, DH must be renewed and subjected to major improvements [2].

After summarising the ideas concerning the required improvements for the future sustainable development of DH, a group of researchers proposed the concept of the 4th Generation District Heating (4GDH) in 2014 [3]. According to this concept, future district heating systems (DHS) must be able to:

- supply low temperature for space heating and domestic hot water supply to buildings (i.e., low-temperature space heating and low-temperature hot water heating, intelligent control in buildings, etc.);
- distribute heat over networks with low heat losses (low-temperature network, smaller pipe dimensions, improved insulation, intelligent control and metering);
- enlarge the share of renewable (non-fuel) energy heat sources (solar and geothermal heat) and recycle heat from low-temperature sources (heat from combined heat and power production (CHP) and waste incineration, excess heat, geothermal heat, central solar heat with seasonal thermal energy storage (TES));
- become an integrated part of smart energy systems, including smart electricity, gas, thermal grids and district cooling (CHP coupled with TES, large-scale heat pumps in CHP, with integrated CHP plants involved in securing grid stabilisation tasks);
- ensure proper planning, cost and motivation structures (integrated strategic infrastructure planning, GIS system-based planning, tariffs based on long-term costs).

Despite the fact that the 4GDH concept has already been implemented in European DHS, there are still numerous DHS that can be described as 2nd or 3rd generation networks. The main questions that should be answered are: Why is the transition process so slow? What are the obstacles, as well as possible solutions in transitioning to the 4GDH, and how can the DHS transition process be evaluated? In recent years, existing DHSs have been

* Corresponding author. Tallinn University of Technology, School of Engineering, Department of Energy Technology, Building U06, Room 227, Ehitajate tee 5, 19086, Tallinn, Estonia.
E-mail address: anna.volkova@ttu.ee (A. Volkova).

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Abbreviations

CHP	combined heat and power
TES	thermal energy storage
DH	district heating
DHS	district heating system
DHW	domestic hot water
4GDH	4^{th} generation district heating
KPI	key performance indicator
HRV	heat recovery
EAHP	exhaust air heat pump
C	transition process criterion

Parameters

Q_s	total heat consumed (sold to consumer), MWh
Qproduced energy, MWh	
E	fuel based energy generation, MWh
B	fuel amount, kg
H	net calorific value of fuel, Wh/kg
$Q_{th}^{CHP(cond)}$	additional heat, produced on CHP, due to flue gas condenser, MWh
Q_{hl}	heat losses from DH network, MWh
K	network effective average heat transmission coefficient, W/m^2
L	network length of pipes, m
D_a	average pipe inner diameter, m
t_s	annual average network supply temperature, °C
t_r	annual average network return temperature, °C
t_{amb}	annual average network ambient (soil) temperature, °C
V_{CO2}	amount of CO_2 emission for heat generation, kg
γ	fuel CO_2 emission relative value, kg/MWh
γ_e^{nat}	average national CO_2 emission for electricity generation, kg/MWh
a_{4GDH}	objective for KPI_i according to 4th generation DH and evaluation of barrier
a_i	value of KPI_i at the moment
a_o	value of KPI_i at the starting point
Q_{CHP}	CHP heat capacity MW
Q_{TES}	share of short-term TES from CHP heat capacity, %

Subscripts

th	produced heat
e	produced electricity
i	KPI number, i = 1 … 6
j	fuel type, j = 1.m

Superscripts

CHP	produced in CHP plant
H	produced in heat only boilers
NF	produced from renewable (non-fuel) energy
total	total

undergoing massive changes to become more competitive in the energy market and to offer better service to consumers in comparison to local heating. The transition process is slowed down by obstacles, and in most cases, there are ways to overcome these obstacles. Numerous researches have been focused on the challenges faced by existing DHSs in transitioning to the 4GDH. Examples of such obstacles are lower supply temperature levels [4–6] and high return temperatures [7–9]. Other examples include obstacles concerning consumer equipment [10–12], the Legionella bacteria in domestic hot water (DHW) [13,14], heat loss reduction in DH network pipes [15–17], as well as the implementation of renewable energy sources [18–21]. Additionally, there are researches, where the challenges faced by large-scale DHS have been studied [22–24]. Study results on said barriers and ways to overcome them are described in detail in the second section of this paper.

It is important to analyse the transition process towards the 4GDH. A complex multi-perspective model for assessing the transition towards the 4GDH was proposed in [25]. This complex model was designed to evaluate DHS development scenarios and draft various perspectives for the system in the future. In addition, the complex model includes system dynamics model, where the results of applying the model depend on assumptions made by stakeholders (producers, consumers, policymakers). On the other hand, the general method for evaluating the transition towards the 4GDH is required, one that it is not influenced by stakeholders but rather based on the analysis of the clear engineering indicators with input data, available for each DHS. The development of this method should be based on the analysis of the main barriers encountered by the existing DHS during the transition. The method includes DH transition progress monitoring in both past and present, which is essential for future DH development and strategy formulation. The results of this evaluation can help pinpoint weak links in the system that do not allow it to make progress as fast as possible. A detailed description of this method is presented in the third section. The application of this method is demonstrated in the fourth section using the example of the Tallinn DHS evaluation.

2. Barriers for large DH in transition to the 4th generation

In the following section, the main barriers encountered by large DHS during the transition to the 4GDH are described. Despite the fact that the main goal is to find obstacles faced by the large DH networks, most of the described problems are also found in small networks, and the solutions provided are applicable to both large and small DHS. Additionally, it must be kept in mind that all parts of DHS are interconnected and affect each other, and thus, it is not possible to concentrate only on barriers because changes in parameters on one side also lead to changes on the other side.

2.1. Barriers to low-temperature DH for space heating and DHW

A low supply temperature between 50 °C and 60 °C is one of the main characteristics of the 4GDH [3,26]. There appear to be no barriers from the production side, as it is always possible to mix the flow past the heat source with the DH to lower the temperature to the required level [27]. The first barrier arising from the network can be described as follows:the supply temperature is reduced while the return temperature remains the same or is reduced slightly, to the point that the heat is not delivered to all consumers because of hydraulic factors [28]. It is possible to compensate for this to an extent by installing more powerful pumps; however, this requires larger investments, and electricity consumption for pumping is also increased [27].

During the building renovation process, heat consumption may decrease [29], and the supply temperature may be reduced by 5–10 °C without any additional investments. However, a further decrease in temperature may prove to be a challenge, as proposed by Bolonina et al. [6]. Still, the most important barrier here is the consumer. The heating devices are often designed to operate at high temperatures, often up to 80 °C in order to decrease the heat exchange surface, and thereby reduce investment costs. Small heat exchange surfaces are one of the main reasons for higher return temperatures. One of the possible solutions to maintain a significant temperature difference in a space heating system is to use a larger radiator [4]. Otherwise, the analysis of possible temperature reductions in existing radiator systems has been provided [10,11]. Jangsten et al. studied the possibility of lower operating temperatures than those of the radiator systems that were initially designed for use in multi-family houses, and concluded that it is possible to reduce the DH temperatures to an extent [10]. However, it depends on the DH system specifications and location. Østergaard and Svendsen reported, based on case-studies with single-family houses, that it is possible to heat existing single-family houses with hydraulic radiator systems using ultra-low-temperature DH [11]. While developing this study further, the researchers analysed the possibility where only critical radiators are replaced by larger-sized radiators while the remaining radiators operate at a lower temperature [12].

A major source of high return temperatures is the DHW circulation system in multi-family houses, where an average temperature in the range of 40–50 °C is very common [13,30,31]. In order to avoid this, the following solution for DHW preparation is offered for multi-family houses:consumer substations for each flat, where each flat has its own completely separated DHW system (with instantaneous DHW heat exchanger and water volume in piping below 3 L) [27]. Yang and Svendsen studied the possibilities of reducing the return temperature for DHW under ultra-low DH conditions by installing micro-hot water storage tanks [32]. These solutions require additional investments from the consumer, and therefore, the consumer should be highly motivated.

Another reason for higher return temperatures that came to light in recent years is heat parallel consumption, i.e., heat pumps are installed to recover heat from ventilation and used to cover the base load [7–9]. Thalfeldt et al. compared the influence on return temperature of two ventilation system types with heat recovery:the supply and exhaust ventilation with heat recovery (HRV) and exhaust ventilation with exhaust air heat pump (EAHP). The results obtained by simulating the energy needs of a typical renovated five-storey apartment building in Estonia showed that the return temperature with EAHP was between 32 °C and 37 °C, while the return temperature with HRV was 22 °C [8].

Temperatures below 50 °C in DHW are considered to be one of the factors that influence the growth of Legionella. Yang et al. concluded that a decentralised substation can prove to be a good solution to not only decrease the return temperature reduction but also to decrease the risk of Legionella growth [13]. Elmegaard et al. proposed maintaining hot water temperature via supplementary electric heating between the DH and the hot water tank [14]. The main disadvantage of this method is that direct electric heating is thermodynamically inefficient.

There are ways to overcome the barrier to low-temperature DH; however, they strongly depend on the consumer. A possible solution is to introduce multi-component rates with a bonus-malus component based on the return temperature, as is the case in Copenhagen, Stockholm and Saclay [33]. Such a solution is aimed at increasing consumer awareness about heating systems and stimulating the installation of proper low-temperature devices. Local laws and regulations for heating system design are also good incentives to change consumer behaviour.

2.2. Barriers to the use of renewable (non-fuel) energy

The global idea of DH is to recycle energy that otherwise would be wasted:this kind of energy can serve as renewable (non-fuel) energy. The most significant barrier here is the location: wind, geothermal, solar, and excess energy is highly dependent on location and/or time. There is no provision of natural heat sources in case these resources are not available. Excess energy sources can be planned by a local/national government; however, it requires a precise long-term development agenda.

Ziemele et al. analysed the possibility to integrate renewable (non-fuel) energy technologies, such as heat pump and solar collectors within existing DHS. It was concluded that the main barriers to this integration are:relatively low prices of fossil fuels, fossil-based heat sources that were recently installed, and high investment costs for non-fuel energy sources [18]. While continuing the research, Ziemele et al. evaluated the following policy and support measures to overcome the barriers: subsidies for renewable energy technologies, risk reduction instrument, and energy efficiency-increasing instrument (R&D measures) [19]. Urbaneck et al. analysed possible solutions to overcome the following barriers to solar heat energy integration within existing DH system: low cost of fossil fuels and the fact that DHS is designed for very high temperatures. The solution requires a complete restructuring of the heat supply, including optimisation of hydraulics, operation, installation of a low-temperature network, development of energy transfer station for multiple dwelling units, etc. [20]. Winterscheid et al. proposed the evaluation methodology for solar thermal energy unit integration into large CHP-based DHS that entails that solar thermal energy unit supplies heat to DH subnetwork [21]. Another solution to the problem of non-controllable solar heat is a seasonal TES [34–36].

2.3. Barriers to low heat losses in networks

Reasons for network heat loss can be divided into two categories: pipe properties and environment properties. Mašatin et al. proposed to identify the pipes by heat transmission coefficient (W/m^{2}K), which is influenced by network temperature level, insulation heat transmission coefficient, network average diameter and length [37]. Pre-insulated pipes provide low heat loss levels [17]; however, pipe renovation is not always economically viable, due to the comparatively short lifespan of the network transmission part and long technical service life [16]. Barriers, in terms of the surrounding environment properties of the pipes, cannot be affected and, therefore, overhead pipes should be avoided as the yearly average heat loss from the same underground pipes is about 20%–30% less [38].

Pipe diameter is one of the heat loss factors. Pipe sizing can be calculated precisely; however, the main problem is the inability to predict consumer consumption in the long term. Additionally, rapid consumption changes during the night lead to high consumption peaks that require larger pipe diameters than otherwise required. However, it should be mentioned that a night setback control is only suitable and profitable for buildings with high specific demands and lower energy efficiency [39]. It is important to consider both prospects of heat demand and peak heat load reduction for existing consumers and connection of new consumers. Long-term DH network planning is possible only through cooperation between DH companies and local authorities.

2.4. Barriers to CHP plant integration

It was mentioned in the 4GDH concept that CHP is one of the more flexible technologies essential for future DHS [3]. The main idea of CHP is to utilise energy that otherwise would be wasted. CHP is a good way of supplying heat to DH; however, its capacity is limited by DH heat load parameters. When CHP is set up as a baseload utility, it can operate in all seasons. In case CHP has a capacity higher than that of the base load, there are a few options:CHP operates only during cold seasons when the heat load is sufficient; CHP operates with partial loads; CHP operates in condensation mode (in this case there are no benefits for the DH system). It is important to choose both the optimal capacity for the newly installed CHP plants (e.g., see Refs. [40,41]) and optimal operation mode for the existing CHP plants (e.g., see [42]). One of the barriers to CHP implementation is the economic feasibility of CHP operation, which is affected by electricity and fuel prices. The CHP integration can be achieved through various policy and support measures (e.g. tax advantages, feed-in tariffs, certificates, grants, etc.) [43].

2.5. Barriers to thermal energy storage integration into DHS

TES technologies allow DHS to become an integrated part of a smart energy system [3]. Short-term TES are mainly used for daily peak compensation in order to load CHP plants evenly during the day while avoiding the use of peak boilers [44].

Short-term TES is used along with CHP in numerous DHS. TES have been widely and successfully used in Austria and Germany [45]. Another example is Denmark, where almost all of the larger CHP plants have TES units installed [46]. In 3rd generation DHS, short-term TES are not usually used alongside CHP. For example, there is no TES used together with CHP in Estonia [47] and Latvia [48]. This can be explained by the fact that new CHPs are often installed to provide baseload during the year, and in this case, the installation of TES won't lead to a rapid payback. Because of a series of improvements made to DHS, the interest for the TES integration with a DH system has risen in recent years.

2.6. Barriers to intelligent metering

According to the 4GDH concept, remote intelligent metering is an important aspect of the future district heating [3]. It provides additional information about consumer behaviour that, on the one hand, allows a DH company to manage the grid efficiently by making precise hydraulic calculations, managing production, TES optimisation, and finding faults in substations quickly. On the other hand, the consumer will be better informed about heat consumption and, thus, motivated to decrease it [49]. The remote metering technology is well developed, and data transmission technologies are fast and inexpensive, so there are no obstacles to installing the remote intelligent metering system from the consumer's side.

2.7. Other barriers common to large DH systems

Based on the experience of a large DH system transition process towards the 4th generation, the following barriers, common to large networks were identified:

- Due to their large scale, it is impossible to make changes to the entire network over a brief period of time, these changes require years and even decades, e.g. changing pipeline for better insulation or corrected diameter. Additionally, pipe changes often have longer payback period or are altogether unreasonable from a heat loss reduction point of view.
- Hourly temperature profile optimisation might be inefficient because of long delivery times. In small and medium-sized DH networks, the supply temperature can be changed hourly to compensate for consumption peaks and keep network diameters small. But for large networks, heating media delivery time from source to the consumer can sometimes take up to 8 h depending on pipe diameter and length. Consumption peaks that are compensated by quantity and diameters in the network must be larger than optimal.
- Lack of trust between large DH companies and consumers is an obstacle to the introduction of intelligent remote substation control.
- Insufficient cooperation between production and distribution companies doesn't allow to produce and deliver heat in the most efficient way. Sometimes it is more reasonable to produce heat from one source, from a hydraulic or environmental point of view, although the economic aspect will suffer. Agreements regarding profit sharing are necessary.
- Legislation might negatively affect system efficiency sometimes in order to protect consumers. E.g. it is reasonable from a technical perspective for a heat production company to deliver and provide additional substation maintenance; however, in this case, it becomes a monopoly. Additional regulation methods are needed here for consumer protection.

The assessment of the barriers shows that there are some DH characteristics that can be improved, and the obstacles can be overcome by such improvements. The methodology for the DHS transition process evaluation was developed through the analysis of the barriers faced by the existing DHS in transition to the 4GDH.

3. Evaluation of the DH system transition process towards the 4GDH

The 4GDH concept consists of numerous comprehensive factors, and by fulfilling these conditions, the system can transit towards the 4th generation. The analysis of the encountered obstacles in the previous section allows us to determine the characteristics that can be improved in order to overcome said obstacles. Determining the achievement rate for these parameters and the potential for further improvement of these parameters can be done using the following methodology.

Based on the 4GDH concept, transition barrier analysis, and customised to large DHS, the following key performance indicators (KPI) for DHS transition were defined:

KPI_1 – DH supply and return average temperatures, °C
KPI_2 - network effective average heat transmission coefficient, W/m^{2}K
KPI_3 - the share of consumers covered by intelligent metering, %
KPI_4 - annual total renewable (non-fuel) energy for heat generation, MWh
KPI_5 - CHP heat capacity, MW; KPI_6 – the share of short-term TES from CHP heat capacity, %.

KPI_1- DH supply and return average temperatures is the most important transition process parameter directly related to the main 4GDH challenge - a reduction of supply and return temperature for space heating and DHW in buildings. *KPI_2-network effective average heat transmission coefficient* and *KPI_3-the share of consumers covered by intelligent metering* reflect the change in dynamics related to heat loss reduction in the network. *KPI_4-annual total renewable (non-fuel) energy* shows the challenge to enlarge the share of renewable (non-fuel) energy sources in DH heat production. *KPI_5-CHP heat capacity* and *KPI_6 -the share of short-term TES* describe how successful is DH in becoming an integrated part of a smart energy system.

These KPIs do not reflect all of the challenges identified by the 4GDH, such as district cooling, use of excess heat, etc. The proposed

KPIs mostly deal with 3rd generation DHS that require improvements. Integrating district cooling and excess heat largely depends on external factors. It is possible to expand the methodology and add more KPIs to the analysis for the DHS evaluation process, in case there is a potential for these improvements, and it has not been considered before.

After studying and analysing the selected KPIs, it was determined that the selected KPIs should directly or indirectly affect, to varying extents, one or two of the following criteria:

***C**$_1$* - Fuel based primary energy per delivered heat energy, MWh/MWh
***C**$_2$*- CO_2 emissions per delivered heat energy, $kgCO_2/MWh$

Reduction of C_1 is one of the processes that move DHS towards the 4th generation because heat production efficiency rises, heat losses reduce, and renewable(non–fuel) energy share in heat production rises as well. In regards to C_2, electricity produced in CHP mode (which is considered “bonus”) is the electricity that is being avoided at power plants. The national average CO_2 emission per MWh_e is subtracted from the total emission for energy generation [50] (see Eq. (5)). Such challenges as heat loss reduction, renewable energy share, CHP usage efficiency, etc. can be demonstrated by these criteria.

Graphically it can be depicted as shown in Fig. 1, where the upper right corner (Zone1) indicates 1st-2nd generation, with the highest primary fuel energy and CO_2 emission per delivered heat energy, explained by the use of fossil fuel, heat-only boilers, highest heat losses and higher supply and return temperatures. During the transition period, the DHS increases the use of the biomass-based CHP, lower temperatures, and improves the conditions of DH networks, which leads to a reduction of CO_2 emissions and a minor reduction of fuel-based primary energy usage once the DHS moves to the bottom right corner (Zone 2), which indicates 2nd -3rd generation DH. When the share of renewable (non-fuel) energy increases, heat losses decrease along with supply and return temperatures in DH networks, the transition process moves to the bottom left corner (Zone 3), which means that the DHS can now be considered a 4th generation DHS with lower primary fuel energy and reduced total CO_2 emissions per delivered heat.

Equations 1–12 show mathematical relations between some KPIs and transition process criteria. Criterion C_1 is calculated using equation (1) and C_2 using equation (2).

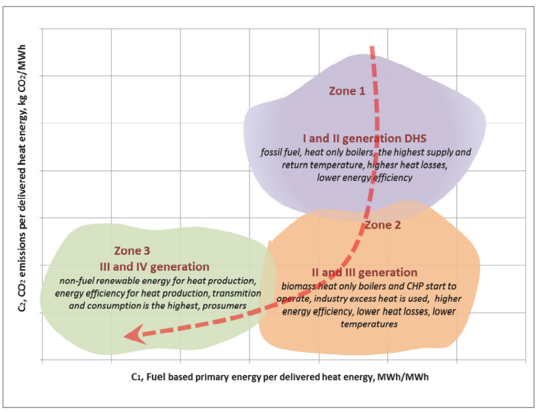

Fig. 1. DHS transition process dynamics.

$$C_1 = \frac{E_{th}}{Q_s}, \tag{1}$$

$$C_2 = \frac{V^{TOTAL}_{CO_2}}{Q_s} \tag{2}$$

Total fuel-based energy for heat generation E_{th} is calculated using equation (3)

$$E_{th} = E^H_{th} + E^{CHP}_{th} \tag{3}$$

For the fuel allocation between heat and electricity, the thermodynamic energy method is used (4) [51].

$$E^{CHP}_{th} = E^{CHP}\frac{Q^{CHP}_{th}}{Q^{CHP}_e + Q^{CHP}_{th}} = \sum_{j=1}^{m} B^{CHP}_j \cdot H_j \frac{Q^{CHP}_{th}}{Q^{CHP}_e + Q^{CHP}_{th}} \tag{4}$$

The total amount of CO_2 emissions for heat generation was calculated assuming, that produced electricity in CHP mode is considered as electricity which production is avoided at power plants, and national average CO_2 emission per MWh_e are subtracted from the total emission for energy generation (5).

$$V^{total}_{CO_2} = \sum\nolimits_{j=1}^{m} E^H_{th}\cdot\gamma_j + \sum\nolimits_{j=1}^{m} E^{CHP}_j\cdot\gamma_j - Q^{CHP}_e\gamma^{nat}_{el} \tag{5}$$

The heat, sold to consumers, can be calculated as a difference between produced heat Q_{th} and heat losses in DH networks (6)

$$Q_S = Q_{th} - Q_{hl},$$
$$\text{where } Q_{hl} = K\cdot\pi\cdot D_a\cdot 2L\cdot\left(\frac{1}{2}(t_s + t_r) - t_{amb}\right)\cdot 8760 \tag{6}$$

where produced heat Q_{th}, is calculated using equation (7).

$$Q_{th} = Q^H_{th} + Q^{CHP}_{th} + Q^{CHP(cond)}_{th} + Q^{NF}_{th} \tag{7}$$

Based on equations (1–6) final equations for criteria are

$$C_1 = \frac{\sum_{j=1}^{m} B^H_j\cdot H_j + \sum_{j=1}^{m} B^{CHP}_j\cdot H_j\frac{Q^{CHP}_{th}}{Q^{CHP}_e + Q^{CHP}_{th}}}{Q_{th} - K\cdot\pi\cdot D_a\cdot 2L\cdot\left(\frac{1}{2}(t_s + t_r) - t_{amb}\right)\cdot 8760} \tag{8}$$

$$C_2 = \frac{\sum_{j=1}^{m} E^H_{th}\cdot\gamma_j + \sum_{j=1}^{m} E^{CHP}_j\cdot\gamma_j - Q^{CHP}_e\gamma^{nat}_{el}}{Q_{th} - K\cdot\pi\cdot D_a\cdot 2L\cdot\left(\frac{1}{2}(t_s + t_r) - t_{amb}\right)\cdot 8760} \tag{9}$$

The influence of some indicators, such as short-term TES use or CHP share,H can be evaluated by a simulation process (Table 1).

The 4GDH goal for each KPI is defined based on the 4GDH concept [3]. For KPI_1 and KPI_3 these goals are clear. The goal for KPI_2 can be based on calculations and application of hydraulic optimisation software (e.g., NetSim). For KPI_4 and KPI_5 the goals can be defined based on energy potential calculations for national and municipal energy development plans and strategies. The goal for KPI_6 can be defined using simulation software (e.g. EnergyPro).

The methodological algorithm for systems analysis of DHS transition evaluation consists of the following steps:

1 *Defining the starting point of the transition.* In order to evaluate the progress of the transition towards the 4GDH, it is important to define the starting point of the transition. This point should be defined by experts; it can correspond with changes in national or EU legislations, changes in DH company ownership (purchase or privatisation), changes in DH company strategy, etc.

Table 1
Key performance indicators for DHS transition evaluation.

KPI	Symbol	Unit	Relation to C_1	Relation to C_2	4^{th} generation goal
KPI_1 - DH supply and return average temperatures	t_s,t_r	^oC;	$KPI_1 = \frac{1}{2}(t_s + t_r)$(10) Equations (9) and (10)	Equation (9) (10)	t_s=50 °C t_r=20 °C
KPI_2 -network effective average heat transmission coefficient	K	W/ m^2K	Equation (8)	Equation (9)	Calculated using hydraulic optimisation software, e.g. NetSim, Termis
KPI_3 -the share of consumers covered by intelligent metering, %	IM	%	The influence of KPI_3 should be evaluated by experts. This includes avoiding energy theft (up to 1% from total heat consumption, equations (8) and (9) can be used for calculations. Forecasting, cost planning possibilities can only be shown empirically.		100% coverage
KPI_4 -annual total renewable (non-fuel) energy for heat generation	$E_{nf.th}$,	*MWh*	Equations (7) and (8)	Applying equations (7), (9)	Limited by absolute natural geographic barriers. Potential calculations
KPI_5 -CHP heat capacity,	Q_{CHP},	MW	Equation (8) using the results of the simulation defined as $E_{th\,j}^{CHP}=f(Q_{th}^{CHP})$, (11)	Equation (9), (11)	CHP potential calculations (national, municipal)
KPI_6 - the share of short-term TES from CHP heat capacity	Q_{TES}	%	Equation (8), regression function can be formulated $E_{th\,j} = f(Q_{TES})$, (12) using simulation results	Equations (9) and (12)	Simulation software

2. *Defining the KPI value for the starting point and existing situation.* Normally, historical data is available for each KPI.
3 *Defining the 4GDH objectives for each KPI, considering the barriers.* Some *KPIs* are easy to define, such as the share of intelligent metering, or temperatures. Other *KPIs* can be evaluated using forecasts, expert opinions and analysis, simulations and modelling, etc.(Table 1).
4 Calculating the achievement rate for each KPI using equation (13)

$$R_i = \frac{a_i - a_0}{a_{4GDH} - a_0} 100\% \tag{13}$$

where

a_{4GDH} - KPI_i objective according to the 4GDH and barrier evaluation;
a_i - the value of KPI_i at the moment;
a_o - the value of KPI_i at the starting point.

5. Evaluating the KPI_i effect on two criteria: C_1 and C_2, using equations (1–12).
6. Defining transition criteria C_1 and C_2 goal values, in accordance with the 4GDH goals for this DHS.

Based on the results of the evaluation, it is possible to analyse DHS transition process dynamics during different time periods and compare different DHS, using the proposed methodological algorithm.

4. Case study: Tallinn DH system

The methodology for evaluating the DHS transition was approbated at the Tallinn DH system. It is a large system with almost 4000 consumers (buildings) and over 430 km of pipes. The main parameters of the Tallinn DHS are listed in Table 2.

The methodology was used to evaluate the transition process over the last ten years. The year 2007 was chosen as the starting point because it was the year the implementation of the company's development strategy started, and the process of the first CHP installation begun. The 2007 DH system was natural gas-based only, and heat was produced in heat-only mode.

First, the KPI were evaluated to show the extent to which these indicators have moved towards the 4GDH goals. The 4GDH goals for KPI were proposed after conducting an analysis based on the 4GDH concept and business development policy.

In order to define the 4GDH goal for KPI, the following assumptions were proposed:

- The goal for *KPI_1 - annual average supply and return temperature* was proposed as 50/20 °C according to the 4GDH concept [3].
- The goal for *KPI_2 - network effective average heat transmission coefficient* (0.4 W/m^2K) was established based on calculations using hydraulic optimisation. NetSim software by Vitec was used for the calculations (other simulation programs are also available on the market, e.g. Termis). For the calculation, the following assumptions were made: network layout remained the same; all pipe properties were removed; Logstor pre-insulated single pipe catalogue was used for choosing diameters with the following criteria [53]: pipes with D < 100 mm had velocity limit <1 m/s, pipes with D > 100 mm - pressure drop gradient <100 Pa/m; nominal consumption at −21 °C with 60/25 °C at plants and maximum pressure of 16 bar in the network [54].
- The goal for *KPI_3 — the share of intelligent metering,* for the 4GDH is 100%.
- The goal for *KPI_4 - annual total renewable (non-fuel) energy for heat generation* was calculated based on solar heat potential specific for Estonia [55], and available land, owned by the company, for solar panel installation. This value is equal to 105 MWh/year.
- *The goal for KPI_5 - CHP heat capacity*, equals 205 MW and was determined based on the DH company potential evaluation using EnergyPro simulation software [56];
- The goal for *KPI_6 - the share of short-term TES* was proposed as 20% of CHP heat capacity in order to prevent daily heat load variations. This value was calculated with EnergyPro simulation tool for DHC with CHP and short-term TES based on hourly heat load data [56];

The achievement rate for 2017 for each *KPI* is shown in Fig. 2.

It is evident that the KPIs that are closest to the 4GDH goals are *KPI_3-the share of intelligent metering* and *KPI_5-CHP heat capacity*. At present, only around 20 consumers are not connected to intelligent metering because of the data transmission problems. Regarding

Table 2
Tallinn DH system parameters (2016) [52].

Production	Biomass, CHP	28% (2017: 35%)
	Waste incineration, CHP	15% (2017: 15%)
	Natural gas	57% (2017: 50%)
	Total	1970 GWh
Consumers	3911 buildings	
Consumption	1685 GWh	
Network	Length	438 km
	Pre-insulated pipes	38%
	Heat losses	14.5%

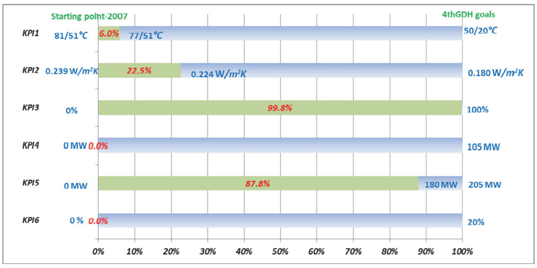

Fig. 2. KPI achievement rate (%) at 2017.

KPI_5-CHP heat capacity, the higher achievement rates for this KPI can be explained by the fact that over the last ten years, two biomass-based CHP have been providing heat; additionally, one of the plants has switched from natural gas and heat-only regime to waste incineration CHP.

Less developed KPI is *KPI_1- annual average supply and return temperature* that has been reduced only by 6% during the last decade.

KPI_2 - network effective average heat transmission coefficient, has changed by 22.5%. About 10 km of pipes are built or changed to pre-insulated pipeline every year, the number of pre-insulated pipes has risen from 20% to 40% in 10 years, with the largest pipe diameters remaining the same. There are still large pipes in use, about 1200 mm in diameter where only the insulation was changed because full pipe replacement was not economically feasible [15].

KPI_4 - renewable (non-fuel) energy for heat generation and *KPI_6 - the share of short-term TES*, are not used in Tallinn DH at the moment; therefore the achievement rate is the lowest possible, while the potential for improvement is the highest.

It is also important to evaluate KPIs' impact on the transition criteria C_1 and C_2. Fig. 3 shows the impact of each KPI on criteria C_1 and C_2. The values of the criteria were calculated, assuming that only one KPI has been changed during the transition towards the 4GDH goal, while all other KPIs remain the same. Temperature, transition coefficient and the share of renewable (non-fuel) energy resources have the highest impact on both criteria. CHP heat capacity has the highest impact on C_2 because of the CO_2 bonus approach mentioned in the previous section.

For the calculation of C_2, it was assumed that biomass burning is carbon neutral and emission factor is zero, as it is under current EU and national legislation [57]. This approach is based on the assumption that when biomass is burned, the carbon will be re-absorbed during tree growth. It should be mentioned, that there are disputes related to emission factor of biomass burning and, according to the proposal for a revised Renewable Energy Directive, CO_2 emission factor for wood chips from forest residues or poplar for a transport distance of <500 km (typical for Estonia) is 18–32.5 $kgCO_2$/MWh (5–9 gCO_2 eq./MJ) [58]. Changes to the biomass

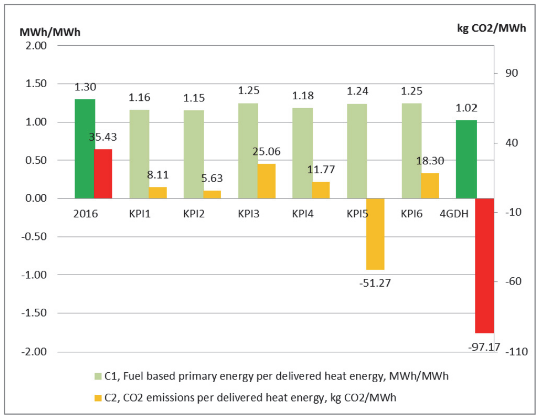

Fig. 3. Impact of KPI on transition criteria.

burning CO_2 emission factor will lead to changes in the results of transition criteria calculation.

The last marker in Fig. 3 shows the situation when all indicators have changed to 4GDH proposed goals. This point is used on Fig. 4, which is a graphic representation of the Tallinn DH transition process.

Since 2007, the amount of CO_2 emissions has been rapidly decreasing due to the new biomass-based CHP that started operation (in test mode) and partially replaced heat-only gas boilers. Furthermore, a fuel gas condenser was installed onto the operating Tallinn CHP, thereby increasing the efficiency of production. Since

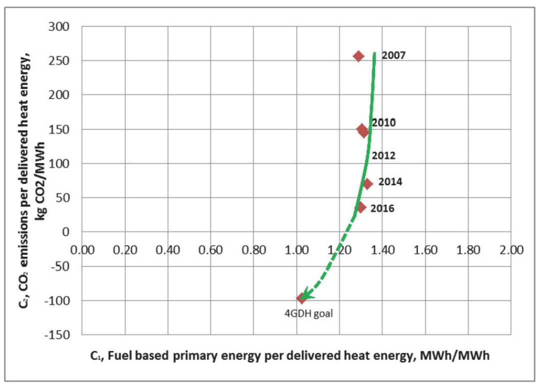

Fig. 4. Tallinn DHS transition process in 10 years.

2013, a new waste fuel energy unit of the Iru plant started its operation; it should be mentioned, that before that, the Iru plant produced heat using natural gas only. C_1 fuel-based primary energy per delivered energy has been changing very slowly. There are additional factors such as heat consumption reduction due to building renovations and warm winters. C_1 and C_2 criteria have been reduced in 2016, and it is apparent that the DH system is moving towards the 4th generation.

5. Discussions

The method presented in the paper can be used to monitor the transition process of the existing DHS that fall under the definition of 3rd generation DHS. The transition process characteristics mentioned are consistent with the transition process of many DH companies that are interested in improving the system. However, the direction for the improvement is not always obvious. The proposed method allows the evaluation of the weak links within the system that can be improved first, based on the input data, readily available for each DH company.

In case other characteristics, such as district cooling, excess heat use, etc., will turn out to be relevant to the transition process of analysed DHS, the method can be expanded by adding new KPI.

Another direction for the improvement is to use a multi-criteria approach. Through this approach, the DHS transition coefficient can be obtained to demonstrate the success of the overall DH system transition process. According to this approach, it is necessary to define the value for each parameter and indicate its relative importance. These values have a direct influence on the results of the modelling [59]. It should be noted that the determined values will be different for each network depending on actual technical, environmental and legislative circumstances.

6. Conclusion

Over the last few years, existing DHS have been further developed by way of implementing lower network supply and return temperature profiles, reducing heat losses, and increasing the share of renewable and excess energy utilisation.

Based on the reviewed literature and experience, the most significant barriers are the inability to consume low-temperature heat by the consumer and return heat media at about 20 °C; lack of knowledge and motivation for consumers to change heat-emitting devices and consumption behaviour; lack of cooperation between DH companies, government, and consumers.

It has also been stated that one of the most important barriers in large DHS is system inertia, which leads to a situation, both in the long term and in the short term, where improvements and changes can be implemented over a longer period of time as compared to small DHS, e.g., pipeline changes may require years and even decades. Most barriers can be overcome by applying a variety of solutions. However, the motivation for improvements is usually based on the financial interest of DH companies and consumers. It is possible to influence companies and consumers' behaviour by implementing measures at the national level, such as feed-in tariffs, providing reliable and comprehensible regulating mechanisms which benefit participants who use the best technologies available.

The methodology for the DHS transition process evaluation shows how successful the transition process was during the defined time period and how far has DHS moved towards the 4GDH goals. The methodology includes the analysis of the following key performance indicators: DH supply and return average temperatures, network effective average heat transmission coefficient, the share of consumers covered by intelligent metering, annual total renewable (non-fuel) energy for heat generation, annual heat produced by CHP and the share of short-term TES from CHP heat capacity. These KPIs were selected based on the 4GDH concept and analysis of the main transition barriers. The methodology allows to determine the achievement rate for each KPI and identify the factors with the highest improvement potential. Future DHS improvements should be focused on KPIs with lower achievement rates and highest impact on the transition process. The efficiency of the DHS transition process towards the 4GDH can be evaluated based on two criteria: fuel based primary energy per delivered heat energy and CO_2 emissions per delivered heat energy. The data for calculating these two criteria is usually available for each DHS. This methodology can be used by DH companies to evaluate the efficiency of their implemented development strategy.

The proposed methodology was approbated at the Tallinn DHS. The results showed that future improvements should be focused on reducing the supply and return temperature, implementing renewable (non-fuel) energy in heat production, and addressing pipe conditions.

Further research is needed in order to analyse how the proposed solutions can affect DHS transition towards the 4th generation.

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Curriculum vitae

1. Personal data

   Name: Vladislav Masatin
   Date and place of birth: 07.01.1986, Tallinn, Estonia
   E-mail address: vladislav.masatin@utilitas.ee

2. Education

Educational institution	Years	Education (field of study/degree)
Tallinn University of Technology	2011-2018	Thermal Engineering, PhD
Tallinn University of Technology	2009-2011	Thermal Engineering, Master of Science
Tallinn University of Technology	2005-2009	Thermal Engineering, Bachelor of Science

3. Language competence/skills (fluent, average, basic skills)

Language	Level
Russian	Native language
Estonian	Fluent
English	Fluent

4. Special courses

Period	Educational or other organisation
2013-2015	Open University of Tallinn University of Technology International Engineering Educator

5. Professional employment

Period	Organisation	Position
2016-…	AS Utilitas Tallinn	Production manager
2012-2016	AS Utilitas Tallinn	Research department manager
2007-2012	AS Utilitas Tallinn	Network specialist
2005-2007	Private company	Gas equipment specialist

Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi: Vladislav Mašatin
Sünniaeg ja -koht: 07.01.1986, Tallinn, Eesti
E-posti aadress: vladislav.masatin@utilitas.ee

2. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	Aeg	Haridus (eriala/kraad)
Tallinna Tehnikaülikool	2011-2018	Soojusenergeetika, doktor
Tallinna Tehnikaülikool	2009-2011	Soojusenergeetika, magister
Tallinna Tehnikaülikool	2005-2009	Soojusenergeetika, bakalaureus

3. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	Tase
Vene keel	Emakeel
Eesti keel	B2
Inglise keel	B2

4. Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja nimetus
2013-2015	Tallinna Tehnikaülikooli Avatud Ülikool Inseneri pedagoogika

5. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2016-…	AS Utilitas Tallinn	Tootmisjuht
2012-2016	AS Utilitas Tallinn	Uuringute osakonna juhataja
2007-2012	AS Utilitas Tallinn	Võrgu spetsialist
2005-2007	Eraettevõtte	Gaasiseadmete spetsialist